POLITECNICO DI TORINO

MASTER's Degree in Ingegneria Energetica e Nucleare

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Techno-economic assessment and benefit allocation in solidarity-based renewable energy communities

Supervisors

Prof. MAURIZIO REPETTO

Dott. GIANMARCO LORENTI

Candidate

IVAN ALFONSO MARIA GENTILE

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Abstract

The energy transition is a crucial aspect nowadays; the development toward sustainable and decentralized energy systems also passes through renewable energy communities. This thesis explores the development and implementation of Renewable Energy Communities, emphasizing their environmental, economic, and social impact. The study provides a comprehensive evaluation of the legal and regulatory frameworks, particularly in the Italian context, and the role of energy democracy in fostering local participation in renewable energy projects. Focusing on the case of the "Energie di Comunità" Foundation, a recently born initiative that has the aim of creating new configurations of renewable and solidarity-based energy communities on the initiative of the Archdiocese of Turin. This thesis has a focus on the methodology of the evaluation process to add new configurations to the foundation, starting from the data collection, which are then processed to obtain from the monthly consumption divided by time bands the energy profiles for every hour of the year. These profiles overlapped on the renewable generation profiles are used to evaluate the amount of electricity produced within the configuration that is consumed in the same hour; this quantity is called energy shared. Using that and other quantities calculated in the elaboration phases, it is possible to calculate the reduction of carbon dioxide emissions related to the energy consumption, the self-consumption and self-sufficiency factors, and the amount of incentives related to the energy shared. With a focus on the possible allocation of the incentives related to the configuration, which has to follow the criteria dictated by the regulation of the foundation, for example, a part of the income has to be involved in a social project in the territory of the configuration. Also reporting the case studies on which this evaluation was carried out, four configurations situated in the metropolitan area of Turin: two with only one photovoltaic plant financed by the religious participant of the configuration with 20 kW of power installed and respectively 29 MWh/year and 22 MWh/year; one configuration located in a district of Turin with two photovoltaic plants financed by religious participants with a total power installed of 32 kW and 39 MWh/year; and the last one is a more complex configuration with multiple plants financed by religious participants and private investors with total capacity of 181 kW installed and 206 MWh/year, with the possibility to access non-repayable funds for municipalities with less than 5000 inhabitants. From the results of these case studies is possible to evaluate that the configuration with less plants have higher self-consumption, so adding other members would be less effective than for the case study D configuration that would benefit more of new consumption members. At the same time, the case study D configuration, having more plants and access to higher incentives, has a higher reduction of carbon dioxide emissions than the others. Finally, a discussion of possible allocation methods is presented, not using fixed criteria as those used in the case studies but dynamic allocation methods.

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Nomenclature

α The coefficient of contemporaneity between supply and withdrawal, equal to 0.60

C_{ACI} The effective rate

CAP Threshold value of the applicable tariff

E Electric energy

F A parameter varying linearly depending on the capital contribution

FC_{zone} Correction factor for the tariff based on the location

H_j Annual intake hours of the installation/UP j, estimated according to predefined values

k coefficient for buildings

P Power

P_z Hourly zonal price

S the floor area of the building at ground level

SF Self-consumption index

TIP_a Incentive premium rate

TP_{base} Part of the tariff premium rate that dependent of the size of the plant

A_{ACI} Down payment of a production plant n

$\mathrm{Emission}_{\mathrm{REC}}$ Energy virtually self-consumed in a REC at a time t

epsilon emission factor of CO_2 equivalent for a form of energy production

SC The ratio between the sum of the total self-consumption of the users and the shared energy and the total production

SS How much of the domestic electricity demand is met through self-generation of renewable energy

Acronyms

REC
: Renewable Energy System

IEM
: Internal Electricity Market Directive

RED
: Renewable Energy Directive

CECs
: Citizen Energy Communities

CEP
: Clean Energy for All European Package

FiTs
: feed-in-tariffs

PNRR
: Piano Nazionale di Ripresa e Resilienza

GSE
: Gestore dei servizi energetici

SMEs
: small medium enterprise

PODs
: point of delivery

BoD

Board of Directors

SREC

Solidarity-based Renewable Energy Community

capex

Capital expentditure

CSV

Comma separated value file

ToU

time of use

PZO

"prezzo zonale orario"

PUN

"Prezzo Unico Nazional"

MGP

"Mercato del Giorno Prima"

NSGA-II

Non-Dominated Sorting Genetic Algorithm II

Introduction

The global transition towards sustainable energy systems has become a central objective in the efforts to mitigate climate change and promote energy democracy. Growing political instability has also led European governments to consider more the idea of becoming more independent from foreign states in the production of electrical energy. Renewable Energy Communities (RECs) have emerged as an innovative solution to integrate decentralized energy production with socio-economic benefits for local communities [1], promoting the development and dissemination of renewable technologies which, unlike fossil fuels, do not depend on resources that are located in large quantities only in certain areas of the globe. By allowing collective participation in energy generation, storage, and consumption, RECs contribute to reducing greenhouse gas emissions, enhancing energy self-sufficiency, and fostering social equity [1]. They also help to create a greater sense of collaboration among the citizens involved, as well as giving them a greater sense of responsibility by having an active role in the energy transition [2].

Energy communities have existed since the second half of the twentieth century, but they have developed mainly in some northern European states [2]. Most of these early attempts were off-grid movements, eco-villages, and basic renewable energy projects [2]. Only in the last 20 years have projects been born that aim to be partially self-sufficient while still connected to the network. This was possible thanks to a regulation on the individual states and the European Union. Studies show that without proper regulation and support in terms of incentives, RECs find it difficult to compete and develop [1].

This is precisely why Italy, which has a much smaller presence of such Community projects in its territory than other European countries such as Germany and Denmark, has decided to embark on a regulatory process based on the European RED II "Renewable Energy Directive" (RED II) and "Internal Electricity Market Directive" (IEM), developing from 2021 until the CACER TIAD decree [3] the regulation that codifies and encourages RECs.

This thesis explores the techno-economic assessment and benefit allocation within solidarity-based renewable energy communities. It focuses particularly on the Italian regulatory framework and case studies. The study aims to evaluate the financial, environmental, and social impacts of RECs. It also highlights their role in shaping the future of energy distribution. [2].

The present work is centered around the "Energie di Comunità" Foundation, an initiative promoted by the Archdiocese of Turin. The stated aim of this foundation is to establish solidarity-based energy communities that promote renewable energy adoption and allocate financial incentives to support social projects within their respective territories [4]. Acting as a community contact person, dealing with the bureaucratic part linked to the constitution of the REC.

The present thesis undertakes an in-depth analysis of four case studies within the metropolitan area of Turin, examining different REC configurations, their energy consumption and production patterns, and their overall impact on local communities. A methodological approach is developed to assess the potential of new REC configurations, starting from data collection and processing to obtaining detailed energy profiles. By overlapping these profiles with renewable generation patterns, the study evaluates key performance indicators such as self-consumption rates, self-sufficiency levels, carbon emission reductions, and financial incentives. The findings provide insights into the economic viability of different REC models and offer recommendations for optimal incentive allocation, considering both fixed and dynamic methodologies.

The study contributes to the existing literature on energy communities by proposing a comprehensive framework for evaluating their benefits and challenges. Moreover, it emphasizes the importance of regulatory support in fostering REC development and ensuring their long-term sustainability [3]. Through its findings, this research aims to provide policymakers, stakeholders, and community members with valuable insights into the potential of RECs as a pathway toward a more democratic and resilient energy system [3].

The structure of the thesis is as follows: Chapter 1 presents an overview of sustainable and solidarity-based energy communities, including their historical development, legal framework, and socio-economic impacts. Chapter 2 delves into the foundation "Energie di Comunità ETS," outlining its objectives, structure, and financial model. Chapter 3 details the methodology employed for data collection, energy analysis, and economic assessment. Chapter 4 discusses the case studies, providing real-world examples of REC implementation. Finally, Chapter 5 presents the results, followed by a discussion on the implications and future developments of energy communities in Italy and beyond.

Chapter 1

Sustainable and Solidarity-based Energy Communities

In recent years, the concept of energy democracy has become more central to common interest [5]. This concept is an innovative, grassroots approach to the transformation of energy systems [5] and was finally formalized by the Lausitz Climate Camp that said:

> “Energy democracy means that everybody is ensured access to sufficient energy. Energy production must thereby neither pollute the environment nor harm people. More concretely, this means that fossil fuel resources must be left in the ground, the means of production need to be socialized and democratized, and that we must rethink our overall attitude towards energy consumption" [5].

This inspired various initiatives that enable ordinary people to play an active role in the energy transition process and ensure that their choices have a real and direct impact on the energy balance.

One of the most successful and wide-opening in Europe are self-consumption and energy communities.

1.1 General aspects

Self-consumption refers to the ability of individual or collective consumers to generate, store, and consume electricity within their premises, reducing dependence on traditional energy supply [6]. The individual that is able to produce and consume electricity is a combination of a producer and a consumer, it is called prosumer.

The legal framework differentiates between individual self-consumption, where a single consumer generates and uses electricity, and collective self-consumption, where multiple users share locally produced energy, often within the same building or other geographical boundaries [6].

The energy communities are legal entities with various ranges of action in the energy sector that involve the participation of citizens in various forms [1]. The Clean Energy for All European Package (CEP) introduces two main types: Citizen Energy Communities (CECs) and Renewable Energy Communities [6].

- CECs, focusing on electricty only, have no geographical limitation and can operate across renewable and non-renewable energy sources

- RECs must be located near renewable energy projects and are strictly limited to renewable energy sources, not necessarily limited to electricity

Both models prioritize environmental, economic, and social benefits over profit generation, aiming to enhance local energy resilience, democratic energy governance, and sustainability.

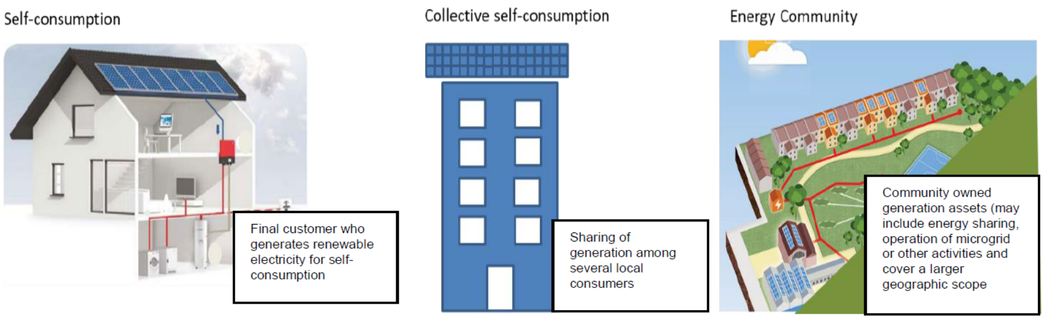

Figure 1.1: Diagram showing self-consumption, collective self-consumption and energy community [6]

In the figure 1.1 are represented different types of self-consumption and a scheam of energy community.

In the European law, energy communities are defined in two separate laws of the CEP. The revised Renewable Energy Directive (EU) 2018/2001 and revised Internal Electricity Market Directive (EU) 2019/944 [7]. The first sets the framework for 'renewable energy communities' covering renewable energy and the second one introduces new roles and responsibilities for 'citizen energy communities' in the energy system [1]. This will be treated in more detail in the next section.

1.2 History of Energy Communities in Europe

The development of Energy Communities (EC) in Europea had 3 main phases. The first phase, which is from the 1970s to early 2000s, was significantly driven by oil crises, which revealed the vulnerabilities of a centralized, fossil-fuel-based energy system [2]. Also, environmental movements for sustainability and self-reliance were on the rise. This initial development has included off-grid movements, eco-villages, and basic renewable energy projects [2]. In fact, the focus of this period was precisely the engineering practicality of renewable energies [2].

The second phase, from the early 2000s to 2008, saw a radical shift towards community energy, largely facilitated by policy frameworks and government incentives [2]. Feed-in tariffs (FiTs) and various other subsidy mechanisms introduced in many European countries have provided a strong financial motivation for the expansion of EC initiatives. At this stage, renewable energy cooperatives began to spread mainly in countries such as Germany, Denmark, or Scotland, which had advanced standards for stimulating localized energy production [2]. They tended to focus on wind and solar energy.

The third phase began in 2008 and is underway, driven by the global financial crisis and the subsequent economic recession, which has revealed the vulnerability of the current energy system, especially in southern Europe [2]. In this framework, community energy initiatives have gradually adopted energy democracy principles that emphasize citizen participation, collective ownership, and equal access to the availability of renewable resources [2]. Cooperatives like Som Energia, which integrated the generation of renewable energy with active community participation, emerged in nations like Spain and Italy. Crucially, this stage emphasizes how CE projects serve as both sources of renewable energy and catalysts for more extensive social change, tackling problems like social justice, climate change, and local economic resilience [2].

1.3 Legal framework

The Clean Energy for all Europeans Package, based on a proposal of the European Commission of November 2016 and approved in its most recent June 2019 version, includes several legislative measures in the fields of energy efficiency, renewable energies, and electricity markets. The CEP, consisting of four regulations and four directives, places the focus on the Union's energy policies and the role of consumers in meeting the challenging decarbonization targets set in Paris in the Meeting of the Conference of the Parties to the Convention on Climate Changes (COP 21) in 2015 [7]. In fact, laying the groundwork for the promotion of consumers' active participation in the energy transition through enabling tools is one of the goals of the package of regulations. This will involve end users' collective participation in accelerating the energy transition from fossil fuels to renewable [7]. Two European directives are of particular importance in relation to the End-user centrality in the transition process:

1. Directive 2001/2018 of the European Parliament and of the Council of 11 December 2018, on promoting the use of energy from renewable sources, better known as the "Renewable Energy Directive" ;

2. Directive 944/2i019 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market in electricity, also known as the "Internal Electricity Market Directive" .

1.3.1 Renewable energy directive II

The RED II directive was created to promote the development of energy from renewable sources on the territory of the European Union, encouraging the active participation of citizens and more generally of final customers [7]. The directive introduces the active role of consumers in the energy transition, defining and normalizing individual self-consumption, collective self-consumption and Renewable Energy Communities [7].

The RED II first defines:

> ''Renewable self-consumer' means a final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption, and who may store or sell self generated renewable electricity, provided that, for a non-household renewable self-consumer, those activities do not constitute its primary commercial or professional activity ." [8]

The Directive therefore defines "renewable energy self-consumers acting collectively" as a group of at least two renewable energy self-consumers acting collectively and located in the same building or condominium [7]. These new figures are being introduced to increase participation in the processes of the energy production and consumption of households; for example, the energy produced by the system built on the roof of a building can also be made available to individual condominiums and no longer only to the common services of the building.

1.4 Structure and Impact

The energy communities, as energy democracy, aim to make common people aware of *«the decisions that shape our lives should be established jointly and without regard to the principle of profit»* [5].

This prompts the business model of energy communities, which is well described in Fig. 1.2.

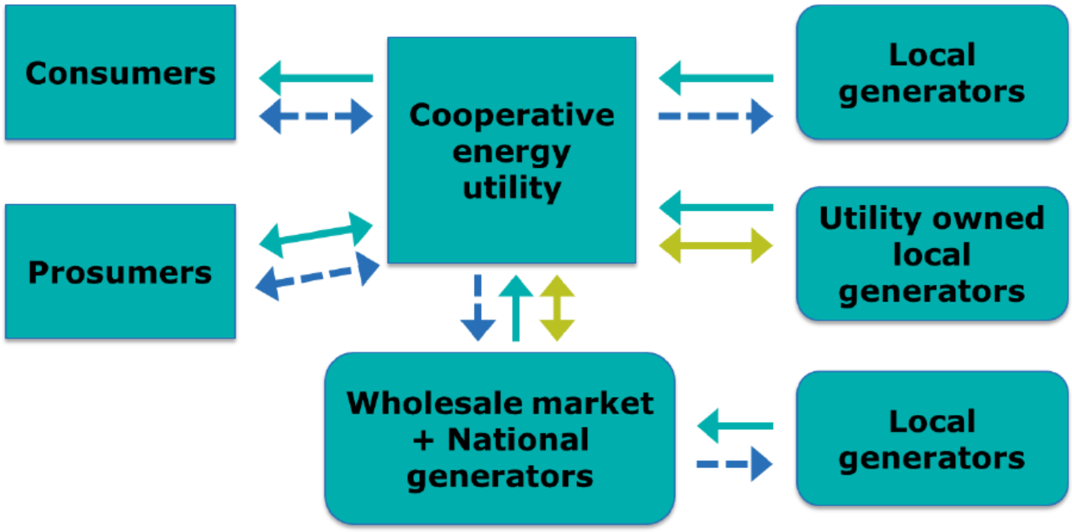

Figure 1.2: The cooperative energy utility business model [1]

This business model is based on the fact that consumers do not simply consume the energy introduced passively, but manage their demand actively or use various forms of energy storage [6], with the aim of consuming energy in the same hours that the renewable energy plant produces within the configuration, obtaining incentivize based on the current regulation from this activity. At the same time, they aim to reduce the overall consumption, to be more energy efficient [6]. This flexibility is used to increase the self-consumption, this benefits both the members of the energy community and the aggregator that has less difficulty in balancing the network [1], due to the fact that face part of the energy production and energy demand partially balance each other inside the energy communities.

This potential to generate revenue adding flexibility to the network is a relatively closed market for ordinary consumers, who with the energy communities, have the right to access these markets directly through aggregators [6]. The fact that many countries are operating under concession-based systems, ensuring that only licensed or authorized entities are permitted to develop and operate energy distribution networks [6]. The spreading of these types of configurations could lead to an higher penetration of this player in the flexibility market.

In the context of energy communities, consumption management services fulfill a dual role. Firstly, they serve to empower members by enhancing their awareness of consumption patterns. Secondly, they have the potential to reduce overall consumption [6].

The establishment of energy communities has the potential to offer a novel perspective on extant regulatory issues. For instance, an emphasis on social and environmental objectives, as opposed to economic gain, may result in a reduced focus on market-based price signals [6].

A crucial factor for these emerging business models is the potential for cost savings in grid fees compared to traditional individual connections [6]. However, the viability of these models is heavily dependent on national regulations regarding concession rights [6], as the other possible actions of energy communities are established by their Statute and the relevant European and Member State rules.

1.4.1 Activities

This leads to the fact that the activities of energy communities could be various as well as the types of energy communities there are in Europe. The most common activity in energy communities is the generation of energy [1], mostly from renewable sources such as solar, hydro, wind. The most common is solar generation [1], due to his high scalability as the plants are divided into modules that can cover from a few m^2 to hectares of land, making their use versatile for different available surfaces. For small plant the initial cost is much lower compared to hydro and wind plants, making it more easily accessible to individual private investors without imposing major limits on the investment possibilities of large companies [9]. Another point in favor of photovoltaic production plants is the distribution of the resource present in different ways throughout the globe, with various data bases that estimate with great accuracy the hourly availability of the latter in the entire solar year [9]. Most of the time, the energy communities own the generation assets.

Moreover, some of them are involved in supply activity, having different retail customers near by [1]. Retailed to that, in most of the cases, not all the energy is sold outside [1]. The energy could be shared and consumed in the energy communities, taking incentives from it [7]. This is the case of self-consumption as previously mentioned, which could be measured using the self-consumption factor, which is calculated as follows:

$$SF: \quad SF = \frac{E_{selfcons} + E_{shared}}{E_{prod}} \tag{1.1}$$

- $E_{\text{self cons}}$: Energy produced by a photovoltaic plant and self-consumed by the sampling point connected to him.
- E_{shared} : Shared energy of the energy community
- E_{prod} : Energy produced by the plant of the energy community

It also possible that energy communities manage the distribution network, as well as other energy services such as flexibility, energy storage, energy efficiency and smart grid integration [1].

1.4.2 Socio-cultural and Economic impact

The interdependency of social, cultural and economic interests can strongly affect the aspect of an energy community [1], such as the size, type and design.

Studies show that geographical location is a crucial aspect to be observed. For a economic point of view, the studies show that states with higher average income are more likely to be part of an energy community [1], this is because they have greater possibility to invest in power generation plant. This shows a limit in energy communities that while having as its basic principle in most cases the equality of its members, can lead to a de facto division of the members into classes according to the possibility of investment, in addition to limiting the spread of energy communities.

The willingness to participate in a community project is also influenced by the geographical location of the project. The social perspective highlights that there are states with a longer history of community projects that are more inclined to be a part of an energy community [1], [2]. Some examples are Denmark, Germany or Belgium which have a strong tradition of social enterprise communities [1], rather than Eastern European states, which are skeptical of community projects and have less trust in centrally planned economies [1]. Also, a higher education level is correlated to the spread of these community projects [1] because a greater knowledge of the issues concerning the energetic transition, the benefits derived from association in communities for this type of projects and a greater possibility of investment are related with a high level of education.

The European states, regardless of their social and economic context, could encourage the spread of the energy community projects adopting regulations in support of that. In fact, the rapid growth of energy community projects is correlated to policy support schemes [1], [2]. The feed-in-tariffs (FiTs), tax incentives and grants have been crucial for the development of energy community projects as shows in Fig. 1.3.

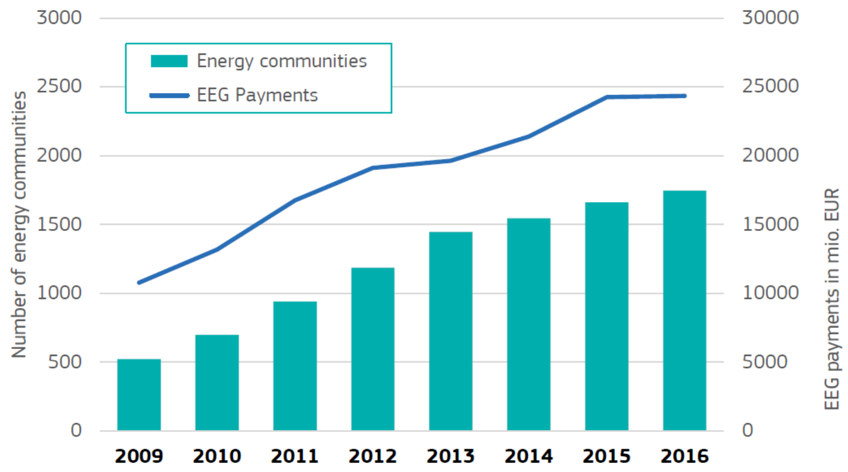

Figure 1.3: Growth of payments under the German Renewable Energy Sources Act (EEG) and citizen-led initiatives in Germany [1]

The participation in energy communities projects and therefore their success, depends on several different factors, *«Research shows that a mix between social capital, civic minded behavior, environmental concerns and interpersonal trust are important factors that motivate members to join energy cooperatives»* [1].

