UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Department of Industrial Engineering (DII)

Master's Degree Course in Energy Engineering

OPTIMIZATION AND ECONOMIC ANALYSIS OF A RENEWABLE ENERGY COMMUNITY

Student: De Biasi Luca
Prof: Lorenzoni Arturo

Academic Year: 2023-2024

Abstract

Due to the inconstant nature of the renewable energy sources the use of batteries becomes very important, but the installation of storages on all the utilities is unfeasible at the moments due to the high costs and the lack of technology. Thus the capacity of the consumers to use the energy immediately, when it is produced, become essential and here it is the role of CER (Comunità Energetiche Rinnovabili) in italian, or REC (Renewable Energy Communities). The basic principle is that the members, that have different loads and production profiles, should share the energy in excess in order to limit the wastes and consequently also the usage of the grid, this system permits the maximization of the load factor and increases the total efficiency since it avoids the grid dissipations.

A great problem raises when the fluxes of energy has to be necessarily measured and managed. In this thesis a photovoltaic plant of 1 MW located in Motta di Livenza (TV), Italy, is supposed to be the source of electricity for some typical customers of the zone. The goal is understand if for the company owner of the plant is convenient to start a REC, and if for the private citizens, companies, public amministration is convenient to join it.

To do this all the new incentives released from the Italian government on this field are analyzed. Following, an optimization of the number of users is performed in order to maximize the benefit under the energetic and economic point of view for all the members.

At the end there will be a comparison between some systems with the goal to understand how to manage and optimize all the REC in the best way.

Table of Contents

Nomenclature

- REC: Renewable Energy Community
- POD: Point Of Delivery
- E_{prod}: Total energy produced
- $E_{\text{prod plant}}$: Total energy produced by the plant
- $E_{\text{prod pros}}$: Total energy produced by prosumers
- E_{cons}: energy consumed (not auto consumed)
- E_{buy}: Energy to buy
- E_{loc}: Energy auto consumed locally
- E_{inj}: Energy injected on the grid and potentially shared
- E_{exc}: Energy injected that cannot be shared (sold) and in excess
- E_{sh}: Energy shared
- $E_{\text{no sh}}$: Energy not shared
- NPV = Net Present Value
- ROI = Return Of Investment
- LCOE = Levelized Cost Of Electricity
- IRR = Internal Rate of Return

1 Introduction

Climate change represents one of the most urgent and complex challenge facing humanity in the 21st century. The scientific consensus is unequivocal: human activities, particularly the burning of fossil fuels and deforestation, have dramatically altered the Earth's climate system, leading to rising temperatures, shifting precipitation patterns, and more frequent and severe extreme weather events. These changes have deep implications for ecosystems, economies, and societies worldwide, exacerbating vulnerabilities and threatening livelihoods, health, and well-being.

In response to the existential threat of climate change, there is a growing recognition of the need to transition to low-carbon, sustainable energy systems. The energy sector is a major contributor to greenhouse gas emissions, accounting for approximately three-quarters of global emissions. Therefore, transforming the way we produce, distribute, and consume energy is critical to mitigate climate change and building resilience to its impacts.

At the forefront of this transition there are energy communities: locally based initiatives that empower individuals, households, and communities to actively participate in the generation, management, and consumption of renewable energy. Energy communities represent a paradigm shift in energy governance, challenging the centralized, top-down model of energy production and distribution and promoting decentralized, democratic, and inclusive approaches.

This thesis seeks to explore the role of energy communities in contrasting climate change and advancing the transition to sustainable energy systems. It examines the potential of energy communities to harness the power of renewable energy sources, promote energy efficiency, and foster community resilience in the face of climate-related challenges. By analyzing case studies