Not only does the context affect the energy communities, but is also true the opposite. The participation in energy community projects improve the sense of community in the members [1], also shifts the focus on energy matters from a profit driven to one that takes into account also environmental and social aspects [2].

The role of the communities is also technological, because they incentivize the construction of renewable power energy plants [1], specially for private investor in small scale plants that are highly dependent of form of incentivization [1], contributing to the energy transition to a more sustainable form of production, taking care also of the sustainability of the project in terms of energy balance, reducing the variation for the aggregator and decentralizing the production.

Energy communities also have the purpose of creating social innovation [1], in fact they can be seen as *«a type of grassroots or niche innovation that can experience learning curves within the socio-technical landscape»* [1]. They bring local value to the territory [1], creating infrastructure and reinvesting part of the profits in the community in case of community of place or solidarity energy communities, which differs from community of interest for a focus on the social aspects instead of a more profits-base one [1].

1.4.3 Participation to energy communities

Various are the reasons why people decide to be a part of an energy community; many of this are linked to the energy democracy. The main reasons are related to the environmental factor, people are more likely to invest in renewable energy production [5], to be a part of the energy transition and to reduce the pollution related to energy production [1]. Central to the will to be part of an energy community is the economic reason: the participation open the possibility to reduce energy bills and receive dividends from energy infrastructure investments [1]. In addition to these reasons, there is the lust to be a part of a community, the want to be in energy matter and the aspiration to have a positive impact on the local area [1].

1.5 Italian context

Energy communities in Italy have emerged as a promising yet still underdeveloped model for decentralized energy production and citizen participation in the transition towards a renewable energy system.

In contrast to the flourishing of community energy initiatives observed in Northern European countries, particularly in Germany, Denmark, and the Netherlands, Italy has witnessed a more gradual and distributed progression of CE projects [1], [10].

The Italian CE sector has been highly dependent on policy incentives [10], particularly the feed-in tariffs introduced between 2008 and 2013. This policy provided strong financial support for renewable energy projects, especially photovoltaic (PV) installations. During this period, several small-scale, locally focused CE initiatives were established [10], with municipalities and grassroots organizations playing a key role in their promotion. In fact most of CE at this time were created by this entity and only a small fraction by citizens [10]. However, the discontinuation of FiTs in 2013 resulted in a substantial contraction of the sector [10], thereby exposing its vulnerability to changes in government support and highlighting structural weaknesses, such as limited financial resilience and regulatory constraints [6]. Consequently, numerous CE initiatives that were initiated in the early stages either stagnated or ceased operations, encountering difficulties in maintaining economic viability in the absence of direct subsidies [10]. Despite the challenges faced, some community energy initiatives have demonstrated a capacity for adaptation, expansion, and sustainability through a transition from small, single-project models to larger, [10] diversified energy cooperatives.

Notable examples include Retenergie/È Nostra, WeForGreen, and Energia Positiva, which have successfully expanded their scope beyond local boundaries, developed multiple renewable energy projects, and integrated additional energy services [10]. These organizations have evolved beyond the mere production of renewable energy [10], progressing to the provision of electricity supply, collective purchasing schemes, and advisory services for energy efficiency and sustainability [10]. Their success has been largely attributed to innovative business models, including the integration of energy consumption and supply services, enabling members to directly benefit from lower electricity bills and stable returns on investment [10]. By expanding their operations to a national scale and introducing novel financing mechanisms, these initiatives have been able to sustain their financial viability despite the absence of FiTs and successfully navigate the regulatory barriers [10] that have historically constrained the growth of CE in Italy. The legal and regulatory landscape for energy communities in Italy has also evolved, albeit at a slower pace compared to other European countries. Until recently, the regulatory framework did not fully recognize CE initiatives, creating uncertainty regarding their role in the national energy market [10]. However, recent EU directives, cited previously, have introduced a framework for supporting decentralized, citizen-led energy initiatives, involving the member states [7], [10], including Italy, to implement national policies facilitating their development.

The key milestone in this process was the Italian Law 8/2020 [10], has allowed for small-scale collective self-consumption projects (for renewable energy plants below 200 kW) and laid the groundwork for a more comprehensive legal framework for energy communities [10]. These policy changes indicate a renewed commitment to promoting local energy initiatives, but challenges remain in terms of grid integration, financial incentives, and balancing local autonomy with national energy regulations [10].

1.5.1 Regulatory framework

The regulation in Italy is relatively young; in fact, in the figure 1.4 there are the last milestones in the Italian regulation.

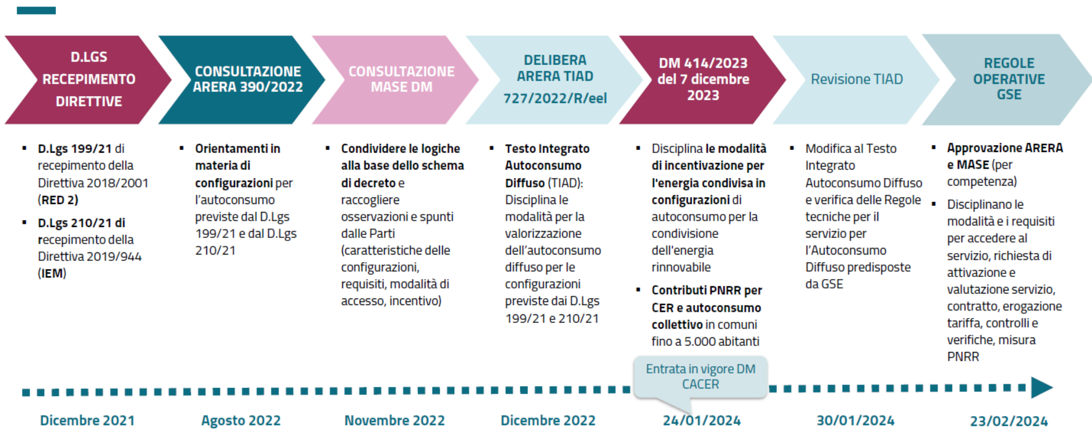

Figure 1.4: Time line of Italian regulation process [11]

The latest and the relevant legislation today is the "decreto Cacer e Tiad". That discipline the incentives tariff correlated to the electricity shared in virtual auto consumption, produced from renewable energy sources and define the criteria for the access to " Piano Nazionale di Ripresa e Resilienza " (PNRR) founds [3].

Structure of REC

There are different actors in the configuration of a renewable energy community. The referent is the person who stands between the "Gestore dei servizi energetici" (GSE) and the REC, he is registered with the active invoices issued by the GSE relating to costs and will issue them to the GSE for income [3]. Also have to ensure full, adequate and prior information to the entities belonging to the above mentioned configurations on their benefits resulting from access to incentive rates [3]. The REC referent is the person who has legal representation, alternatively it can be a producer or end customer member of the REC [3].

In order to create a REC, there have to be also present electricity producers and end customers, both have to be holders of the connection point and have to be at least one for each connected to two different connection points [3]. The connection point must be connected to the same primary cabin, whose map is on the GSE site [3]. Storage systems with accompanying technical documentation may also be included, including charging infrastructures [3].

In order to be able to configure a REC there must be at least two members who are producers and/or final consumers, at least two separate connection points to which a consumer user and a production facility is connected [3].

The REC's constituent act must have the following essential elements:

- The main objective is to provide environmental, social or economic benefits to its members, partners or airlines in which it operates, not to make profits.

- Members or partners may only be natural persons, small and medium-sized enterprises.
- The community is free and autonomous, provided that the companies that are part of it have the REC as their main activity
- The freedom for members to choose their vendor and exit the configuration at any time.
- The amount of any excess premium rate will be allocated only to natural persons or for social purposes with an impact on the territory of the REC.

Only end customers and/or producers are eligible to be members of the REC [3]. In order to exercise a power of control, they must be natural persons, small medium enterprises (SMEs), territorial authorities or religious bodies [3], the SMEs must not have the REC as their main commercial activity. Supervisory powers are those which are intended to ensure the achievement of the stated purpose and compliance with the relevant legislation [3]. If the SME is linked to other companies, it is necessary to take into account employment and balance sheet data of the associated companies in order to verify that it falls into this category [3] . It is not possible for the parties involved in the exchange on the spot or large companies to participate, their are able only to have their input energy included in the shared energy count, this includes also producers that are not members of the REC [3].

Production plants in REC

The plants included in the REC configurations must be powered by renewable sources [3], the only exception are the plant that produce energy from non-renewable sources for less then 5% of their total production [3]. Also, they need to be newly built, that is, the production site must not have been powered by the same renewable source or major parts of it in the last 5 years [3]. If the above condition is not fulfilled, they can access through upgrading existing plants, for which the share of electricity produced by existing plants must be less than 30% [3]. The share of existing plants does not access the incentives, however the electricity that is supplied by these latter is considered in the calculation of shared energy and will also be necessary to include special measuring equipment for the new section [3].

The installations must have a maximum power of 1 MW, if the installation exceeds this value only the energy produced by the part of the installation which has the said power will be taken into account [3].

Installations shall be put into operation from the day following the effective date, if not, documentation shall be submitted to prove that the installations were constructed for inclusion in a REC [3]. The components of the systems must be built to the best of the art according to the IEC standards [3], this must be certified at the request stage both for the components and for the system/UP, with documentation that attests technical specifications flooded [3]. The installed photovoltaic modules must be tested and verified according to the test specifications of UNI CEI EN ISO/IEC 17025 [3]. As regards installations to be carried out for new buildings, the part of the installation that can access the incentives and premium rate and the power share exceeding the mandatory power calculated as:

$$P_0 : \quad P_0 = k * S \tag{1.2}$$

The P_0 stands for the minimum power, S is the floor are of the building at a ground level and the building coefficient k has a value of $0.0275\,\mathrm{kW/m^2}$ for public buildings and $0.025\,\mathrm{kW/m^2}$ for other buildings [3].

The deliberate splitting of initiatives in order to increase economic profits is not allowed, in case the plants are contiguous or close, they will be considered as a single plant equal to the sum of the powers of the individual and recognized to a single owner [3].

All plants belonging to the REC must be owned by it, which must have availability and control of them [3]; this must be made possible by the producer in compliance with the agreements defined with the REC.

Request to create a REC

The access request must be submitted via the GSE portal [3], all requests sent by other means will not be considered. The application for access to the service of widespread self-consumption will include all the production plants whose electricity is used for the configuration, with prior verification by the contact person that all the plants underlie the same primary cabin [3] . This can be verified through the interactive map on the GSE portal. The referent must keep all documentation to prove what was stated in the request. Any on-site exchange contracts pertaining to producers within the configuration would be terminated by the GSE.

After the application is sent, a technical and administrative examination will be carried out in order to verify the information submitted [3], after that will be sent by certified e-mail to the address provided by the referent, acceptance of the request and if it is necessary the request for integrations, for which the referent will have 30 days to provide the necessary documentation [3]. It is possible to request a preliminary verification of eligibility for the service of widespread self-consumption, using the same channels as the official request. The GSE will reply within 60 days.

After the notification of acceptance of the request, the service of widespread self-consumption is activated, except in the case where the request has arrived within 120 days of making available the functionalities of the GSE's computer portal, in this case the service will start on the date of entry into force of the CACER decree [3].

Incentivize calculation

The financial contributions due to the configurations admitted to the REC are transferred to the referent, which, if replaced, could only be accessed by prior formal request on the GSE portal and subsequent authorization after the institution's verification of the requirements of the new contact [3]. These contributions are to promote shared electricity power, to recover the electricity consumed by the company and to withdraw the electricity supplied to the grid. The first two are recognized by the GSE for a period of 20 years, with the possibility of extension [3]. The contribution comes on a monthly basis in the form of down payment according to the power of the plants. The value of the monthly payment on account depends on the source and the sum of the powers of the production plants/UPs present in configuration that have access to the incentive [3].

the down payment is calculated as the sum of the down payment of each plant [3] according to the following formula:

$$\text{Down payment}_{\text{ACI},m} = \sum A_{ACI,i} \tag{1.3}$$

The $Downpayment_{\text{ACI},m}$ is the payment based on the power installed deliverd by GSE each month.

The value $A_{ACI,i}$ is the down payment for a certain production plant, renewable in this case is calculated as:

$$A_{\text{ACI},i} = P_i \times \frac{H_j}{12} \times \alpha \times (\text{TIP}_a) \tag{1.4}$$

where:

- P_i = incentive power of the plant/UP i
- j = power source of the system/UPi
- H_j = annual intake hours of the installation/UP j, estimated according to the values below:
  - 900 hours for photovoltaic plant in North regions
  - 1050 hours for photovoltaic plant in Center regions
  - 1100 hours for photovoltaic plant in South regions
  - 1500 hours for wind power plants
  - 1500 hours for hydroelectric plants

- 5000 hours for biogas or biomass production plant
- 500 hours for other types of renewable plants

- α = the coefficients of contemporaneity between supply and withdrawal, equal to 0.60

- TIP_a = Incentive premium rate, determined as follows:

$$TIP_a = (TP_{\text{base}} + Z + FC_{\text{zone}}) \times (1 - F) \tag{1.5}$$

- TP_{base} depends on the available power of the plant:
  - 60 €/MWh for $P_i > 600$ kW
  - 70 €/MWh for 200 kW $< P_i \leq 600$ kW
  - 80 €/MWh for $P_i \leq 200$ kW

- FC_{zone} is the correction factor for the tariff, based on location:
  - +4 €/MWh for Central Regions
  - +10 €/MWh for North Regions

- F is a parameter which varies linearly between 0 and 0,5 depending on the capital contribution.

the following year, again on a monthly basis, the contribution actually due is recalculated based on the energy measurements transmitted by the GSE [3], which makes available to the referent the data and energy quantities of each connection point on the basis of which the contributions actually due have been calculated [3]. The calculation of the effective rate is a complete calculation in the case of the valorization of all electric measure in the different time for each "point of delivery" (POD) [3], as shown in the equation 1.6. In case of some readings are missing, proceed with the partial calculations [3]. Which are only published if the resulting economic value is greater than the advance payment already granted.

$$C_{ACI} = \sum TIP_h \times EACI_h \tag{1.6}$$

The effective rate of the month "m" C_{ACI} is equal to the sum of products on an hourly basis between the premium rate $TIP_h$and the shared electricity eligible for incentive $EACI_h$.

The incentivized shared electricity for hour h is determined based on the following algorithm:

$$EACI_h = \min(E_{\text{injected},h}; E_{\text{withdraw},h}) \tag{1.7}$$

Here $E_{\text{injected},h}$, the electric energy injected inside the grid, is calculated as :

$$E_{\text{injected},h} = \sum_{y=1}^{n_y} E_{\text{injected POD } y} \tag{1.8}$$

And the electric energy withdraw from the grid is calculated as:

$$E_{\text{withdraw},h} = \sum_{y=1}^{n_y} E_{\text{withdraw POD} y} \tag{1.9}$$

- h is the generic hour of the month;
- y is the generic connection point;
- $\sum_{y=1}^{n_y} E_{\text{injected POD } y}$ is the electricity injected for sharing, expressed in kWh, as defined in Appendix A;
- $\sum_{y=1}^{n_y} E_{\text{withdraw POD } y}$ is the electricity withdrawn for sharing, expressed in kWh, as defined in Appendix A.

The incentive tariff TIP is variable on an hourly basis because it depends on energy market prices; it is calculated for hour h as follows:

$$TIP_h = \{\min\left[CAP; TP_{\text{base}} + \max(0; 180 - P_z)\right] + FC_{\text{zone}}\} \times (1 - F) \tag{1.10}$$

where:

- P_z is the hourly zonal price;
- TP_{base} is the same of 1.5
- CAP is the threshold value of the applicable tariff, defined based on the plant/section power of the same UP:

$$CAP = \begin{cases} 100 \text{ €/MWh} & \text{if } P_i > 600 \text{ kW} \\ 110 \text{ €/MWh} & \text{if } 200 \text{ kW} < P_i \leq 600 \text{ kW} \\ 120 \text{ €/MWh} & \text{if } P_i \leq 200 \text{ kW} \end{cases} \tag{1.11}$$

- FC_{zone} and F are the same of 1.5

If the actual premium rate is attributable to a share of shared energy greater than 55% if not accessed to the capital account or 45% if accessed [3], the premium rate attributable to the share of shared excess energy calculated by the formula 1.12 may be directed only to consumers other than businesses and for social purposes with spillovers on the territories where the RECs are located.

$$\%E_{\mathrm{ACI,ecc},j,n} = \max\left[0; \left(\frac{E_{ACI,j,n}}{E_{\mathrm{injected},j,n}} \times 100\right) - \text{threshold value}\right] \tag{1.12}$$

Where:

- $E_{\mathrm{ACI,ecc},j,n}$ is the incentivized shared electricity of the plants belonging to set j for year n;
- $E_{\mathrm{injected},j,n}$ is the electricity injected into the grid by the plants belonging to set j for year n;
- threshold value = 55% for plants accessing only the premium tariff; 45% for plants combining the premium tariff with a capital contribution.

The annual economic amount related to the share of excess shared electricity is determined as follows:

$$C_{\mathrm{ACI,ecc}} = \sum_j (\%E_{\mathrm{ACI,ecc},j,n} \times C_{ACI,j,n}) \tag{1.13}$$

where $C_{\mathrm{ACI,ecc}}$ is equal to the economic contribution granted for year n with reference to the plants belonging to set j.

Contributions must exceed 50 euros, otherwise they are cumulative to the following month [3].

As for the contribution to the shared electricity power, the contribution for the exploitation of electricity consumed by the company is first calculated and paid as a deposit on the contribution, then recalculated and scaled using the values taken from the measurement structures [3].

These values are then added together for all the plants belonging to the same REC configuration. For the contribution linked to the real value of electricity self-consumed, the GSE uses the amount of electricity self-consumed hourly and monthly, the latter calculated as the sum of the hours of the reference month [3]. This value is recorded for each installation and multiplied by the monthly flat rate unit charge of self-consumption, which is equal to the variable unit part of the transmission tariff defined for low-voltage users [3].

The modalities and timing are the same as for the other valorization mentioned above.

Measurements system and information needed for the GSE

The GSE acquires the data necessary for the above-mentioned actual calculations through different measurement systems. For the energy produced, meters are used with code M2 placed in each plant, the input energy is recorded in the single-section systems which do not share the sampling point with other plants by meters M1, in the other cases or upgrading of the installation or other installation with which the connection point is shared, the measurement is transmitted by the same device and allocated to each installation using algorithms defined by the GSE [3]. The energy taken is then recorded by the meter with code M1. In case one or more time data are not available, they would be estimated using standard profiles that are explained for each case in a specific document published on the GSE portal [3]. To access this service and the incentive rates, REC members are required to pay a fee to the GSE on an annual basis by offsetting the amounts paid to the referent. If one or more of the following changes are made, they shall be reported to the GSE [3].

- Addition of one or more connection points in collection;
- Removal of one or more connection points in collection;
- Addition of production plants or upgrades to production plants for which the configuration is requested;
- Upgrades to production plants already included in the configuration for which request configuration is requested;
- Removal of production plants;
- Request for withdrawal or closure of the service of withdrawal of the electricity supplied.

In addition to these, all those that involve a change in the data used for the calculation of the contributions due must be reported [3]. Maintenance work which does not involve a change in power is permitted [3]. As to comply with these prohibitions and the veracity of what is stated and demonstrated during acceptance, GSE reserves the right to carry out verifications at any time with its operators or through third parties [3]. At the end of the audit, a report will be drawn up and submitted to the contact person, who has the right to submit written submissions and documents regarding the findings highlighted in the report if they exist [3]. The obstruction of the owner of the installation to such verification, as well as any form of specified violation of the document may result in the disqualification from the right to incentives [3].

"Piano Nazionale di Ripresa e Ripartenza"

Some plants may apply for a capital grant covering up to 40% of the possible costs made available in the "Piano Nazionale di Ripresa e Ripartenza" (PNRR) [3]. It is possible to ask for it from those who have a quotation of connection to the electricity network accepted in a definitive way for the construction or the improvement of a new plant of power not exceeding 1 MW, that is located within a REC configuration and a municipality with a population of less than 5 thousand inhabitants [3]. In addition, the start of work must be after the application has been submitted and the project must be operational within 18 months of the date of eligibility. This request must be submitted by the beneficiary, who must also be the entity supporting the investment for the installation for which the contribution is requested [3]. If there are several parties that correspond to this description for the same installation, the person or persons to whom the direct or indirect ownership is attributable shall be indicated as the beneficial owner [3]. Direct ownership is a participation of more than 25 % in the capital by the natural person, and indirect ownership if this share is held with control by subsidiaries, trust companies or an intermediary person [3]. If this discriminant is not sufficient for the identification of the beneficial owner, the following discriminants will be used [3]:

- Control of the majority of votes exercisable in an ordinary meeting;
- Control of sufficient votes to exercise a dominant influence in an ordinary meeting;
- Existence of particular contractual constraints that allow a dominant influence to be exercised.

This beneficial owner is required to send the identification data and all necessary documentation (the documentation related to the plant/UP and the energy community of which it is a part) through the GSE's computer portal, at the time of sending the request, if the request is handled by another form of communication, it won't be handled according to the instructions in this document [3]. The beneficiary must keep and make available in case of verification all documents necessary to prove what was stated when applying for access to benefit. The eligible expenditure items for the capital grant include various activities necessary to build and integrate renewable energy installations [3]. These include the purchase and installation of essential components, such as inverters, support structures and electrical components, as well as the supply and installation of storage systems [3]. Costs for machinery, hardware and software equipment, including installation and commissioning costs are also included [3]. Eligible costs include construction works strictly necessary for the intervention, connection to the national electricity grid and pre-feasibility studies, including the cost of setting up configurations [3]. Design activities, geological and geotechnical surveys, construction management and safety measures are also eligible. Finally, the grant covers the costs of technical and administrative tests, as well as essential advice and support for project implementation. These expenses are eligible within the maximum investment cost of the following list [3]:

- 1500 €/kW, for plants up to 20 kW;
- 1200 €/kW, for plants with a power of more than 20 kW and up to 200 kW;
- 1100 €/kW, for power above 200 kW and up to 600 kW;
- 1050 €/kW, for plants with a power of more than 600 kW and up to 1000 kW.

The above expenses must be incurred by the beneficiary after the start of the work and supported with documentation attesting such as electronic invoices and payments made by bank transfer or postal [3]. To be eligible for the capital grant, the beneficiary must pay a contribution to the GSE to cover the costs of the investigation and must submit an application no later than the 31st of March 2025 [3]. The procedure shall begin with a technical and administrative examination of the information and documentation submitted in support of the application, with the aim of verifying the applicant's eligibility for access to the contribution [3]. Subsequently, a communication is sent to the beneficiary with the results, informing whether and what is the maximum amount of contributions that may be recognized, in addition to the technical characteristics of the plant and the CUP code, public investment project identification code [3]. If necessary, supplements will be requested. This procedure shall be concluded within 90 days of the request to the time taken by the beneficiary or other persons contacted [3]. The PNRR contribution is cumulative with other capital grants not granted by the European Union, of an intensity not exceeding 40%, calculated as the ratio between the grant received per kW and the maximum investment cost in euro/kW [3] . If there are more than one contribution, the PNRR's contribution is equal to the difference between 40% of the maximum investment cost and the capital contributions per kW already obtained. Without this limitation, it is cumulable with contributions to cover the costs of pre-feasibility studies and the expenses necessary for preliminary activities, in addition to the incentive rate reduced by 50% [3]. Super bonus, tax deductions with ordinary rates and other forms of state aid other than capital account are not cumulative. It is possible to obtain an advance of the contribution of 10% of the maximum value payable for all types of plants, which will then be followed by the balance of the remaining share [3]. For plants with a power between 200 kW and 1000 kW there is another possibility, to request the advance supply of 40% [3]. In this case, to obtain the 40% advance payment of the contribution, the beneficiary must have borne 40% of the eligible expenditure and must have communicated the start date of the work within 30 days of that date [3] . In both cases, however, to obtain the balance of the capital contribution due, the entity must have borne 100% of the expenses and have started running the plant. All by 31st of August 2026 [3].

1.5.2 Future developments

Looking ahead, the future of energy communities in Italy will depend on a combination of regulatory support, financial mechanisms, and technological innovations that can enable their scalability and economic sustainability [10]. While small-scale, localized CE projects may see a resurgence under new regulatory frameworks, larger cooperatives like Retenergie/È Nostra and WeForGreen are likely to continue expanding through national-scale community-driven models that integrate renewable energy production, supply, and efficiency services [10]. Additionally, the growth of digitalization, smart grids, and blockchain-based energy trading platforms presents new opportunities for energy communities to enhance their operations and increase citizen participation in decentralized energy systems [10]. However, policy stability and clear regulatory guidelines will be crucial in ensuring that CE initiatives can operate effectively without being overly dependent on government incentives [10]. If properly supported, energy communities in Italy could play a significant role in democratizing energy production, fostering local economic development, enhancing grid resilience, and accelerating the country's transition towards a sustainable and decentralized energy future [10].

Chapter 2

The foundation "Energie di comunità ETS"

2.1 General framework

The creation of a renewable energy community, proposed by Archdiocese of Turin has been possible thanks to the creation of the foundation named " FONDAZIONE ENERGIE DI COMUNITA'ENTE DEL TERZO SETTORE" [4], also known as "FONDAZIONE ENERGIE DI COMUNITA' ETS".

The creation was inspired by the encyclical "Laudato si", in particular by article 179 which reads (translation of the original version in Italian):

«In some places, cooperatives are being developed for the exploitation of renewable energies that allow local self-sufficiency and even the sale of excess production. This simple example shows that, while the existing world order is showing unable to take responsibility, the local authority can make a difference. It is there that a greater responsibility, a strong sense of community, a special ability to care and a more generous creativity, a deep love for one's own land, as well as thinking about what you leave to your children and grandchildren. These values have very deep roots in the aboriginal peoples. Because the law sometimes proves insufficient due to corruption, a political decision under pressure from the population is required. Society, through non-governmental bodies and intermediary associations, must compel governments to develop more stringent regulations, procedures and controls. If citizens do not control political power, national, regional and municipal even a comparison of the environmental damages is possible. On the other hand, municipal legislation can be more effective if there are agreements between neighboring populations to support the same environmental policies» [12].

The foundation created for an indefinite period [4], aims to promote energy sharing in a territory that subvert the same primary cabin [4], to establish a stable model for supporting fragility [4]. The foundation is a non-profit organization and is managed efficiently, effectively and economically [4]. The registered office is in Turin, however the operations are in the north of Italy [4].

2.2 Aims and Activities

The main mission of the foundation, as written in the statute is (translation of the original version in Italian):

«The main objective of the Foundation is to provide environmental, economic and social benefits at community level to its members or local areas in which the community operates and not that of financial profits.» [4].

In addition to this, has its main object the assumption of the exploitation and encouragement of shared electricity produced by the plants owned or under the control of the same [13].

To be able to perpetrate this objective, the foundation pursues civic purposes, solidarity and social utility, inspired by the values of fraternity, solidarity, charity and the social thought of the Church [4]. This is possible with intervention and service to protect the ambient and his resources [4], as well as the production, storage and sharing of renewable energy [4]. The energy produced inside the configuration comes from the photovoltaic plant of his property or the one under the control of the foundation It also undertakes to provide charity and aid for disadvantaged people [4].

The foundation to produce, consume, store and share will relish the production plant of its property or acquire the availability [4], the energy produced will first be used inside the energy community by the members and secondly sold outside of the renewable energy community [4]. It organizes the sharing of energy produced by the plant they own or the one made available to it [4], [13], monitoring the production and consumption of the members to be able to verify and report [4]. To be able to do that, the participants give the foundation a mandate for the request to access to the exploitation and sharing of shared electricity [13].

The foundation will also cure the relations with the GSE [4], [13], through which it is able to access to incentives and refunds connected to the energy shared, permitting that the members achieve the benefits correlated to that, with the respect of the modality chosen by the board [4].

The foundation also involves the entire local community on the importance and value of environmental sustainability, inspired by the paradigm of integral ecology outlined in Laudato Si' [4]. The aim is to support a transformation in our lifestyles and energy consumption habits, both individually and collectively, starting with participants from the Solidarity-based Renewable Energy Community (SREC) [4]. To help the people in need, the foundation develops projects to combat energy poverty, including the installation of renewable energy facilities, for the benefit of its members and third parties in energy-stressed situations [4], [13].

To achieve these objectives, the foundation could collaborate with public or private entities, institutes, associations, foundations, universities, bodies, companies, cooperatives, and consortium, whether or not they are for profit [4], [13]. The foundation could also organize fundraising activities.

2.3 Finances and Wealth

The foundation has its own assets, which are made up of an initial donation of 30,000 euros from all the movable and immovable property owned by the foundation [4]. This wealth can be increased by donation of contributions from public or private bodies [4], in the form of a spontaneous donation or stimulated by fundraising activities organized also in continuous form by the foundation, with the aim of offering goods and services of moderate value in order to obtain an economic return [4]. Another form of entry is obviously linked to the renewable energy community configurations. Related to the renewable energy communities the foundation accesses the "tariffe premio incentivanti" recognized by the decree CACER and the rules of the GSE and the contribution for the valorization of electricity self-consumed determined by art.6 of the TIAD, as better described in 1.5.1.

The repartition of the amounts linked to the above incentives follows the following criteria in descending order of priority [13]:

1. Ensure the sustainability of the foundation and its legal and fiscal support, shared energy analysis and management, as well as social projects, the return of results to the citizen and the promotion of the foundation.

2. Ensure the sustainability of the investment of religious and ecclesiastical participants by covering the living expenses related

3. Ensure coverage of agreements with third parties.

4. To devote a share to social activities in the foundation's territory

5. Allocate a quota to the producers and private prosumers that are part of the configuration and are not ecclesiastical religious participants, share which will be distributed proportionally to the contribution made to the shared energy.

6. Allocate a share to consumers contributing to shared energy, in proportion to the contribution.

The refund of amounts will be made by bank transfer from REC [13]

The foundation excludes any direct or indirect profit [4], the assets, including all forms of income, are used for carrying out the state activity for civic purposes, solidarity and social utility [4]. It is forbidden to distribute the surplus of management to the founders, workers, collaborators or administrators [4] . Indirect forms of distribution of earnings are considered as not proportional to the activity performed, payment to workers more than 40% compared to those provided for in collective agreements and the disposal of goods on terms more favorable than the market [4]. Any profit or surplus from operations will be used to carry out institutional activities or those directly related to them [4]. The foundation, assuming the role of referent, will share the inventions in the manner defined by the rules and by the assembly of participants, having the obligation to inform the final consumers of the benefits resulting from access to incentive rates [4].

2.4 Members of the Foundation

> "In addition to the Founders, only entities with sampling points or feeding points located on the national electricity network can obtain the qualification of Participants, have the requirements of the current legislation on renewable energy communities and whose purposes and interests do not conflict with those of the Foundation" [4].

Participants are admitted by resolution of the Board of Directors (BoD), based on the presence of the requirements necessary to ensure the effectiveness of the energy community [4].

The request for admission must be related to different documents. For the subjects that aren't a physical person, by a copy of the resolution authorizing and ordering the entry of the subject into the Foundation and a copy of the last approved financial statements [13]. For the producer, the commitment to enter into an agreement to confer the availability and control of production facilities on the foundation [13]. For the consumer, the commitment to enter into an agreement to valorize and incentivize the electric energy shared inside the configuration [13]. For all, a copy of the Foundation's Articles of Association and Rules signed and a copy of the identification document of the applicant or legal representative [13]. After receipt of such a request, if the board of directors needs to request clarifications and/or supplements on the documentation originally submitted, the reply must be received within 20 days of such request [13]. If the request is made for a configuration that for the correct, efficient and economical management, does not need to expand the number of participants, the applicant will be placed on a waiting list [13].

If there is transfer of ownership of a take-up or an input point, the participant position would also be passed on [4]. However, the transferee would not assume all obligations of the transferor except for commitments regarding plant availability [4]. The participants may be of various types, the archdiocese of Turin is founder promoter and can attribute the status of founder to other archdioceses that request to join the foundation [4]. Religious and ecclesiastical bodies as well as territorial bodies also have their own category. Finally, in addition to the ordinary participants who are the holders of collection points who decide to join the foundation [4], there are senior figures in a given area who are unanimously appointed by the BoD and who do not participate in benefit sharing but may be mandated to coordinate and perform high-profile activities [4].

All the information and documentation of every participant is stored in a database [13], which is updated at the time of admission of a participant and by 31 January of each calendar year [13]. In the event of a change in the information provided, the participant is required to notify such change voluntarily and promptly [13].

The status of a participant gives rights to the owner of the title, such as choosing the electricity vendor, participating in activities promoted by the foundation, filling certain positions in the foundation, voting at meetings, and consulting the books of the foundation [4]. In addition to that, there is also the obligation to comply with the rules of the Statute.

The qualification may be terminated at any time by the participant, with a notice of receipt by the foundation, such as a registered letter [4]. Notice must be given 30 days in advance for simple consumers and 6 months in advance for those with a plant. The foundation reserves the right to exclude participants in case of loss of eligibility, for non-cooperative conduct or for moral or material damage to the foundation [4]. For institutions and legal persons, a settlement may be effected without a specific reason. The member who is excluded or removed does not have any right to the assets.

2.5 Organization

2.5.1 The President

The foundation is composed of various bodies, at its top there is the President of the Foundation, who is appointed for 3 years by the Archbishop of Turin [4]. Its function is to legally represent the foundation to third parties, promoting relations with institutions and business entities in order to establish relationships. In addition, the President convenes and chairs the meetings of the Board, as well as the Meeting of Participants and the Scientific Technical Committee [4].

2.5.2 The Board of Directors

The Board of Directors shall consist of a minimum of 3 and a maximum of 6 members [4]. It is normally composed of the President and a member appointed by each of the following entities: Founder Committee, Meeting of Participants and Public Participants [4]. If there are more than ten configurations, the Founder Committee and the Meeting of Participants shall be entitled to appoint another member of the Board [4].

The members of the Board of Directors lapse after approval of the financial statements for the third year following their appointment, at least 120 days before this date the President is required to request the expected bodies the appointments due to them [4]. These bodies will have 60 days from the receipt of the above-mentioned communication to indicate the names, if this does not happen the appointment would be made by the committee of founders, which in case of no agreement would transfer this responsibility to the Archdiocese of Turin [4]. Members of the Board of Directors may be reappointed, dismissed or removed from office even if no cause is present [4]. However, there are reasons for exclusion from the statute, such as loss of qualifications, failure to comply with statutory and regulatory rules, damage to the image of the Foundation or its assets, or failure to attend three consecutive meetings of the Board of Directors without justification [4]. The exclusion is carried out by a majority vote of the Board of Directors, excluding the subject matter of the resolution; in case of parity, the President's vote prevails [4]. In the event of dismissal or resignation, the body that appointed the member who resigned or was dismissed must make the appointment [4].

The Board of Directors is convened by the President of the Foundation, on his own initiative or at the request of at least one of its members [4], its members are notified 5 days before the date of the meeting or in case of urgency 2 days before. The sessions can be held in person or by teleconference, provided that all are identifiable and have the possibility to intervene in real time on the treatment of the topics discussed [4]. The Supervisory Body is also present at these meetings, although it does not have the right to vote, in addition to the secretary who is responsible for drawing up the minutes signed by him and the President, where the topics discussed at the meeting are also described in the notice of convocation of the members of the Committee and the decisions taken at the meeting [4]. The secretary is chosen by the members of the board from among them [4]. In order to be considered valid, a majority of the members of the Board of Directors must be present and, if all the members of the Board of Directors and the members of the Supervisory Body are present even without prior notice, the time may be dealt with as in a regular meeting provided that no one objects to the subjects discussed [4].

The topics that can be dealt with by the Board are various . In the economic and financial field, the Board of Directors establishes the directives concerning the investments of the assets of the Foundation, manages the conclusion of contracts with public and private bodies and deals with the employment relations, recruitment, dismissal [4]. Approves the foundation's annual financial statements and decides on the allocation of any operating surplus [4]. In the administrative sphere, the Board of Directors implements the programs of the foundation, according to the general guidelines and objectives of the latter, promotes the participation of the foundation in any calls for proposals, competitions or events organized by it [4]. The Board of Directors approves the REC Regulation, defines the number and extent of the configurations and admits participants who request it in accordance with the rules laid down by the Regulation [4]. In addition to the above topics, the Board of Directors is obliged to consult the Public Participants on matters within their competence [4], although their opinion is not binding, and they are obliged to take up proposals on matters submitted by representatives of the configurations [4].

2.5.3 Other bodies of the Foundation

Another central organ in the foundation and the Founders' Committee, it establishes the goals and directions of the foundation [4]. It is composed of the founder promoter and the founders and in order to be able to deliberate, it is necessary that at least the majority of the founders are present, besides the founder promoter [4]. The Founders' Committee appoints two members of the Board and two members of the Scientific Technical Committee.

The Scientific and Technical Committee has a high-profile advisory function, with members serving for five years [4]. It is composed of the foundation president and the following bodies: Board of Directors, Founders' Committee and the assembly of participants.

The Meeting of Participants, composed of a representative of the founders, a representative of the public participants and a representative for each configuration, gives advisory opinions on the matters to be decided and has the task of appointing the Control Body [4].

The Control Body, composed of one or three persons, at least one of whom is a member of the Bar Association, oversees compliance with the law, the Articles of Association, carries out the statutory audit of accounts, monitors compliance with civic purposes , social unity and draws up a report on each meeting, which reports on its control activities [4]. Its components last in office for about three years [4].

For each configuration, a configuration assembly composed of ordinary participants and ecclesiastical religious participants is constituted. The assembly may decide to approve a configuration regulation, express opinions that are not binding on the board of directors or appoint its own configuration representative [4]. The deliberation is based on the vote points of its members, the ecclesiastical religious members have 15 points/vote each, with a maximum of 45 points/vote total for this category [4]. The rest of the points/votes are divided among the ordinary participants, the number of maximum points/votes is 100 [4].

Chapter 3

Methodology

3.1 Data collection

Data collection is the first phase in the evaluation process.

Public and private entities, that have shown interest in joining a REC shall provide some data to enable the veracity of requirements necessary for being part of a configuration and to carry out the activities required for the preliminary feasibility study of the configuration [3], [4]. The data made available by possible new participants are :

- General information (first name, last name).
- Point of delivery, an alphanumeric code consisting of 14 or 15 digits, the first two are IT in Italy [14]. It identifies the physical point where the electric energy is provided by the supplier and taken from the final consumer.
- Address of the POD.
- Power and contract type of the POD, the type of electric user could be public illumination (ip), a low-voltage user connected to the distribution grid (bta), a medium-voltage user connected to the distribution grid (mta).
- Electricity bills refer to the previously mentioned POD for each month of the year. The electricity bill is a document provided by the distributor with the information about the electricity consumption of the final user.
- If the user is a prosumer, a user that consumes and produces electricity, details about the roof where the photovoltaic system would be installed.

The general information correlated to the reference point of delivery is necessary to be able to verify the necessary requirements to enter in a REC configuration and in the Foundation, as well explicated in 1 and in 2.

Instead, the power, contract type and electricity bills collected for each new possible member are used for the creation of consumer profiles used in the REC evaluation phase. The electricity bills have the consumption distinguished into 3 time bands [15]:

- F1 from Monday to Friday, from 8:00 to 19:00, excluding national holidays.
- F2 from Monday to Friday, from 7:00 to 8:00 and from 19:00 to 23:00; the Saturday from 7:00 to 23:00, excluding national holidays.
- F3 from Monday to Friday, from 00:00 to 7:00 and from 23:00 to 00:00, the Sunday and national holidays.

The different time bands are associated with different energy demands, that influence the price of electricity, a time band with lower demand has a lower price. It's possible to have a mono-phase contract, in which all the electricity taken from the grid is paid at the same price no matter the time.

All the data collected are saved into two different Excel files, one that contains for each POD the information useful to identify it, such as the address, the available power at the point of withdrawal, the type of contract of the consumer and a general description of the activity in that POD, for example residential, enterprise and the type of enterprise, as shown in the table 3.1.

Table 3.1: Structure of the data collected for different users

POD	Address	Type	Power (kW)	Description
IT************1	Via *** N **	bta	10	Church
IT************2	Via *** N **	bta	3	Church
IT************3	Via *** N **	bta	3	Church
IT************4	Via *** N **	bta	5	Church
IT************5	Via *** N **	bta	15	Church
IT************6	Via *** N **	bta	6	Church
IT************7	Via *** N **	bta	3	Church

The other excel file has for each POD the consumption data and the total consumption in every month, shown in the table 3.2. The consumption data are used in the elaboration phase to obtain the consumption profile of the users.

3.1.1 Standard profile

In addition to the consumption provided by users, it is also possible to enter standard consumption within the configuration to simulate users for whom consumption data

Table 3.2: Structure of the file with the energy consumption data for each month

POD	Month	Year	F0	F1	F2	F3	Total
IT******1	1	2022	-	390	257	445	1092
IT******1	2	2022	-	293	227	343	862
IT******1	3	2022	-	293	227	343	862
IT******1	4	2022	-	272	211	314	797
IT******1	5	2022	-	272	211	314	797
IT******1	6	2022	-	196	166	257	618
IT******1	7	2022	-	196	166	257	618
IT******1	8	2022	-	224	153	224	601
IT******1	9	2022	-	224	153	224	601
IT******1	10	2022	-	408	295	406	1109
IT******1	11	2022	-	408	295	406	1109
IT******1	12	2022	-	390	257	445	1092

are not available. In this case, consumption data are simulated using a standard consumption profile as shown in the table 3.3. This standard profile of domestic user have 3 kW of available power as the majority of domestic electric user and have a yearly consumption of 3,995 MWh that is an average value for a dwelling in which more people live.

Table 3.3: Electricity Consumption Data

Month	Year	F1	F2	F3	Total
1	2021	101	104	136	341
2	2021	88	87	88	263
3	2021	94	92	92	278
4	2021	79	79	89	247
5	2021	72	71	92	235
6	2021	75	69	89	233
7	2021	78	76	88	242
8	2021	74	66	89	230
9	2021	72	69	76	217
10	2021	77	85	93	255
11	2021	90	85	98	273
12	2021	103	85	117	305

3.2 Evaluation of PV plants

In the latest Italian regulation in the matter of renewable energy communities, the renewable energy plants have to be new and designed and built to be a part of the renewable energy community, with a maximum of 30% of the total power installed that could be of not new build renewable production plant [3].

In Italy, the most widespread renewable technology and the most suitable for RECs is the solar photovoltaic power system [16]. This is due to the great availability of the resource also in the north region of Italy and his low investment cost for residential use compare to other renewable as wind, hydro, biomass that have higher capital expenditure (capex) [16]. For this reasons, the plants that produce the shared energy for the REC are solar photovoltaic plants.

The participants that have shown interest in the realization of a production plant, have also given information about the roof or the land in which the plant would be posed, as the POD of the building in which there will be the photovoltaic plant, the address and the geographical coordination of the POD, a small description of the building and its roof, if it is flat or inclined, the type of surface, the exposition of the roof and other useful information.

This informations are needed for the PV*SOL premium software. This last is a software, developed and distributed from Valentin Software GmbH, for the design and energy simulation of plant photovoltaic, grid-connected or autonomous, installed on roof or ground. In the case of plants designed to be a part of the REC's configuration would be connected to the grid to be able to access the incentives related to the renewable energy communities.

In the software are present different databases for the solar radiation, the one chosen for this study is PVGIS-SARAH3. PVGIS-SARAH3 is a database with data of solar radiation for all location of Europe and Africa, as well as some locations in Asia, North America and South America from 2005 to 2023. Setting the location of the plant, the mounting type, the azimuth and slope (that could be chose optimized) and the technology used is possible to download an hourly based CSV file of the estimated solar radiation of a year, as shown in the figure 3.1.

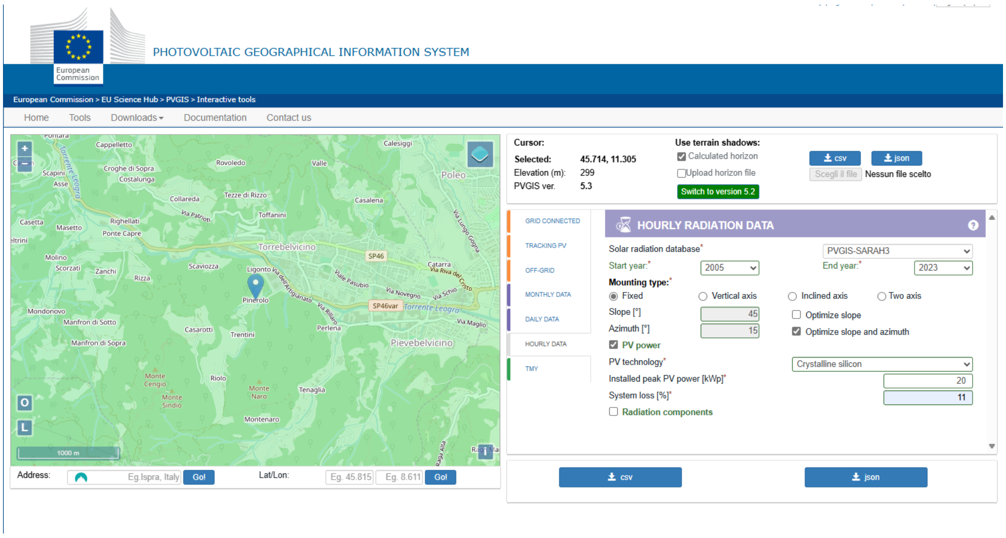

Figure 3.1: Interface of the online tool PVGIS [17]

The estimation is very precise due to the high amount of years of data present in the database that take into account not only clear sky days but also insert different degrees of cloudy days in the CSV file with a distribution based on the collected data [17].

In order to properly design the PV plant, in addition to inserting the CSV file of PVGIS, the first phase is the realization of a 3D model of the building on which the plant would be posed. The PV*SOL software, over the 3D model of the building, takes information from Google Earth of the surrounding area, to be able to take into account possible sources of shading. Then, based on the power to be installed, which depends on the available area and the spending capacity of the REC member, the photovoltaic module and the type of installation are selected. The disposition of the module could be chosen by the software in order to optimize the exploitation of the area, choosing manually the distance between the modules, the distance between the lines, and the distance from the edges of the roof. Or it could be chosen manually for installation constrains. Finally, the type of inverter is specified and the electrical connections have been assumed, taking into account the possible cable losses.

Thanks to this procedure, it is possible to obtain some important data such as: specific annual yield, plant efficiency, reduction of shade yield, and hourly output profiles of plants, based on meteorological data of the specific geographical coordinates.

The figure 3.2 is an example of a 3D design for a photovoltaic system on the roof of a house belonging to the REC.

Panoramica del progetto

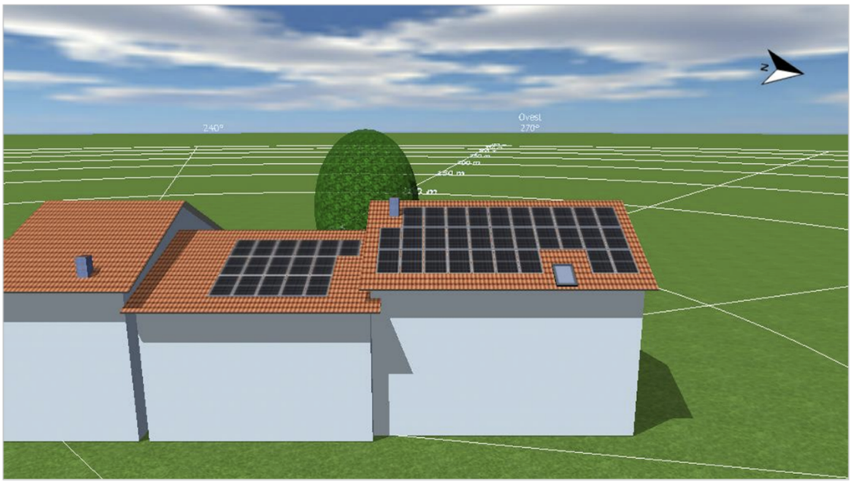

Figura: Immagine panoramica, Progettazione 3D

Impianto FV

3D, Impianto FV connesso in rete

Dati meteo	Torino (UNI 10349), ITA (1986 - 2005)
Fonte dei valori	UNI 10349
Potenza generatore FV	36 kWp
Superficie generatore FV	175,8 m²
Numero di moduli FV	90
Numero di inverter	4

Figure 3.2: 3D model of a member's photovoltaic system in one of the REC configurations analyzed [18]

3.3 Data elaboration

The consumption data of the members are not comparable to the production files produced by PV*SOL software because they have different time definitions. In order to be able to proceed with the assessment , there is the necessity to have the consumption data on an hourly basis.

In order to do that, the files in the table 3.2 and in the table 3.1, are used as input data in Python code, as well as the PVGIS and PV*SOL files for each photovoltaic plant. The code has the function of transforming the raw input data about electricity consumption and electricity production in data sets useful for the evaluation of a configuration of REC.

One of the primary challenges is the harmonization of different data sources, particularly dealing with electricity consumption profiles aggregated into monthly time-of-use (ToU) categories rather than fine-grained hourly datasets. To address this, the script employs a profiling methodology based on GSE standards. The

GSE profiles for the pure consumption take into account different types of users, as the low-voltage domestic consumption is expressed in percentage coefficients defined on the basis of the weight that each hour has within the day and takes into account the seasonal changes, having a different profile for each month [19]. In the figure 3.3 there is a visual representation of the change in consumption according to the time of year, taking as an example the months of January and July.

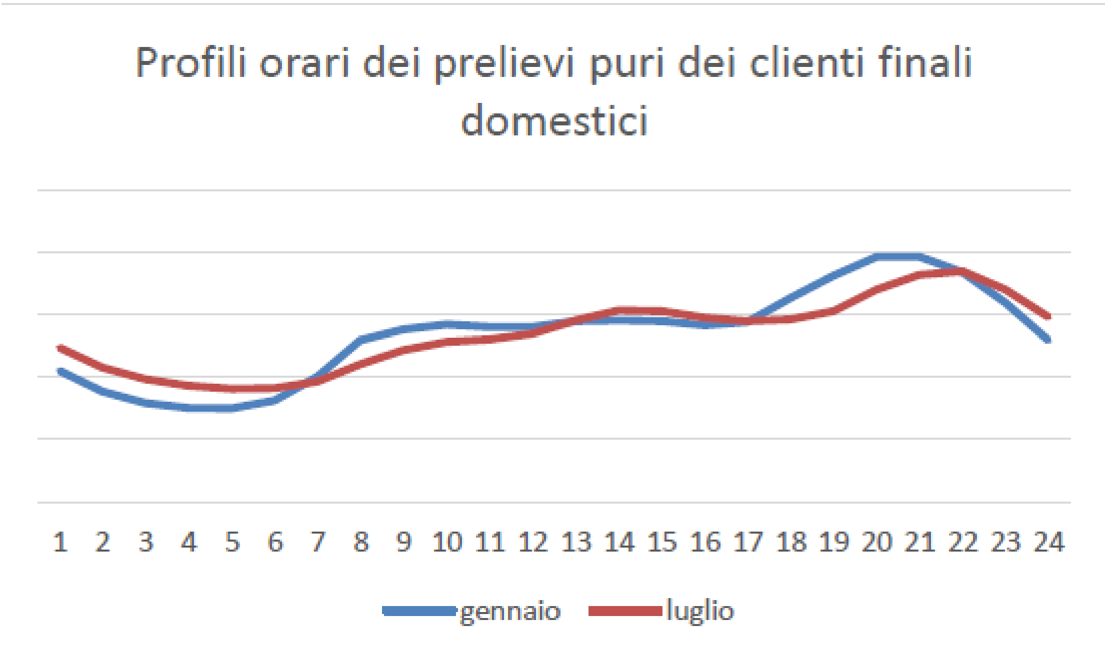

Figure 3.3: Example curves of end-users at home with seasonal effect [19]

Another profile used in this study is the non-domestic pure consumption profile which the domestic one is expressed in percentage coefficients defined on the basis of the weight that each hour has within the day and takes into account the seasonal changes, having a different profile for each month [19]. In the figure 3.4 there is a visual representation of January and July of the non-domestic profile.

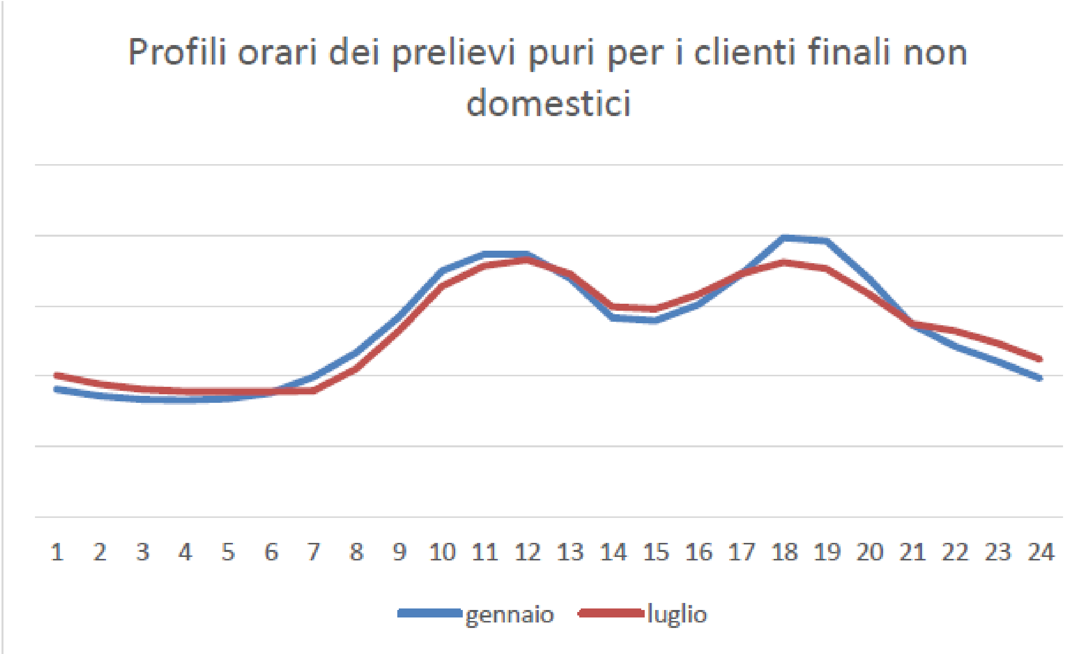

Figure 3.4: Example curves of end-users at home with seasonal effect [19]

The GSE profiles are also available for public illumination and for recharge bases for electric vehicles, but they weren't included in the study. Additionally, the script validates the completeness of each user's billing history, ensuring that every recorded POD code has an associated 12-month consumption dataset; otherwise, missing data points are flagged for further correction.

Another critical aspect of the data elaboration is the integration of PV production data. The script loads information about PV plants, including their installed capacity and expected annual yield kWh/kWp. . It then matches these systems with corresponding consumption points and applies data reshaping techniques to organize PV production data into daily and hourly profiles, ensuring compatibility with the reconstructed electricity consumption profiles.

To ensure data integrity, the script includes multiple sanity checks and assertion rules. These verify that consumption data align with user records, PV production datasets contain valid numerical entries, and all required parameters are correctly assigned before further processing.

3.4 Energy analysis

The hourly profile of electricity production and consumption are used to calculate physical self-consumption and virtual self-consumption, as well as electric energy injected into the grid and withdraw from the grid.

An example of physical self-consumption is the one in the figure 3.5. In this case there is only one POD, that serve all the domestic users and the common areas, that is connected to the grid and the photovoltaic plant. In the path between the photovoltaic plant and the POD there are various loads represented by the users. The energy produced by the photovoltaic production plant following this path before is consumed directly by the users if they have demand in the moment that energy is produced and the energy that could not be consumed is injected to the grid, receiving a monetary compensation from it.

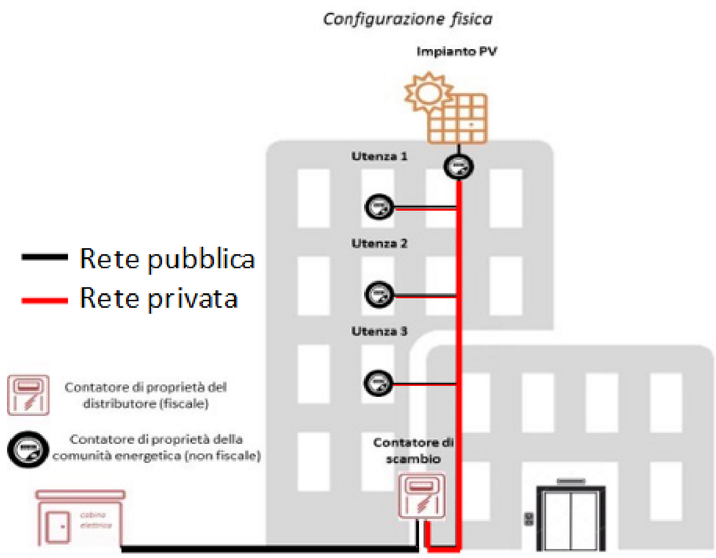

Figure 3.5: Physical self-consumption scheme with private connection of utilities to the production plant [20]

That configuration has the economic advantage due to the savings related to the energy that isn't bought from the grid because is directly consumed from the production plant. However according to the current regulation this configuration is not acceptable because every user has to have his own meter and the possibility to choose whatever distributor he prefer [20]. The physical self-consumption is possible only for the common areas in case of a photovoltaic plant in a flat.

In the figure 3.6 there is an acceptable configuration according to the current regulation. In this configuration the photovoltaic plant is direct connected only to the common areas and each user has his own meter connected to the grid. In this type of configuration the physical self-consumption is possible only for the common areas, except for the energy consumed by that all the energy is injected into the grid [20]. The energy injected into the grid will be sell and in case of participation to a configuration of renewable energy community there is the possibility to access to virtual self-consumption. In the virtual self consumption members of the energy community could receive incentives by consuming energy in the same hour that is produce, in particular the incentive is connected to the amount of energy produced by the plant that is consumed by a member of the REC.

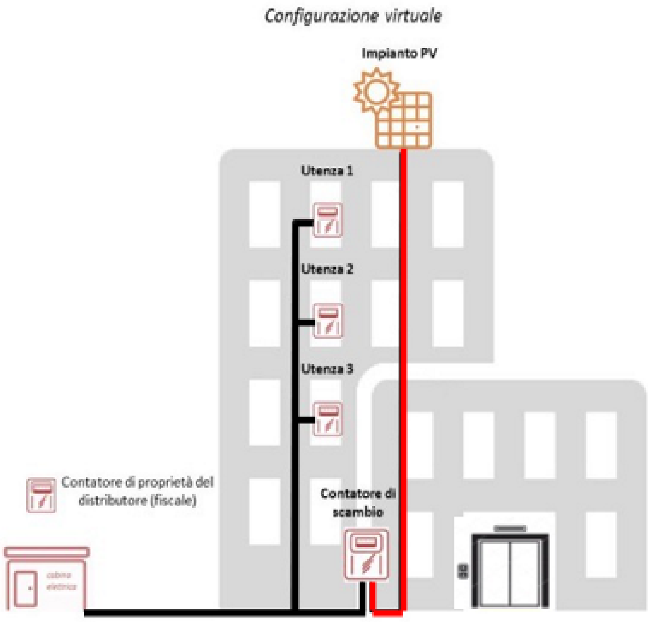

Figure 3.6: Scheme of virtual self-consumption with connection on public network between utilities and production plant [20]

In order to evaluate the energy shared firstly there is the evaluation of the the psychical self-consumption for each user.

The electric energy self-consumed physically in a renewable energy community for each hour is calculated overlapping the the production and consumption profile of an user. The equation to obtain the value of physical self-consumption is:

$$E_{\mathrm{SF},t,j} = \min(E_{\mathrm{prod},t,j}, E_{\mathrm{cons},t,j}) \tag{3.1}$$

The formula (3.1) includes the psychical self-consumption that is not taken into account in the calculation of the incentive, it is a save in the prosumer's bills. To calculate the amount of energy that each prosumer supply to the grid:

$$E_{\mathrm{injected},j,t} = E_{\mathrm{prod},j,t} - E_{\mathrm{PSF},j,t} \tag{3.2}$$

$E_{\mathrm{injected},t}$ is the elctric energy injected into the grid by a prosumer j at a time t and the $E_{\text{PSF},t}$ is the electric energy produced and consumed in the same POD without network interactions at a time t

$$E_{\text{injected},j,t} = E_{\text{prod},j,t} - E_{\text{PS},j,t} \tag{3.3}$$

In the case of pure producer users, since there is no physical self-consumption, the energy injected coincides with the energy produced.

Similarly, the energy taken from prosumer users is calculated as follows:

$$E_{\text{withdraw},j,t} = E_{\text{cons},j,t} - E_{\text{PSF},j,t} \tag{3.4}$$

In which the $E_{\text{withdraw},t}$ is the energy drawn from the grid by a prosumer j at a time t to meet the energy consumption. Whereas for pure consumers the levy is equal to total consumption.

As a result, it is possible to calculate the shared energy within the configuration, using its definition:

$$E_{\text{sh},t} = \min\left(\sum_j E_{\text{injected},j,t}, \sum_k E_{\text{withdraw},k,t}\right) \tag{3.5}$$

The $E_{\text{sh},t}$ is the electric energy virtually self-consumed in a REC at a time t.

All these quantities are finally summed for all the hours of the reference year, so as to obtain annual values in MWh. The E_{sh} is the amount of energy that access to the incentives related to the REC configuration.

To obtain the total energy produced by the photovoltaic plant of the REC consumed inside the configuration are summed the physical self-consumption and the energy shared:

$$E_{\text{tot cons, REC}} = \sum_{t=1}^{8760} (E_{\text{PSF},t} + E_{\text{sh},t}) \tag{3.6}$$

The general functioning of renewable energy communities can be well illustrated in the figures 3.7 and in the figure 3.8, relative to the case of a REC within a multi-apartment building.

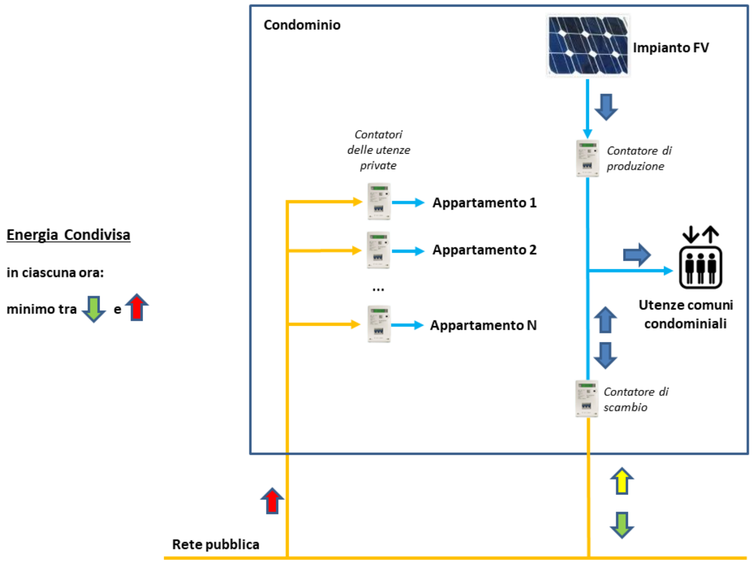

Figure 3.7: Energy flows of a collective self-consumption scheme: energy produced, drawn, self-consumed, fed into the network and shared [20].

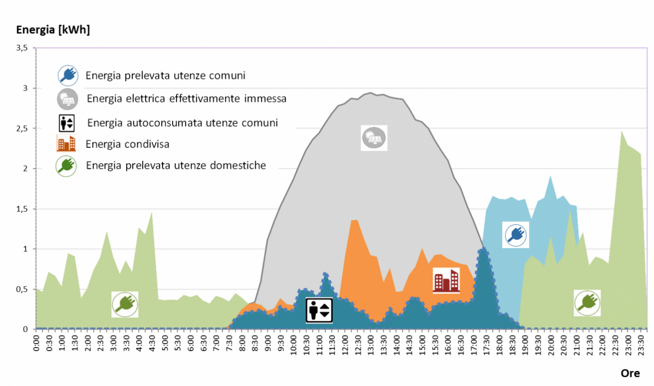

Figure 3.8: Daily representation of the energy input, energy taken and shared energy for self-consumption in a standard scheme [20].

3.5 Energy and Environmental indicators

Based on the energy quantities obtained previously, a series of energy and environmental performance indicators can be derived to properly evaluate the REC configuration. The use of multiple indicators returns a more complete picture of the configuration, showing the impact of it from different prospective as the energetic, environmental and economic.

3.5.1 Energy indicators

The self-consumption indicator (SC) expresses how much of the produced energy is consumed inside the REC, and is then calculated as the ratio between the sum of the total self-consumption of the users and the shared energy and the total production, as follows:

$$SC = \frac{\sum_{t=1}^{8760}(E_{\text{PSF},t} + E_{\text{sh},t})}{\sum_{t=1}^{8760} E_{\text{prod},t}} \tag{3.7}$$

An index of self-consumption is also calculated for shared energy only (virtual self-consumption) to calculate the excess share of TIP provided by the CACER decree of the MASE:

$$SC_{\text{virtual}} = \frac{\sum_{t=1}^{8760} E_{\text{sh},t}}{\sum_{t=1}^{8760} E_{\text{injected},t}} \tag{3.8}$$

The indicator of self-sufficiency (SS) instead expresses how much of the domestic electricity demand is met through self-generation of renewable energy. This indicator is then calculated as the ratio between the sum of the total self-consumption of prosumers and shared energy and the total consumption, as follows:

$$SS = \frac{\sum_{t=1}^{8760}(E_{\text{PSF},t} + E_{\text{sh},t})}{\sum_{t=1}^{8760} E_{\text{cons},t}} \tag{3.9}$$

This indicators are fundamental to evaluate a configuration of REC in the energy sphere, because indicate how much energy is generated within the REC by using it locally before feeding it into the network or virtually self-consuming and how much the REC needs to depend on the network in order to meet its users' consumption.

3.5.2 Environmental indicators

In order to calculate the environmental performance of the REC, an approach based on equivalent CO_2 emission factors is adopted.

In particular, the following assumptions are made:

- Physical self-consumption and shared energy can reduce the energy consumption from centralized generation grid. Due to the fact that the energy mix in Italy is composed of 40% of renewables [21] in 2024 and the presence of REC configurations in the territory benefit all the country because incentivize the construction of new photovoltaic plant and has a much more significant impact on the source of energy consumed by the REC users.

- The installation of renewable generation facilities (and any storage systems) results in community-wide emissions linked to the life cycle of these technologies (production, maintenance, disposal).
- The energy supplied to the grid and not shared, even if it comes from renewable sources, is not assigned a reduction in emissions avoided emissions by the REC, as it is consumed externally.

The REC emissions in a base year are then calculated as follows:

$$Emission_{\mathrm{REC}} = E_{\mathrm{prod}} \cdot \epsilon_{\mathrm{PV}} + (E_{\mathrm{cons}} - (E_{\mathrm{PSF}} + E_{\mathrm{sh}})) \cdot \epsilon_{\mathrm{grid}} \tag{3.10}$$

For photovoltaic systems, an emission factor of 50 $kgCO_2$,eq/MWh [22], while the network 315 $kgCO_2$,eq/MWh [23].

To quantify the environmental benefits of REC, the CO_2 emissions are then calculated related to electricity consumption in the case where all the needs are covered by the grid electricity, as in the case there is not the REC configuration:

$$Emission_{\mathrm{base}} = E_{\mathrm{cons}} \cdot \epsilon_{\mathrm{grid}} \tag{3.11}$$

It is then possible to calculate an emission reduction factor as follows:

$$\Delta_{emission} = \frac{Emission_{\mathrm{base}} - Emission_{\mathrm{REC}}}{Emission_{\mathrm{base}}} \tag{3.12}$$

This factor shows the impact of the REC configuration in the CO_2 equivalent emissions related to the electricity consumption of the REC's users.

3.6 Economic analysis

In the economic analysis, energy data previously calculated are used to obtain REC expenses, revenues and savings year by year. To these are added the possible initial outlay for the installation of renewable installations, as well as the operating costs (maintenance, insurance, GSE costs) and the possible installment of the loan concluded to finance the installation.

The table 3.4 summarizes the various inputs and outputs for REC.

Table 3.4: REC entry and exit items

Exit	Enter
Capital invested	Withdrawal dedicated immissions (RID)
Loan rate	self-consumption savings
Maintenance costs, insurance and management of the installations	Exploitation and sharing incentives
Managmment of the REC	
Tax	

To the exit items is added a share of revenues intended for social purposes that have repercussions on the territory of the REC.

With regard to the costs and revenues linked to the previously calculated energy quantities, the analyses carried out consider that:

- Physical self-consumption means savings in bills for consumers, equal to the retail price of electricity (about 300 €/MWh in 2024).
- The input of electricity into the network entails a revenue that, in the case of dedicated withdrawal, is equal to the market price (zonal hourly price (PZO), on average about 110 €/MWh in 2024 [24]).
- Electricity sharing involves an incentive and compensation for transmission and distribution charges (11.57 €/MWh in 2024) [3]. In the absence of specific reductions (e.g. due to capital incentive), the value of the incentive is assumed to be 130 €/MWh. Specifically, this consists of a fixed part (equal to 80 €/MWh for plants with an output below 200 kWp), a variable part (equal to 40 €/MWh in the case of PZO below 140 €/MWh) and a premium of 10 €/MWh for the regions of northern Italy [3].
- All energy taken from the grid is paid to suppliers at retail price.

The following costs are also calculated:

- For photovoltaic systems, the total installation cost is calculated according to size, using a specific cost of 1250 €/kWp, in the absence of specific estimates. The total cost is increased by VAT (at a rate of 10 % or 22 %, depending on the case).
- According to the information provided by individual prosumer users, the cost of installation is divided between capital invested (thus represented by an initial disbursement) and loan (whose installment is calculated using the following parameters: 10 years, rate 5%).
- Other operating expenses are calculated by taking into account the cost of maintenance (30 €/year/kWp) and insurance of the installations (30 €/year/kWp) and the cost of the GSE (depending on the size, 15 €/year/kWp for sizes between 3 and 20 kWp).

3.7 Allocation

First, the following assumptions are made about the distribution of REC's income and expenses.

The initial disbursement and the installment of the loan for the installation of renewable installations remain with the owner, as well as the operating costs. Unlike the ecclesiastical participants who receive a compensation at most equal to the difference between the cost of the mortgage fee and the revenues related to renewable income. This is done for the first 10 years after the installation of the system, because the ecclesiastical participant undertakes to build a photovoltaic system oversized for its needs. In order to be able to contribute actively and significantly to the establishment of the REC configuration.

The revenue from the sale of energy supplied to the network remains entirely with the prosumers/ producers (as well as any benefit from self-consumption).

The revenues from the energy community are allocated in accordance with the Configuration and Foundation Rules and in the freedom provided for by the latter, as decided by the Foundation Committee [4]. According to the rules of the regulation, the Foundation withholds 25% of the Amounts arising from the Sharing Energy to cover living costs and support social projects, as well as coverage of agreements with third parties. The remaining part will be allocated to the Configurations and should be divided as follows. It will cover the living expenses incurred by Religious and Ecclesiastical Participants, of remaining part, at least 45% should be allocated by the configurations to the financing of social measures. These social initiatives will be proposed by the foundation and accepted by the configuration, they will be mainly engaged in the fight against energy poverty, helping families in difficulty in the territory where the configuration is located [13]. Social initiatives must be carried out in the territory of the REC.

Following the above criteria, the Configurations are free, from year to year, to reorganize the distribution of revenues from Energy sharing by changing the shares allocated to social interventions, private producers and prosumers other than Religious and Ecclesiastical Participants and simple consumers [13]. The REC ensures in any case that the amount of any excess premium rate, is intended only for Consumer Participants other than companies and/ or used for social purposes with repercussions on the territories where the facilities are located for sharing, as provided for in the CACER and TIAD decree [13].

The Participants may not demand anything different from the distribution of the Amounts resulting from from the Sharing of Energy carried out by the foundation.

Chapter 4

Case studies

In this chapter are describe 4 configuration of renewable energy communities that are the case studies of this thesis. They are part of the ETS Foundation and for the feasibility assessment have been used the methodology described in 3.

4.1 Case A

The case study A located in a town in the region of Piemonte, on the impulse of some of its inhabitants, expressed the willingness to create an energy community configuration.

The territory is located in the primary cabin AC001E01157, this information is available on the GSE interactive map of primary cabins, as shown in the figure 4.1. In the same primary cabin there are other towns or villages that are able to enter in the configuration. The residents of the latter that express a desire to be part of the configuration and respect the necessary requirements are capable of joining the configuration.

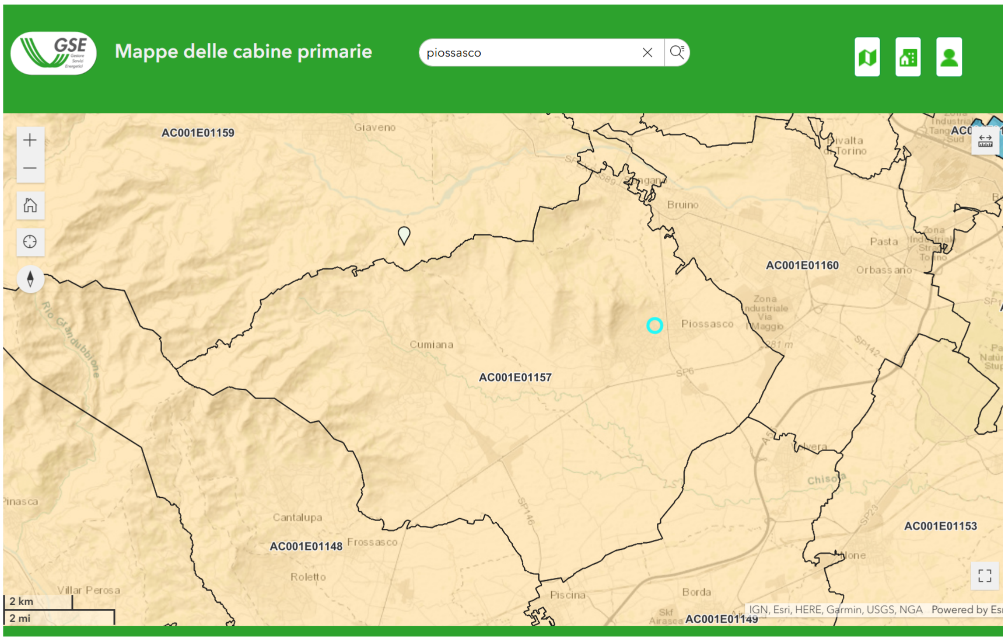

Figure 4.1: Interactive map of primary cabins from GSE website of the case study A [25]

4.1.1 Configuration

The configuration is composed of 37 users, 7 of them are POD related to a church or buildings on his property and 30 are domestic consumers. Each user gave the consumption data of the solar year 2022, which has been organized as explained in 3.1, as well as the information about the available power and the type of contract.

All this informations are synthesized in the table 4.1:

The total power available is 135 kW and the annual total consumption is 119.85 MWh, which could not be covered totally by a photovoltaic plant because part of this consumption is in time slots which are not covered by the electricity produced by that installation. The 30 families have not been modeled using user data due to the lack of them. To model them was used the standard profile, explained in 3.1.1.

This data are used as inputs data in the Python file, to obtain the hourly consumption profiles. In the figure 4.2 are represented the aggregate value of the total consumption for each month and in the figure 4.3 the distribution of the different time slots for each month.

Table 4.1: Consumption data case study A

Name	POD power available [kW]	Annual consumption [MWh]
Church plant A	10	7.1
Church 1	3	2.5
Church 2	3	0.67
Church 3	5	0.78
Church 4	15	10.1
Church 5	6	5.1
Church 6	3	0.04
30 Families	90	93.54
Total	135	119.85

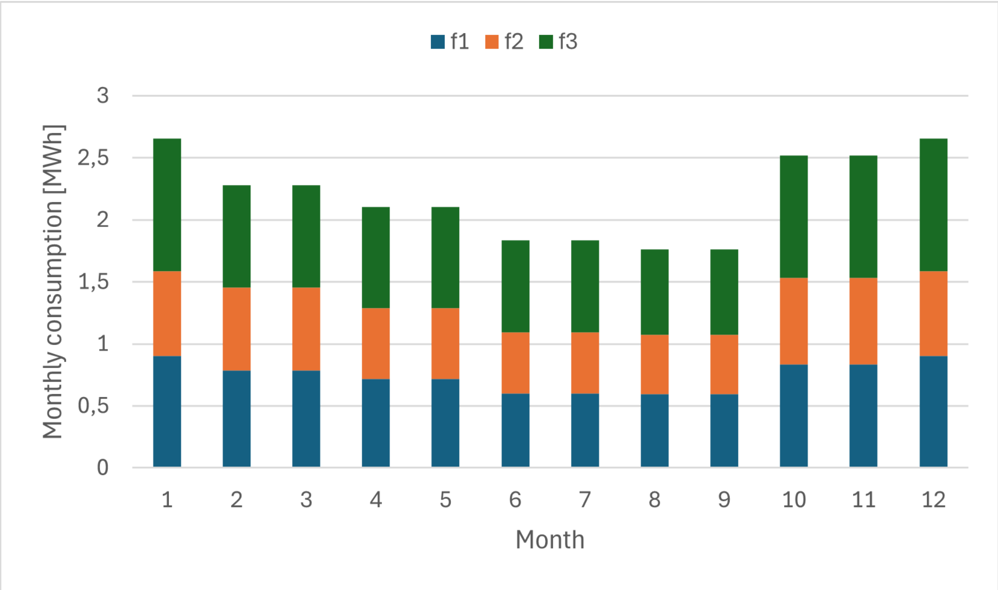

Figure 4.2: REC monthly consumption [author's creation]

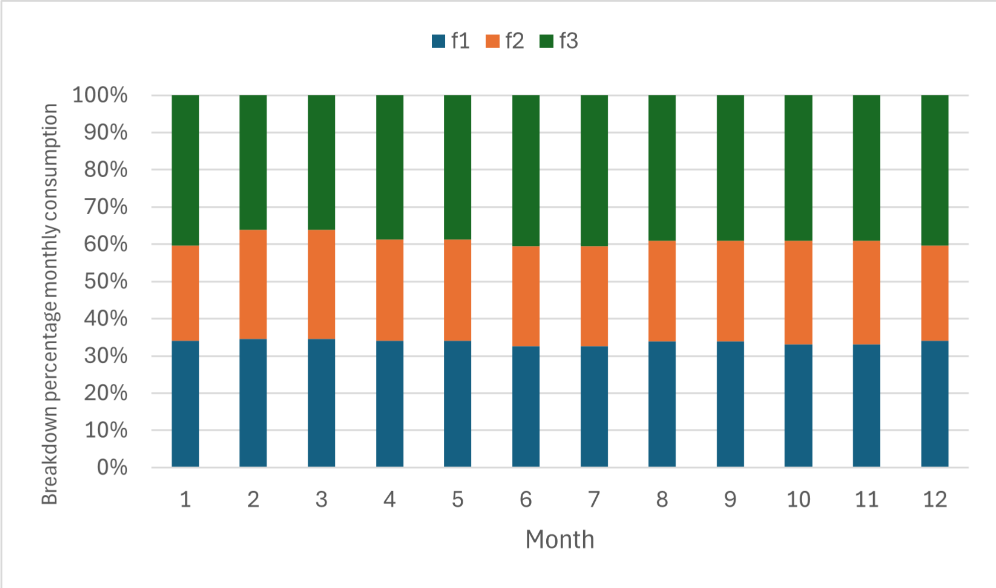

Figure 4.3: percentage breakdown of monthly consumption for the case study A [author's creation]

As shown in the figures 4.3 and 4.2 the level of consumption are higher in the winter months and lower in the other seasons, with a peak in the summer.

This is in contrast with the photovoltaic production of the plants, as it is shown in the section 4.1.2.

4.1.2 Photovoltaic plants

The user church plant A has made available the roof for the installation of a photovoltaic production plant.

The study conducted highlighted that the best option for the available surface and the willingness to buy is a photovoltaic plant composed of different modules with a total peak power available of 20 kWh.

With the software PV*SOL has been modeled the photovoltaic plant choosing the type of modules, the inverter and all the specification explained in 3.2. Also the software using the PVGIS data evaluate the production of electricity for a reference year with an hour definition. A graphical representation of it is in the figure 4.4.

The production in winter months is lower compered to the summer ones due to the higher value of irradiation. There are also period of the same season with different production, this difference is due to cloudy days or other atmospheric events. The different production in the seasons is better described in the the figure 4.5. This figure represent the production during the day in winter, spring, summer and autumn. The reference days choose are respectively the January 5,

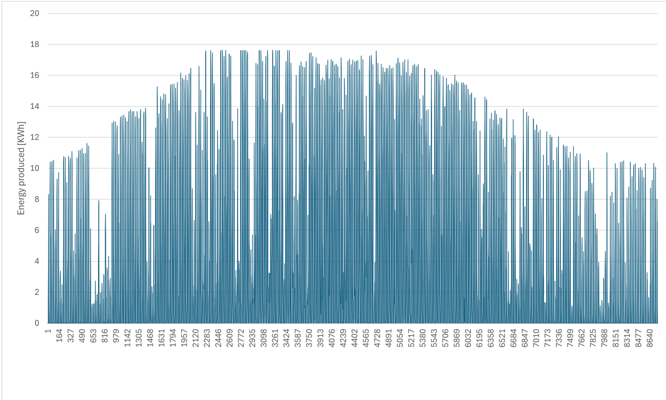

Figure 4.4: Energy produced by the plant of the case A, hour definition [author's creation]

the April 5, the July 5 and the October 5. In the figure is more prominent the different production during the summer and spring days than the other season. In this case the winter and autumn days are also cloudy days, this is deductible by the path of the graphic, that is not a bell like the other two days but it is a broken curve that lowers its value despite approaching the solar azimuth, point of maximum radiation to which in conditions of clear sky follows the moment of maximum production. The variation of the curve is due to the passage of a cloud or other atmospheric events.

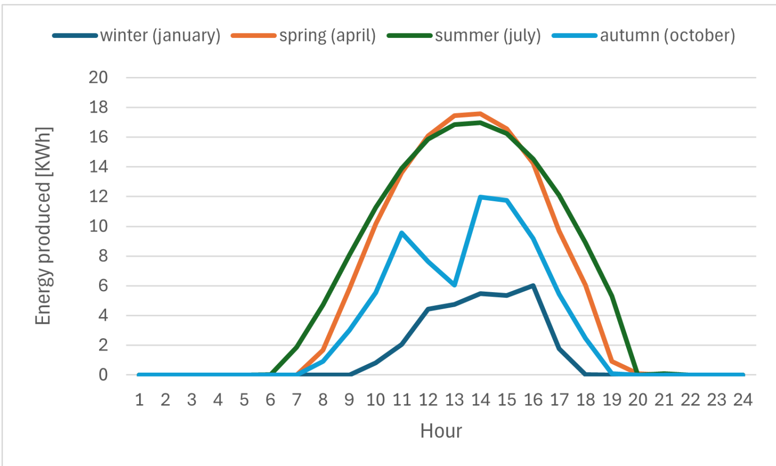

Figure 4.5: Average percentage distribution of consumption in the case study A [author's production]

4.2 Case B

The case study B located in a town in the metropolitan area of Turin. At the instigation of a parish in the territory followed by other residents, was conducted the feasibility study of a renewable energy community in the territory.

The territory is located in the primary cabin AC001E01157, as well as other towns and villages, that are capable of enter in the configuration. As displayed in the figure 4.6 there is a part of the town that belong to another primary cabin, in this case the residents of this part of the town are not capable to enter in the configuration.

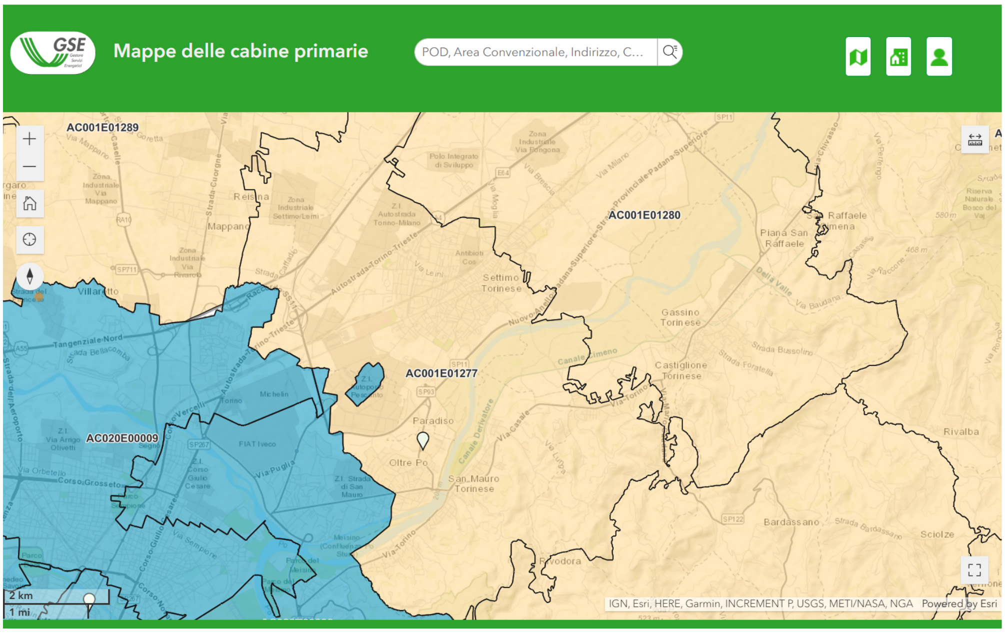

Figure 4.6: Interactive map of primary cabins from GSE website of the case study B [25]

4.2.1 Configuration

The configuration is composed of 36 users, 5 of them are POD related to church or buildings of his property, one is a kindergarten and 30 are domestic consumers. Each user gave the consumption data of the solar year 2022 or 2023, that have been organized as explained in 3.1, as well as the information about the available power and the type of contract.

All this information are synthesize in this table:

The total power available is 141.3 kW and the annual total consumption is

Table 4.2: Summary of Available Power and Energy Consumption of the case study B

Name	POD Power available [kW]	Annual Consumption [MWh]
Church 1	22	16.6
Church 2	3	1.3
Church 3	3.3	1.1
Church 4	3	3.4
Church 5	10	10.9
Kindergarten School	10	6.2
Families (30)	90	93.5
Total	141.3	133.0

133 MWh, which could not be covered totally by a photovoltaic plant because part of this consumption is in time slots which are not covered by the electricity produced by that installation. The 30 families have not been modeled using user data due to the lack of them. To model them was used the standard profile, explained in 3.1.1, as in the 4.1.

This data are used as inputs data in the Python file, to obtain the hourly consumption profiles. In the figure 4.7 are represented the aggregate value of the total consumption for each month and in the figure 4.8 the distribution of the different time slots for each month.

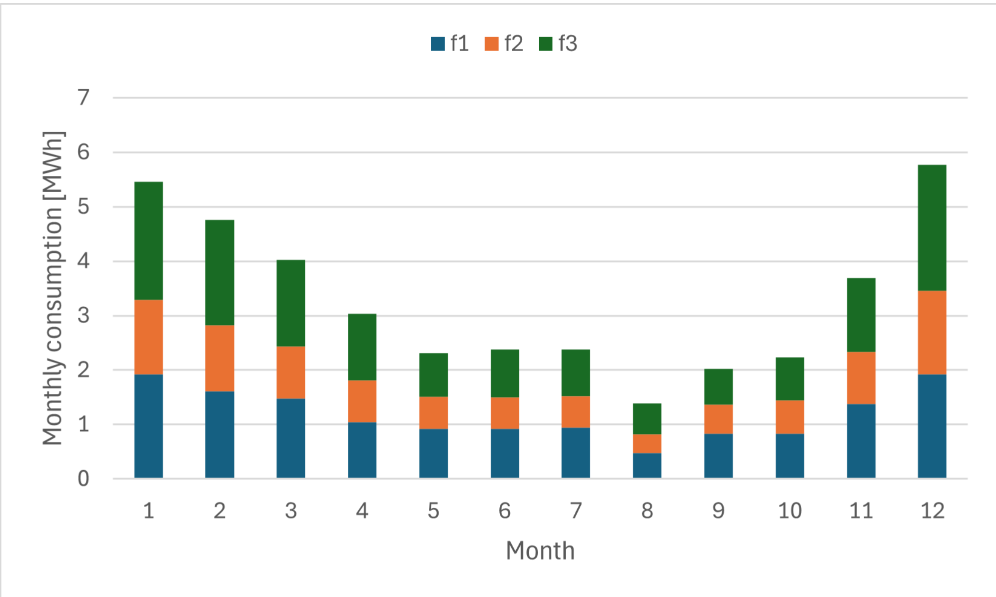

Figure 4.7: REC monthly consumption of the case study B [author's creation]

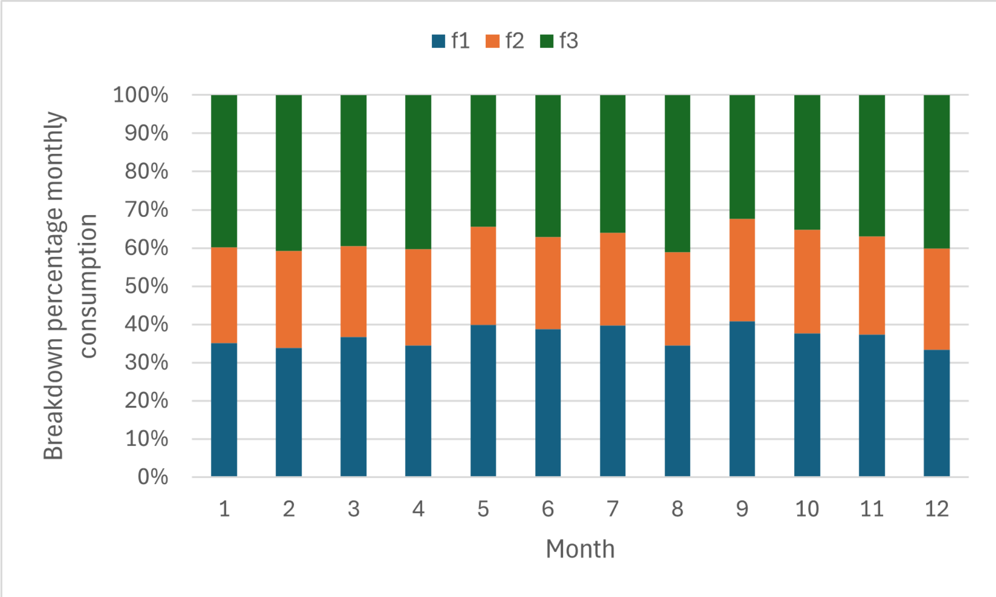

Figure 4.8: percentage breakdown of monthly consumption for the case study B [author's creation]

In the figure 4.7 there is a large gap between the consumption in winter and in summer, this can be linked to the use of electricity as a heating system and the presence of a kindergarten in the configuration that does not have consumption in the summer months, since this activity is closed in those months.

4.2.2 Photovoltaic plants

The user church 1 has made available the roof for the installation of a photovoltaic production plant.

The study conducted highlighted that the best option for the available surface and the willingness to buy is a photovoltaic plant composed of different modules with a total peak power available of 20.4 kWh.

With the software PV*SOL has been modeled the photovoltaic plant choosing the type of modules, the inverter and all the specification explained in 3.2. Also the software using the PVGIS data evaluate the production of electricity for a reference year with an hour definition. A graphical representation of it is in the figure 4.9.

The production in winter months is lower compered to the summer ones due to the higher value of irradiation. In the figure 4.9 the variation in the same period of the year are more uniformly distributed than in the case study A. This is more clear in the figure 4.9

There are also period of the same season with different production due to

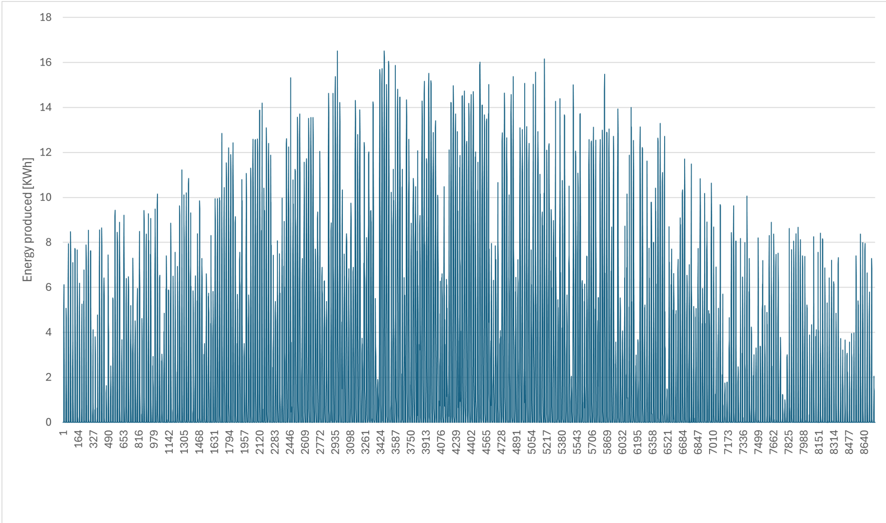

Figure 4.9: Energy produced by the plant of the case B, hour definition [author's creation]

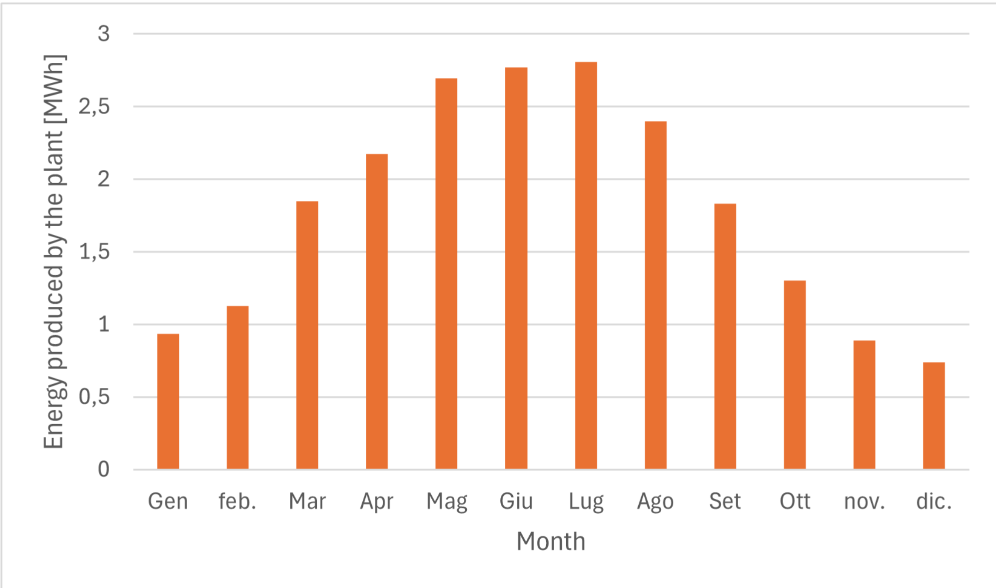

Figure 4.10: Energy produced by the plant of the case study B, for each month [author's creation]

cloudy days. The different production in the seasons is better described in the the figure 4.11. This figure represent the production during the day in winter, spring, summer and autumn. The reference days choose are respectively the January 5, the April 5, the July 5 and the October 5. In the figure is more prominent the different production during the summer respect to the other seasons. In this case all the selected days are also cloudy days, this is deductible by the path of the graphic, that is not a bell but it is a broken curve that lowers its value despite approaching the solar azimuth, point of maximum radiation to which in conditions of clear sky follows the moment of maximum production. The variation of the curve is due to the passage of a cloud or other atmospheric events that influences the amount of irradiation that arrive to the plant .

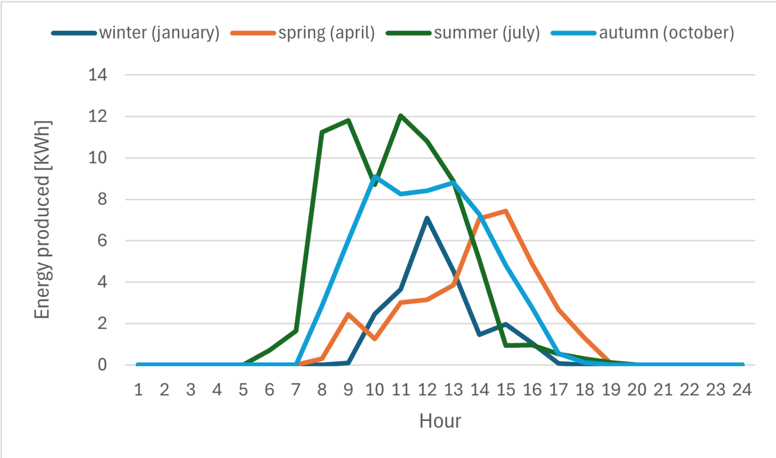

Figure 4.11: Energy production during a day for 4 days in different season, case study B [author's creation]

4.3 Case C

The case study C located in Turin, specifically in a district of the city. Turin being a metropolis, different areas of the city have different primary cabins. The district is in the primary cabin AC020E00006, as shown in the figure 4.12.

Two church of this district has shown interest in enter inside a configuration of REC, as well as some accommodation manage by them and other buildings they own.

4.3.1 Configuration

The configuration is composed of 22 users, 2 are the church where the photovoltaic plant will be installed, 17 are accommodation they manage and 3 of them are POD related to church or buildings of his property. Each user gave the consumption data of the solar year 2023 or 2024, that have been organized as explained in 3.1, as well as the information about the available power and the type of contract.

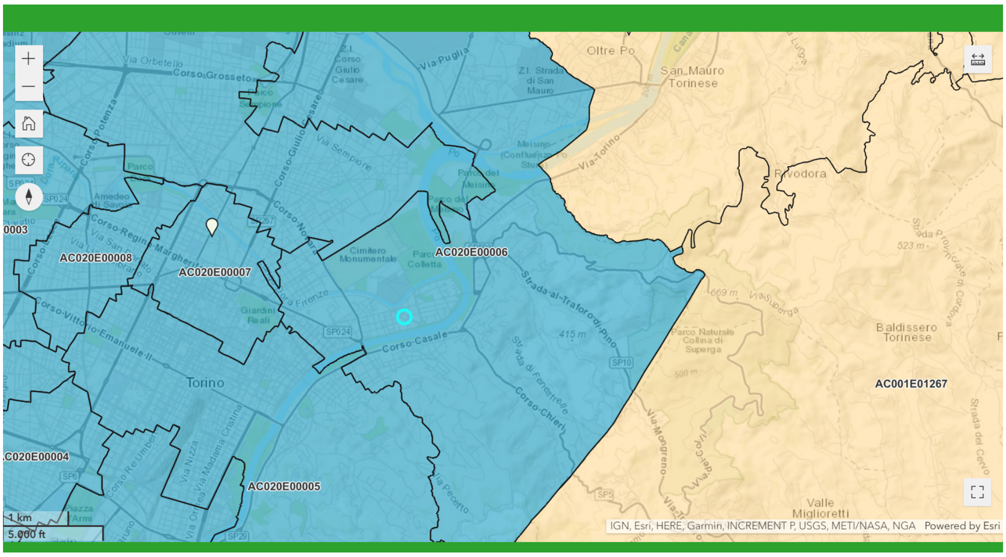

Figure 4.12: Interactive map of primary cabins from GSE website of the case study C [25]

All this information are synthesize in this table:

The total power available is 134.5 kW and the annual total consumption is 100.5 MWh, which could not be covered totally by a photovoltaic plant because part of this consumption is in time slots which are not covered by the electricity produced by that installation and there is not any type of energy storage.

This data are used as inputs data in the Python file, to obtain the hourly consumption profiles. In the figure 4.13 are represented the aggregate value of the total consumption for each month and in the figure 4.14 the distribution of the different time slots for each month.

4.3.2 Photovoltaic plants

The user church 1 and church 2 have made available the roof for the installation of a photovoltaic production plant.

Church 1 plant

The surface made available by the church 1, in which there was modeled the photovoltaic plant, is a roof oriented sud est 150°, it is also an inclined surface, with a angle of 30° from a plane parallel to the ground. The surface occupied by the modules is 41 m^2. The modules use in the evaluation are the Si monocrystalline-HC technology, each module has a power of 400 Wp. The amount of module used are

Table 4.3: Summary of Available Power and Energy Consumption

Name	Available POD Power [kW]	Annual Consumption (Bill Data) [MWh]
Church 1	10	5.8
Church 2	10	5.3
Church 3	45	50.0
Church 4	10	1.3
Church 5	7	1.4
Apartment 1	3	3.4
Apartment 2	3	1.7
Apartment 3	3	1.8
Apartment 4	3	2.1
Apartment 5	3	1.5
Apartment 6	3	2.2
Apartment 7	3	2.9
Apartment 8	3	2.3
Apartment 9	3	0.0
Apartment 10	3	1.9
Apartment 11	3	3.4
Apartment 12	3	1.7
Apartment 13	3	1.8
Apartment 14	3	1.2
Apartment 15	3	2.5
Apartment 16	1.5	2.4
Apartment 17	6	1.3
Total	134.5	100.5

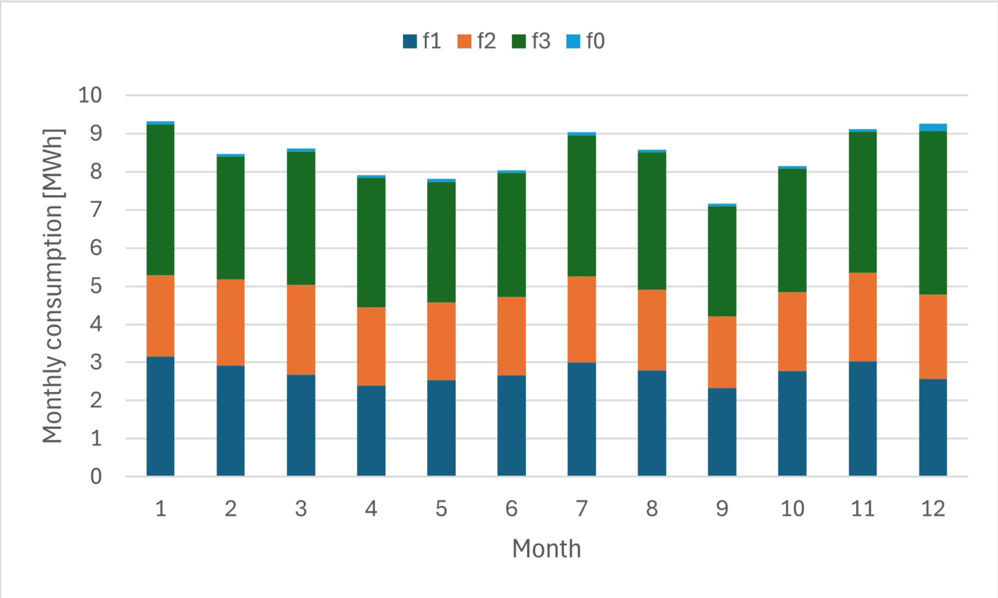

Figure 4.13: REC monthly consumption of the case study C [author's creation]

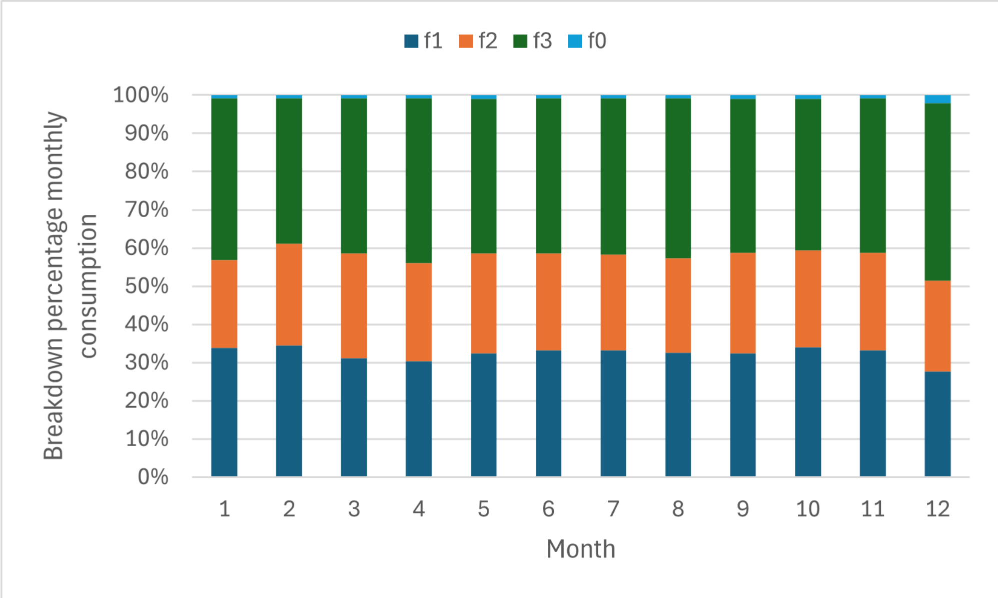

Figure 4.14: percentage breakdown of monthly consumption for the case study B [author's creation]

21 with a total available power of 8.4 kWp. For the inverter have been used 3 inverters HNS2500TL-1 S6/PL (v1), with a size factor of 112 %.

This specification are insert in the software PV*SOL and using it together with the PVGIS database for the irradiation in this surface, have been evaluated the production of electricity for a reference year with an hour definition. A graphical representation of it is in the figure 4.15.

The production in winter months is lower compered to the summer ones due to the higher value of irradiation. Also in the end of the chart there is a zone with lower values compared to the values near it, this is due to atmospheric reasons. This two valuation are more clear in the figure 4.15

The path in 4.15 does not follow the trend in Campania that one might expect, this proves what was said before.

Church 2 plant

The church 2 has made available 3 areas for the installation of 3 photovoltaic systems, the characteristics of these areas are as follows.

The first surface is a roof oriented East 80°, it is also an inclined surface,with an inclination of 14° from a plane parallel to the ground. The surface occupied by the modules is 39.1 m^2. In the evaluation phase the modules use are the Si monocrystalline-HC technology, each module has a power of 400 Wp and there are

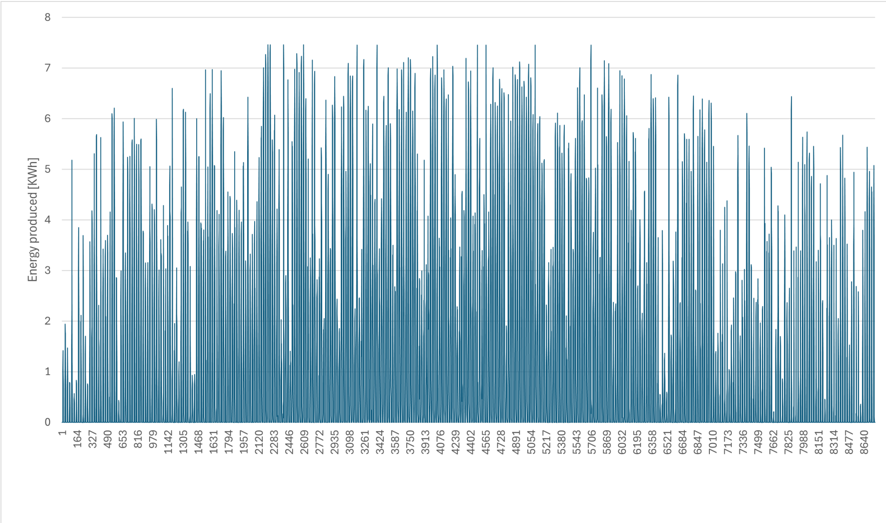

Figure 4.15: Energy produced by the plant of the case C installed in the POD of church 1, hour definition [author's creation]

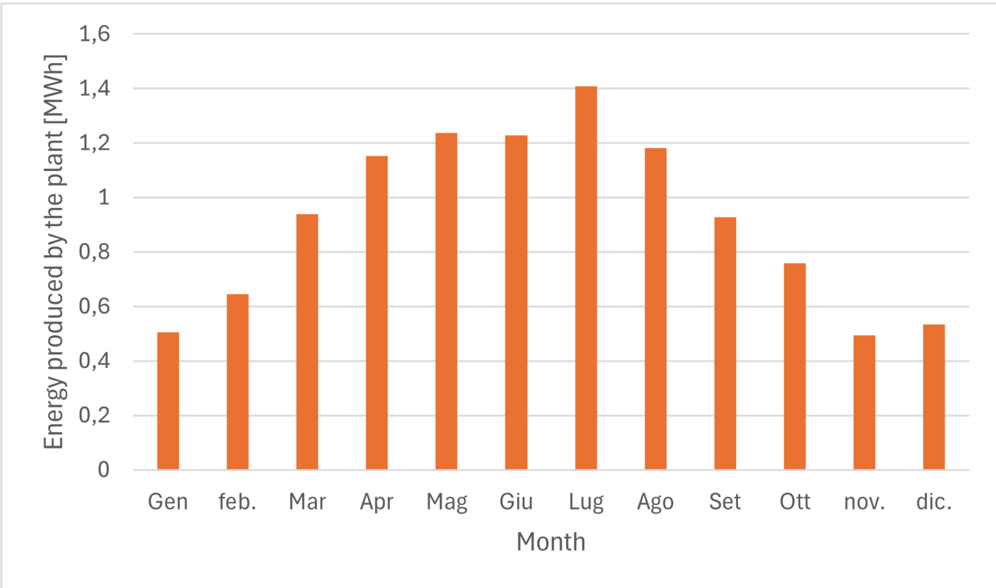

Figure 4.16: Energy produced by the plant of the case study C installed in the POD of church 1, for each month [author's creation]

20 of them.

The second surface is a roof oriented South East 130°, it is an inclined surface, with an inclination of 14° from a plane parallel to the ground. The surface occupied by the modules is 39.1 m^2. In the evaluation were chosen modules Si monocrystalline-HC technology, each module has a power of 400 Wp and there are 20 of them.

The third surface is a roof oriented West 260°, it is an inclined surface,with an inclination of 14° from a plane parallel to the ground. The surface occupied by the modules is 37.1 m^2. In the evaluation were chosen modules Si monocrystalline-HC technology, each module has a power of 400 Wp and there are 19 of them.

The total available power is 23.6 kWp.

For the inverter have been used 5 inverters, 4 in the first 2 surface HNS2500TL-1 S6/PL (v1),2 for each surface with a size factor of 111.1 %. The other one is a AF6K-SL (v1), with a size factor of 126.7 %

This specification are insert in the software PV*SOL and using it together with the PVGIS database for the irradiation in this surface, have been evaluated the production of electricity for a reference year with an hour definition. A graphical representation of it is in the figure 4.17.

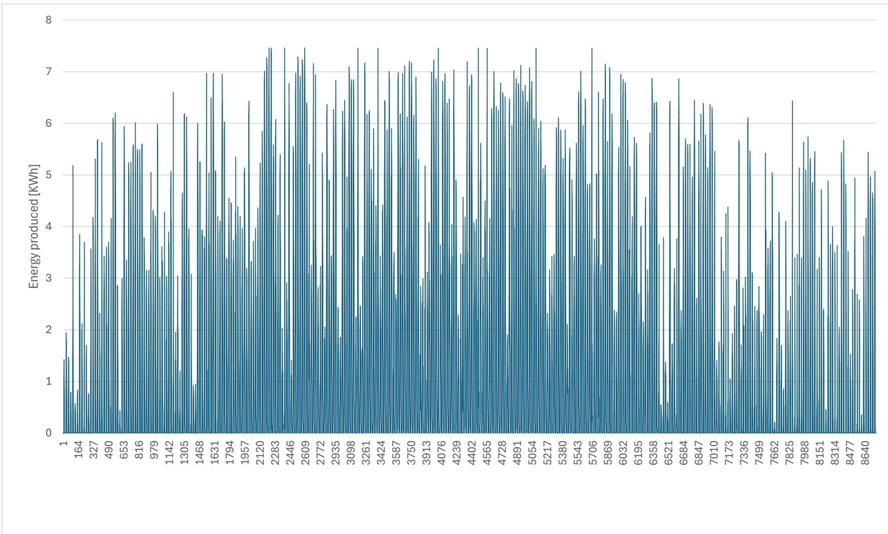

Figure 4.17: Energy produced by the plant of the case C installed in the POD of church 2, hour definition [author's creation]

The production in winter months is lower compered to the summer ones due to the higher value of irradiation. This is more clear in the figure 4.18.

In this case, the profile follows more than the other plant a curve like that of the irradiation in one year, this is given by the fact that there are several plants connected to the same POD, This allows weather events such as the passage of a cloud to have less impact on the production of electricity.

In this study the consumption profiles undergo less variation over the year, this is given by a use of loads that does not have a strong dependence on the seasons.

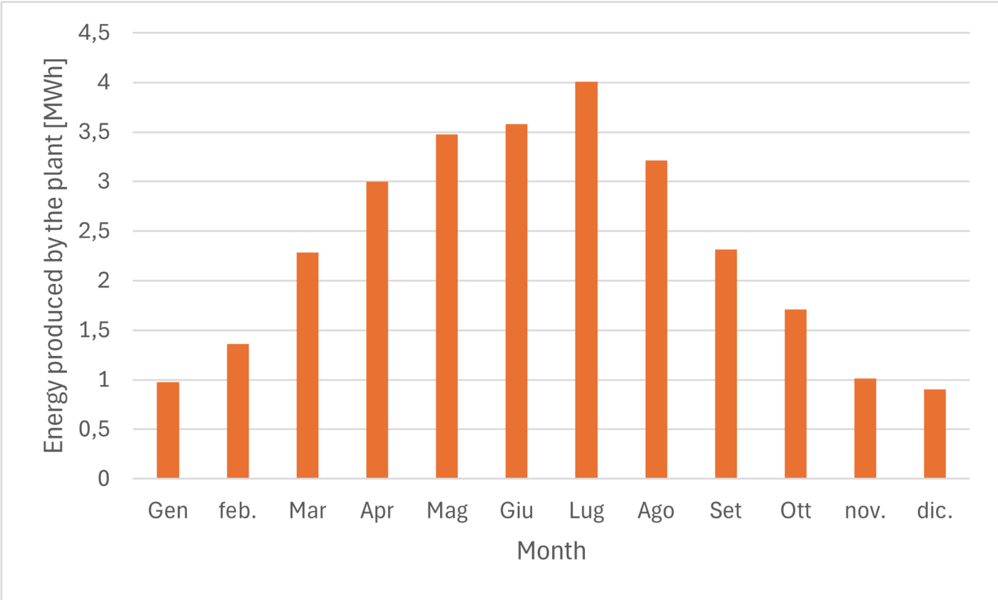

Figure 4.18: Energy produced by the plant of the case study C installed in the POD of church 1, for each month [author's creation]

This will allow photovoltaic systems to have a good impact even in the summer months.

Table 4.4: PV Power Installation and Estimated Annual PV Production

Name	**Installed PV Power [kWp]**	**Estimated Annual PV Production [MWh]**
Church 1	8.4	11.0
Church 2	23.6	27.9
Total	32	38.9

The total production is 38.9 MWh and the power available is 32 kWp.

4.4 Case D

The case study D located in a town of less then 5 thousands people in the region of Piemonte, on the impulse of some of its inhabitants, expressed the willingness of create an energy community configuration. The territory of the town is mostly present in the primary cabin AC001E01275, as well as the people who expressed the willingness to create the energy community. The ground under this cabin is shown in figure 4.19,in this primary cabin there is the presents of other towns or villages that are able to enter in the configuration. The residents of the latter that express a desire to be part of the configuration and respect the necessary requirements are capable of joining the configuration.

Two church of this town has shown interest to create a configuration of REC and some accommodation manage by them. The churches and the foundation have organized meetings with their communities of faithful on renewable energy communities, the ETS Foundation project and the possibility of obtaining in addition to the benefits linked to the renewable energy community also access to capital contribution for municipalities with less than 5 thousand inhabitants, as well explained in 1.5.1. These meetings have led to growing interest in the subject, and some home and business users have expressed their desire to be part of the emerging renewable energy community.

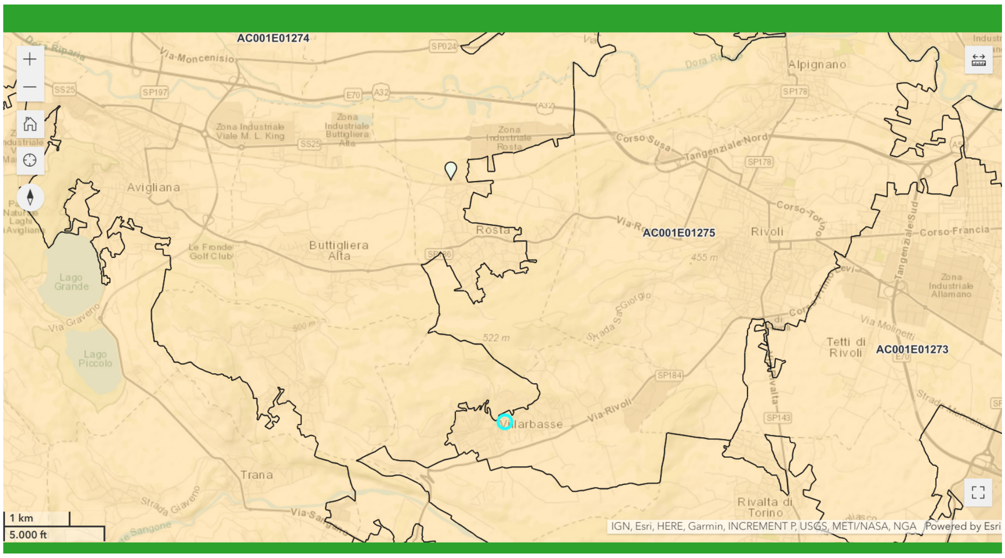

Figure 4.19: Interactive map of primary cabins from GSE website of the case study D [25]

4.4.1 Configuration

The configuration is composed of 28 users, 2 are the church where the photovoltaic plant will be installed, 10 are private prosumer related to a domestic house or a business, 6 are business consumers, and 11 are another type of consumers. Each user gave the consumption data of the solar year 2022 or 2023 or 2024, that have been organized as explained in 3.1, as well as the information about the available power and the type of contract.

All this information is summarized in Table 4.5:

The total power available is 313.4 kW and the annual total consumption is

Table 4.5: Available Power and Annual Energy Consumption of the REC configuration, case study D

Name	**Available Power [kW]**	**Annual Consumption [MWh]**
Church 1	10	0.9
Church 2	6.6	3.0
Business 1	29.1	23.5
Residential user 1	6	1.6
Business 2	22	50.9
Residential user 2	3	2.1
Residential user 3	10	3.7
Residential user 4	3	1.7
Residential user 5	4.5	2.1
Business 3	27	7.1
Residential user 6	3	3.2
Residential user 7	3	1.0
Business 4	30	6.5
Residential user 8	3	2.5
Residential user 9	4.5	2.8
Residential user 10	3	4.6
Residential user 11	23.1	1.2
Elementary School	30	19.3
Business 5	15.8	22.9
Middle School	10.3	14.9
Kindergarten	4.5	6.4
Business 6	10	7.1
Residential user 12	4.5	6.2
Residential user 13	3	2.3
Residential user 14	3	1.4
Residential user 15	6	2.7
Business 7	25	21.7
Church 3	4.5	5.4
Residential user 16	6	6.1
Total	313.4	234.9

234.9 MWh, which could not be covered totally by a photovoltaic plant because part of this consumption is in time slots which are not covered by the electricity produced by that installation and there is not any type of energy storage.

In the figure 4.20 are represented the aggregate value of the total consumption for each month and in the figure 4.21 the distribution of the different time slots for each month.

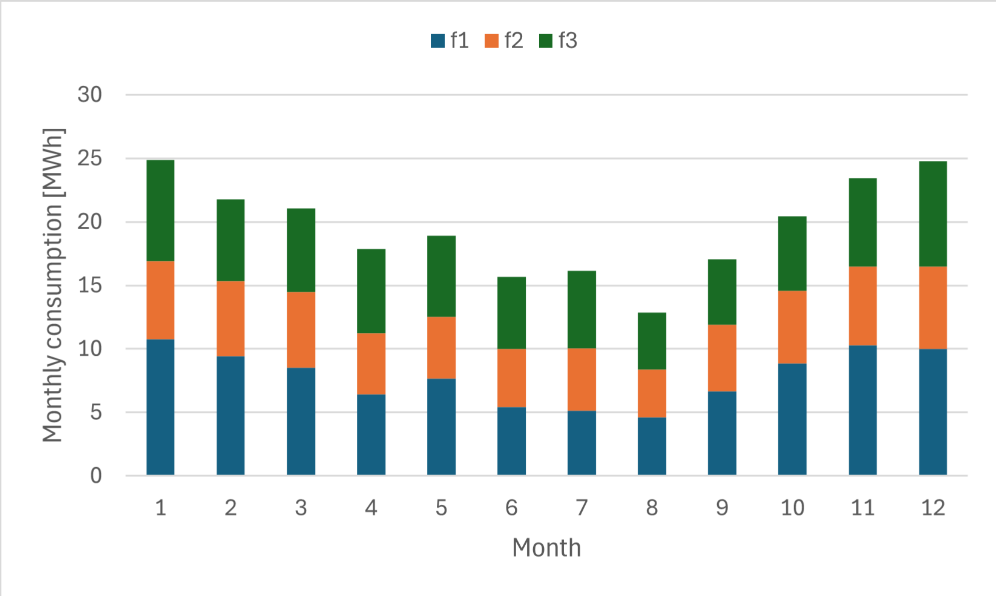

Figure 4.20: REC monthly consumption of the case study D [author's creation]

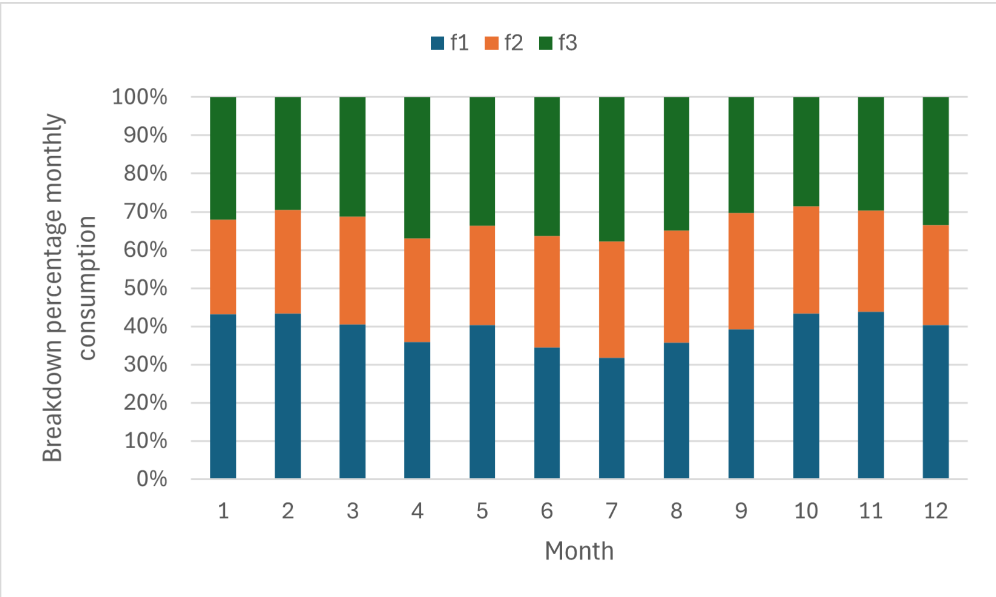

Figure 4.21: percentage breakdown of monthly consumption for the case study D [author's creation]

In this case study there is a clear difference between consumption in winter and summer, with the latter lower than the former. This will not allow to fully exploit the photovoltaic systems, which have a higher production in summer unless they are dimensioned so as to maximize the SC at the expense of the SS.

4.4.2 Photovoltaic plants

The user church 1 and church 3 have made available the roof for the installation of a photovoltaic production plant. As well as other 10 user, the detailed description would focus on the church plant because the private production plant are estimation of the possible photovoltaic plant that could be installed and the final decision depends on them.

Church 1 plant

The surface of the church 1 user is a roof oriented sud 170°, an inclined surface with an inclination of 30° from a plane parallel to the ground. The modules use in the evaluation are Si monocrystalline-HC technology, each module has a power of 400 Wp. The amount of module used are 38 with a total available power of 15.3 kWp. For the inverter have been used AF8K-THA (v1) inverter, with a size factor of 120 %.

This specification are insert in the software PV*SOL and using it together with the PVGIS database for the irradiation in this surface, have been evaluated the production of electricity for a reference year with an hour definition. A graphical representation of it is in the figure 4.22.

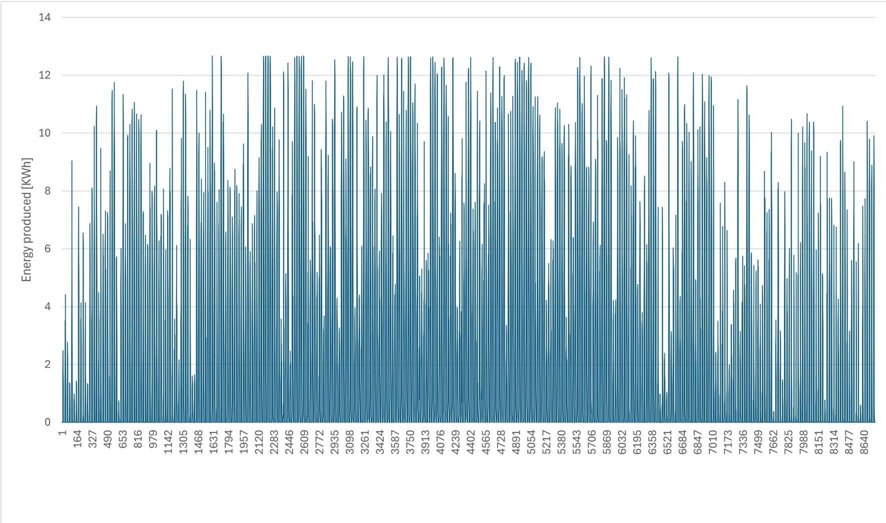

Figure 4.22: Energy produced by the plant of the case D installed in the POD of church 1, hour definition [author's creation]

As can be seen from the figure, there is a big difference in production throughout the year except for the winter months that show lower values than the rest of the year. This is more clear in the figure 4.23

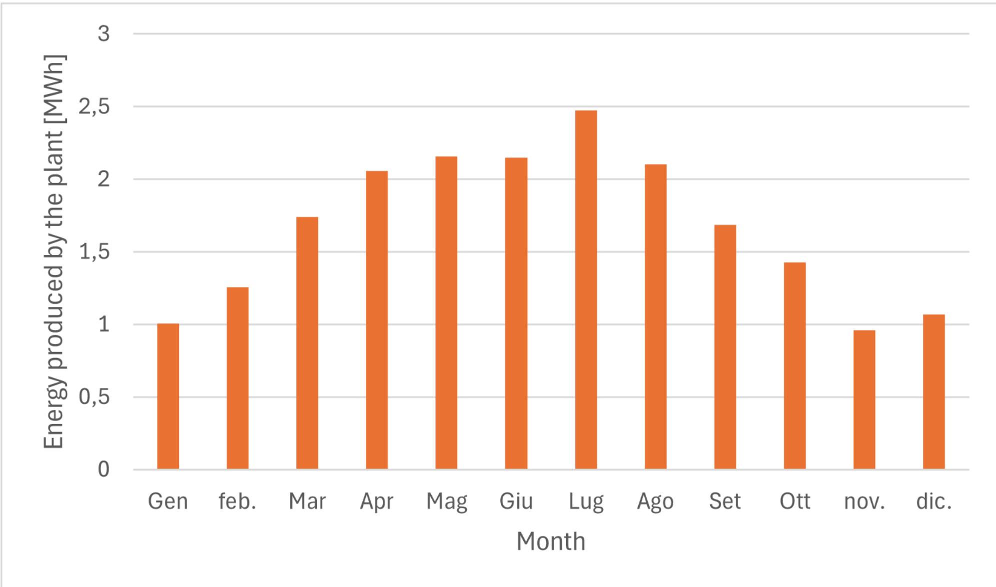

Figure 4.23: Energy produced by the plant of the case study D installed in the POD of church 1, for each month [author's creation]

Church 3 plant

The surface of the church 3 user is a roof oriented sud 170°, with an inclined surface 28° from a plane parallel to the ground. The modules use in the evaluation phase are Si monocrystalline-HC technology, each module has a power of 400 Wp. The amount of module used are 30 with a total available power of 11.9 kWp. For the inverter have been used 3 inverters HNS2500TL-1 S6/PL (v1), with a size factor of 112 %.

This specification are insert in the software PV*SOL and using it together with the PVGIS database for the irradiation in this surface, have been evaluated the production of electricity for a reference year with an hour definition. A graphical representation of it is in the figure 4.24.

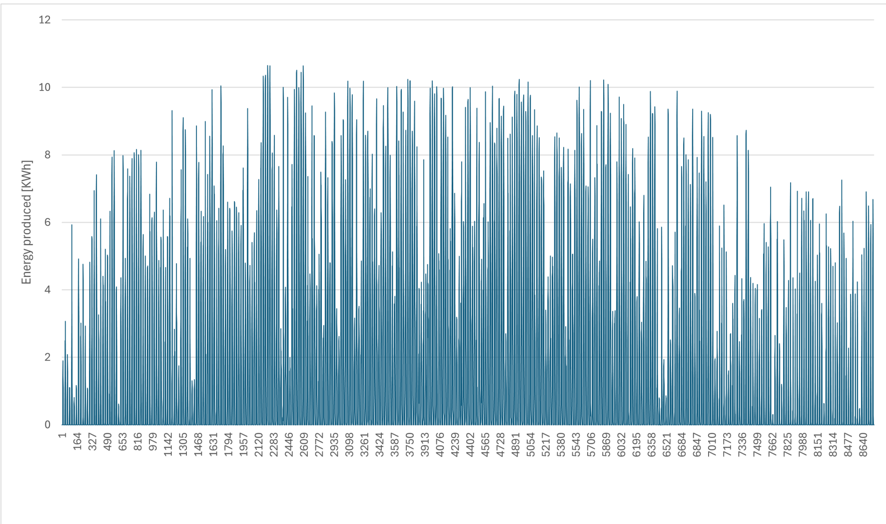

Figure 4.24: Energy produced by the plant of the case D installed in the POD of church 3, hour definition [author's creation]

The production in winter months is lower compered to the summer ones due to the higher value of irradiation, as for 4.22. This is more clear in the figure 4.25.

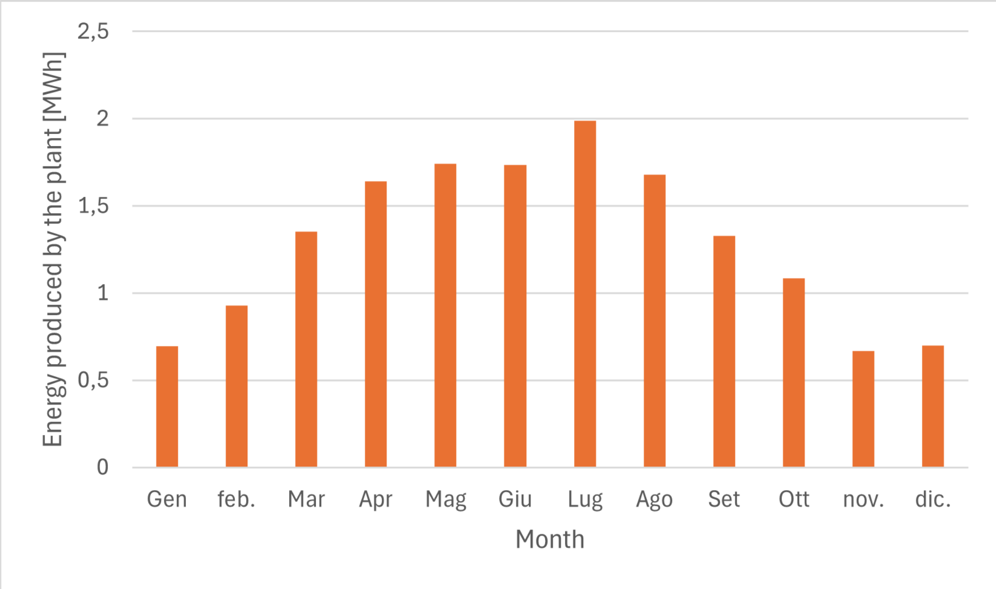

Figure 4.25: Energy produced by the plant of the case study D installed in the POD of church 3, for each month [author's creation]

In the table 4.6 there is the representation of all the plant of the configuration. The total production is 205,6 MWh and the power available is 180 kWp.

Table 4.6: Installed PV Power, Available Power, Estimated PV Production, and Annual Energy Consumption

Name	**Installed PV Power** [kWp]	**Available Power** [kW]	**Estimated Annual PV Production** [MWh]	**Annual Consumption** [MWh]
Church 1	15.3	10	20.1	0.9
Church 2	-	6.6	-	3.0
Business 1	37.2	29.1	37.2	23.5
Residential User 1	3.6	6	4.0	1.6
Business 2	36.0	22	37.2	50.9
Residential User 2	-	3	-	2.1
Residential User 3	-	10	-	3.7
Residential User 4	-	3	-	1.7
Residential User 5	-	4.5	-	2.1
Business 3	-	27	-	7.1
Residential User 6	-	3	-	3.2
Residential User 7	5.2	3	6.2	1.0
Business 4	10.0	30	11.7	6.5
Residential User 8	6.0	3	8.1	2.5
Residential User 9	9.2	4.5	10.2	2.8
Residential User 10	-	3	-	4.6
Residential User 11	-	23.1	-	1.2
Elementary School	-	30	-	19.3
Business 5	-	15.8	-	22.9
Middle School	-	10.3	-	14.9
Kindergarten	-	4.5	-	6.4
Business 6	-	10	-	7.1
Residential User 12	-	4.5	-	6.2
Residential User 13	-	3	-	2.3
Residential User 14	7.2	3	8.4	1.4
Residential User 15	-	6	-	2.7
Business 7	30.0	25	37.9	21.7
Church 3	11.9	4.5	15.6	5.4
Residential User 16	9.2	6	9.2	6.1
Total	180.8	313.4	205.6	234.9

Chapter 5

Results

5.1 Energy values

The consumption and production data of the 4 case studies describer in 4 are used as inputs data for the codes described in 3.3 to obtain the energy values and indicators useful for the assessment of the 4 configuration.

5.1.1 The 4 configuration

In this thesis, there were analyzed 4 case studies located in Turin and his metropolitan area. These case studies have different structures and consumption needs so the production plants differ in size, number and energy produced. In the table 5.1 there is the visual representation of this data for all the case studies.

Table 5.1: System Details and Energy Production for the 4 configuration and the aggregated data

Case Study	**Number of PV plants**	**Installed Power [kWp]**	**Energy Produced [MWh/year]**
Case Study A	1	20.4	29.28
Case Study B	1	20.0	21.52
Case Study C	2	32.0	38.88
Case Study D	12	180.76	205.63
Aggregated Data	16	253.16	295.31

The energy produced is the sum of the energy produced in an hour by a plant, for each hour of the year and for all the system in the configuration. In order to evaluate the other energy values the Python code compare the hour energy produced value of a photovoltaic system with the value of energy consumption of the same POD, in the case both value are different than 0, the minimum value of the two would be considered as self-consumed energy, in physical terms this energy would go from the photovoltaic plant to the load attached at the same POD without passing trough the grid. The excess of the energy produced that is not locally self-consumed is injected to to the grid.

In the case if the energy injected into the grid in a certain hour is consumed in the same hour by an other user of the REC configuration would be counted as energy shared and access the the incentivize related. The calculation of energy shared is better explained in 3.4.

The data for all the configuration and the aggregated data are represented in the table 5.2.

Table 5.2: Energy Consumption and energy shared for the 4 configurations and the aggregated data

Case Study	**Self-consumed Energy [MWh/year]**	**Energy Fed into the Grid [MWh/year]**	**Shared Energy [MWh/year]**
Case Study A	3.62	25.66	24.18
Case Study B	4.7	16.8	16.57
Case Study C	5.34	33.54	25.75
Case Study D	50.78	154.85	47.5
Aggregated Data	64.44	230.85	114.0

The case studies C and D has higher value because they has bigger size photovoltaic plants, however, this does not imply that the SS and SC indices are higher.

5.1.2 Energy results

The value of production represented in the 5.2 are used as explained in 3.5.1 to calculate the energy indicators useful for the valuation of the REC configurations in the energy matters.

In the table 5.3 are shown the value of the energy indicators in all the configurations.

The SS value expresses how much of the domestic electricity demand is met through self-generation of renewable energy, in the case studies C and D is higher respect to the case studies A and B because with the same energy consumption the energy produced is higher.

For the case study A and B would be useful to add new photovoltaic plants, because almost 100% of the energy that is produced by currently installed plants

Table 5.3: Comparison of SS and SC Values Across Case Studies

	SS	**SC**
	[%]	[%]
Case Study A	23.19	94.93
Case Study B	15.99	98.8
Case Study C	30.93	79.96
Case Study D	41.84	47.8
Aggregated Data	**30.33**	**60.42**

is consumed within the REC. However, these installations cover only a small part of the energy supply of the configurations. It is also true that the addition of new members to the current configuration would not bring great benefits to the configuration, since the latter already consumes almost all the energy it produces.

The opposite is true for case studies C and D especially, which have a higher SS values or a greater coverage of consumption by means of renewable energy sources that are part of the REC. With lower values than case studies A and B. For case studies C and D, the best option would be to bring new members into the community in order to make the most of the energy produced by existing installations. The installation of new plants, which would be costly for owner users, would not provide a significant advantage such as in case studies A and B without adding new materials to the configuration.

The SS value indicates that case studies C and D are less dependent on the network, however, having a higher production and being the production mainly in the daytime hours, not all the energy produced is shared and therefore gets the incentive from it.

From an economic point of view is better to have high value of SC because the energy produced in addition to the economic advantage linked to the sale of energy produced by photovoltaic systems to the grid, obtain also the incentivize related to the REC.

5.2 Environmental results

The environmental results show the reduction of emissions related to the consumption of electricity produced from renewable sources. In Italy the electricity withdraw from the gird has different form of production, part of the electricity is produced by fossil fuels that has carbon dioxide emissions related to the production of the electricity and the life cycle of the plant. The photovoltaic electricity production has not emissions related to the production but only for the life time. The value used in this study for the calculation of the emission related the electricity consumption are 315.00 $kgCO_2/MWh$ [23] and for the photovoltaic is 50.00 $kgCO_2/MWh$ [26].

To obtain the emission reduction due to the presents of the photovoltaic plant inside the REC is firstly calculated the emission related to the consumption taking all the electricity from the grid. Then is calculated the emission of the REC related to the energy produced from the photovoltaic and the energy that is still withdraw from the grid. The difference of this two value is the emission reduction.

The value of emission reduction related to the REC in percentage are shown in the table 5.4.

Table 5.4: Delta Emissions Percentage Across Case Studies

Case Study	**Delta Emissions [%]**
Case Study A	19.31
Case Study B	13.42
Case Study C	24.79
Case Study D	27.95
Aggregated Data	**22.36**

5.3 Economic results

This paragraph will show the results of the economic analysis, treating of the initial and operational costs related to the infra-structures necessary for the creation of a renewable energy community configuration and management of the REC. Also, the data relating to revenues and cash flows of the plant owned by the foundation installed on churches that are part of one of the configurations analyzed will be reported.

5.3.1 Cost

The cost are differentiate in investment cost and operative cost. The investment cost are related to the construction of the plant. In this case study in the absence of quotes, the cost of photovoltaic plant is set at 1250 €/kW. To the initial cost have to be added the VAT, an indirect tax that applies to the value added of goods and services during the different stages of production and distribution. The value could be of 10% or 22%, for the plant of the church was used 10%.

The initial investment can be made in a single installment at the time of purchase of the equipment, in this case the cost figure in the table 5.5 as equity. Contrary to this option, it can be done by using a loan. In the case studies the loan interest is set at 5%, for all the church plant except the one of the case study B, the investment would be covered using loan option.

For the plant of the case study B and for the plant financed by private investor in the case study D the cost would be covered by equity.

As explained in 1.5.1, for the town with less then 5 thousands habitant there is the possibility to reduce the initial cost obtaining a capital contribution of up to 40% of the investment cost. The only configuration that access this type of reduction is the case study D, only for the church plants because expect for religious entities and other category explained in 1.5.1, in the case of an installation accessing such capital contribution the incentivize related to the energy shared would be reduced by a factor of 50% .

Table 5.5: Financial and Operating Costs Across Case Studies

Case Study	**Debt [€]**	**Equity [€]**	**Loan Payment [€/year]**	**Operating Costs [€/year]**
Case Study A	20001	0	2590	1259
Case Study B	0	27500	0	1215
Case Study C	44000	0	5698	1974
Case Study D	31802	234240	4119	11129
Aggregated Data	**95803**	**261740**	**12407**	**15577**

The other budgeted cost item are the operating costs. The operating cost is the cost that the owner of the plant or the REC has to face every year. In the table entry operating cost is present the annual value of different types of operating costs. The items in this cost note are the GSE tax for the manage of the energy from the PV plant, his value is 0 €/year for plants less the 3 kWp, 15 for plants less or equal to 20 kWp and for plant with installed power higher than 20 kWp the tax is 15+ the size of the plant. Another operating cost are the operating cost of the plant calculated as 5% of the initial cost of the photovltaic plant, as well as the insurance of the photovoltaic plant that has been hypothesized with the same criteria.

5.3.2 Revenue

Revenues from the installation of photovoltaic systems and the REC configuration can be divided into three categories. The savings related to self-consumption depends on two factors, one is the purchase price of electricity the PUN index.

The PUN index is the "Prezzo Unico Nazionale" (PUN), recently renamed "PUN Index GME" , is the reference price of electricity traded on the "Mercato del Giorno

Prima" (MGP) in Italy. This index is calculated as the weighted average of zonal electricity prices, taking into account the quantities traded in different areas of the country [27]. It plays a crucial role in determining the price at which energy produced by plants is sold.

Total incentives are the sum of the various incentives related to energy communities. Or those explained in the section 1.5.1.

Table 5.6: Economic Analysis of Different Case Studies

	Self-consumption Savings [€/year]	Grid Injection [€/year]	Total Incentives [€/year]
Case Study A	1805	2823	3399
Case Study B	1410	1851	2329
Case Study C	1601	3689	3620
Case Study D	15232.7	17034	6678
Aggregated Data	20048.7	25397	16026

5.3.3 Allocation

The total incentives shown in the table 5.6 are subdivided in each case study following the criteria explained in 3.7.

Case study A

For the case study A the incentives accessed trough the REC configuration are broken down according to the table 5.7.

Table 5.7: Allocation of Shares Among Stakeholders, case study A

Stakeholders	**Share [€/year]**
Foundation	850
Church Prosumer	-
Third Parties	0
Social	1147
Private Prosumer	0
Consumers	1402

The incentives are distributed among different types of participants. The total incentives for this case study are 3399 €/year 5.6.

Firstly 25% of it goes to the foundation as said in the statue of the foundation, precisely 850 €/year. Secondly, the remaining 75% should first be used to cover the

costs of the silent photovoltaic system of the ecclesiastical user. However, in this case these expenses are fully covered by the revenue as can be seen in the table 5.8
.

Table 5.8: Cash flows of the first 10 years of the case study A plant

Year	Expenses [€]	Revenues [€]	Net [€]
0	0	0	0
1	3849.59	3907.56	57.96
2	3849.59	3907.56	57.96
3	3849.59	3907.56	57.96
4	3849.59	3907.56	57.96
5	3849.59	3907.56	57.96
6	3849.59	3907.56	57.96
7	3849.59	3907.56	57.96
8	3849.59	3907.56	57.96
9	3849.59	3907.56	57.96
10	1259.40	3907.56	2648.16

In the table 5.8 are represented the revenues, expenses and the difference between them for the first 10 years of the plant, in which in the expenses are included both operating costs and mortgage fees.

The 75% of the total incentive is subdived as 45% of it is intended for social projects on the territory, the rest is distributed proportionally among consumers in proportion to their contribution to the total share of energy consumed in the total. Consumers can give their share to social projects if they so wish.

Case study B

For the case study B the incentives accessed trough the REC configuration are broken down according to the table 5.9.

Table 5.9: Allocation of Shares Among Stakeholders, case study B

Stakeholders	Allocation [€/year]
Foundation	582.25
Church Prosumer	700.00
Third Parties	0.00
Social	471.30
Private Prosumers	0.00
Consumers	575.71

The incentives are distributed among different types of participants. The total incentives for this case study are 2329 €/year 5.6.

Firstly 25% of it goes to the foundation as said in the statue of the foundation, precisely 582.25 €/year. Secondly, the remaining 75% should first be used to cover the costs of the silent photovoltaic system of the ecclesiastical user. In this case the ecclesiastical prsoumer is given a share equal to 700 €/year .

The rest is subdived in 45% to social projects and 55% to consumers. Consumers can give their share to social projects if they so wish.

Case study C

For the case study C the incentives accessed trough the REC configuration are broken down according to the table 5.10.

Table 5.10: Allocation of Shares Among Stakeholders, case study C

Stakeholders	**Allocation [€/year]**
Foundation	905
Church Prosumer	1680
Third Parties	0
Social	570
Private Prosumers	0
Consumers	466

The incentives are distributed among different types of participants. The total incentives for this case study are 3620 €/year 5.6.

Firstly 25% of it goes to the foundation as said in the statue of the foundation, precisely 905 €/year. Secondly, the remaining 75% should first be used to cover the costs of the silent photovoltaic system of the ecclesiastical user. In this case these expenses for the first photovoltaic plant are almost totally covered by the revenues as can be seen in the table 5.11 .

In the table 5.11 are represented the revenues, expenses and the difference between them for the first 10 years of the plant, in which in the expenses are included both operating costs and mortgage fees and in the revenue there is no incentive portion. By allocating 300 €/year of incentives linked to the energy community it is possible to maintain the net cash flow for the first 10 years.

Different speech for the photovoltaic system 2 that despite a share equal to 1380 €/year maintains a net cash flow of more than 700 €/year negative for the first 10 years, as shown in the table 5.12.

In the table 5.12 are represented the revenues, expenses and the difference between them for the first 10 years of the plant, in which in the expenses are

Table 5.11: Cash flows of the first 10 years of the case study C plant 1

Year	Expenses [€]	Revenues [€]	Net [€]
0	0	0	0
1	2014.78	1723.225	-291.553
2	2014.78	1723.225	-291.553
3	2014.78	1723.225	-291.553
4	2014.78	1723.225	-291.553
5	2014.78	1723.225	-291.553
6	2014.78	1723.225	-291.553
7	2014.78	1723.225	-291.553
8	2014.78	1723.225	-291.553
9	2014.78	1723.225	-291.553
10	519.00	1723.225	1204.225

Table 5.12: Cash flows of the first 10 years of the case study C plant 2

Year	Expenses [€]	Revenues [€]	Net [€]
0	0	0	0
1	5657.02	4946.771	-710.253
2	5657.02	4946.771	-710.253
3	5657.02	4946.771	-710.253
4	5657.02	4946.771	-710.253
5	5657.02	4946.771	-710.253
6	5657.02	4946.771	-710.253
7	5657.02	4946.771	-710.253
8	5657.02	4946.771	-710.253
9	5657.02	4946.771	-710.253
10	1454.60	4946.771	3492.171

included both operating costs and mortgage fees and in the revenue there is the incentive portion intended for the plant.

The reaming part of the total incentive is subdivided as 45% of it is intended for social projects on the territory, the rest is distributed proportionally among consumers in proportion to their contribution to the total share of energy consumed in the total. Consumers can give their share to social projects if they so wish.

Case study D

For the case study D the incentives accessed trough the REC configuration are broken down according to the table 5.13.

Table 5.13: Allocation of Shares Among Stakeholders, case study D

Stakeholders	Quota [€/year]
Foundation	1669.00
Prosumer Church	1270.00
Third Parties	0.00
Social Sector	1682.20
Private Prosumers	1028.03
Consumers	1028.03

The incentives are distributed among different types of participants. The total incentives for this case study are 6678 €/year 5.6.

Firstly 25% of it goes to the foundation as said in the statue of the foundation, precisely 1669 €/year. Secondly, the remaining 75% should first be used to cover the costs of the silent photovoltaic system of the ecclesiastical user. In this case these expenses for the first photovoltaic plant are partially covered by the revenues as can be seen in the table 5.8 .

Table 5.14: Cash flows of the first 10 years of the case study D plant 1

Year	Expenses [€]	Revenues [€]	Net [€]
0	0.00	0.00	0.00
1	2913.16	2290.01	-623.15
2	2913.16	2290.01	-623.15
3	2913.16	2290.01	-623.15
4	2913.16	2290.01	-623.15
5	2913.16	2290.01	-623.15
6	2913.16	2290.01	-623.15
7	2913.16	2290.01	-623.15
8	2913.16	2290.01	-623.15
9	2913.16	2290.01	-623.15
10	930.60	2290.01	1359.41

In the table 5.14 are represented the revenues, expenses and the difference between them for the first 10 years of the plant, in which in the expenses are included both operating costs and mortgage fees and in the revenue there is no incentive portion. By allocating 635 €/year of incentives linked to the energy community it is possible to maintain the net cash flow positive for the first 10 years.

Similar speech for the second plant, as shown in the table 5.15.

In the table 5.15 are represented the revenues, expenses and the difference

Table 5.15: Cash flows of the first 10 years of the case study D plant 2

Year	Expenses [€]	Revenues [€]	Net [€]
0	0.00	0.00	0.00
1	2864.97	2222.45	-642.52
2	2864.97	2222.45	-642.52
3	2864.97	2222.45	-642.52
4	2864.97	2222.45	-642.52
5	2864.97	2222.45	-642.52
6	2864.97	2222.45	-642.52
7	2864.97	2222.45	-642.52
8	2864.97	2222.45	-642.52
9	2864.97	2222.45	-642.52
10	729.00	2222.45	1493.45

between them for the first 10 years of the plant, in which in the expenses are included both operating costs and mortgage fees and in the revenue there is no incentive portion. By allocating 635 €/year of incentives linked to the energy community it is possible to maintain the net cash flow almost positive for the first 10 years.

The reaming part of the total incentive is subdivided as 45% of it is intended for social projects on the territory, the rest is distributed half among the consumers and the other half among the private prosumers, proportionally to their contribution to the total share of energy produced and consumed in the total. Consumers and prosumers can give their share to social projects if they so wish.

Conclusion and future developments

Conclusion

The findings of this study highlight the significant role that Renewable Energy Communities play in advancing the energy transition towards sustainability, decentralisation, and energy democracy. Through a techno-economic assessment of solidarity-based energy communities, this thesis has demonstrated how RECs contribute to environmental, social, and economic benefits, particularly within the Italian regulatory framework. The analysis of the four case studies in the metropolitan area of Turin has provided valuable insights into the performance and viability of different REC configurations. The results indicate that configurations with fewer photovoltaic plants tend to exhibit higher self-consumption rates, while larger configurations, such as case D, have greater potential for integrating additional energy consumers and achieving a higher degree of self-sufficiency. Moreover, the presence of multiple plants and access to higher incentives in certain configurations results in a more substantial reduction in carbon dioxide emissions.

The study's economic analysis indicates that the financial sustainability of RECs is contingent on incentive mechanisms, such as the tariff incentives provided by the GSE. The methodology developed for benefit allocation within RECs suggests that dynamic allocation models, as opposed to fixed criteria, can result in more equitable and efficient distribution of incentives among participants.Furthermore, the inclusion of social initiatives funded by a portion of the REC's income emphasises the potential for RECs to contribute to broader community welfare beyond energy sharing. The financial modelling also revealed that while initial capital investments can be substantial, particularly for larger-scale RECs, the long-term financial returns and savings on energy costs make them a promising solution for both individual members and the community at large.

From a regulatory perspective, the evolution of Italy's legal framework has been instrumental in fostering the growth of renewable energy certificates. Nevertheless, challenges persist in ensuring long-term stability and financial viability, particularly with respect to market dynamics and grid integration. Moreover, regulatory uncertainties and administrative complexities continue to act as significant barriers to entry, particularly for smaller communities that may lack the technical expertise or financial resources to navigate the process of REC formation and operation. The ETS foundation de facto is trying to solve this problem by taking on these burdens, paying for a part of the incentives linked to the community, while maintaining its non-profit purpose.

In terms of environmental impact, the integration of renewable energy within RECs has been shown to lead to significant carbon emission reductions and to encourage greater energy independence. The transition towards local energy production has been demonstrated to reduce reliance on centralised fossil fuel-based energy sources, thereby lowering transmission losses and improving overall grid efficiency. Furthermore, advancements in energy storage technologies and smart grid integration are presenting new opportunities for RECs to enhance their self-sufficiency and resilience, especially in the context of fluctuating energy demand and supply.

In conclusion, this thesis has contributed to the understanding of RECs as a viable model for decentralised energy production and community empowerment. By demonstrating their environmental benefits, financial viability, and social impact, this study provides a foundation for future research on optimizing REC configurations, improving regulatory support, and fostering greater community engagement in the energy transition. Additionally, the role of RECs in the broader European energy strategy should be further investigated, particularly in light of the EU's goals for carbon neutrality and increased renewable energy adoption by 2050. Strengthening international collaboration and knowledge-sharing between different REC models across Europe could provide valuable insights into best practices and new approaches for maximising the impact of community-based renewable energy solutions.

Future developments

Optimizing the design and operation of RECs is inherently complex due to multiple, often conflicting, objectives that must be considered, including economic, environmental, and energy efficiency goals [28]. Traditional multi-objective optimization techniques, such as the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), have been widely applied to identify an optimal set of trade-offs [28]. However, the selection of a final, implementable solution remains a challenge. In this context, game theory offers a novel framework to enhance the techno-economic assessment of RECs by transforming the problem into a cooperative game where objectives act as players negotiating a compromise solution [28].

Game theory, particularly the Nash bargaining approach, can be applied to REC design by treating the different objectives—economic, environmental, and energy efficiency as players in a cooperative game. Unlike traditional Pareto-based optimization, which generates a set of non-dominated solutions, the game-theoretic approach seeks a single Nash-bargaining solution that fairly balances trade-offs among competing objectives. This method is particularly beneficial in multi-objective problems where stakeholders must reach an agreement on a single course of action [28].

The Nash bargaining approach identifies an equilibrium solution by maximizing the Nash product, which represents the distance between the current solution and a disagreement point (the worst possible outcome for all players) [28]. This approach ensures that the selected solution is Pareto-efficient, meaning that no other solution can improve one objective without worsening at least one other [28]. The procedure involves the following steps:

1. Identify Utopia Points: Determine the best possible value for each objective in isolation.

2. Define the Disagreement Point: Establish the worst-case scenario where no cooperation exists between objectives.

3. Solve the Nash Bargaining Problem: Compute the Nash-bargaining solution by maximizing the Nash product, ensuring a fair compromise between competing goals.

The advantages of Game Theory in REC Optimization are:

- Computational Efficiency: Reduces the number of function evaluations compared to NSGA-II, leading to faster convergence.

- Fair and Balanced Solutions: Ensures that all objectives are equitably considered rather than favoring one over others.

- Improved Decision-Making: Provides a single, well-justified solution rather than requiring manual selection from a Pareto front.

- Adaptability: Can be extended to include additional objectives, such as social impact or grid stability.

The integration of game theory into the techno-economic assessment of RECs represents a significant advancement in optimizing decentralized energy systems [28]. By shifting from purely Pareto-based optimization to a cooperative game framework, stakeholders can achieve more balanced and computationally efficient solutions [28].

Future research should explore the extension of this approach to more complex REC configurations, incorporating dynamic pricing mechanisms and real-time demand response strategies to enhance the resilience and efficiency of energy communities.

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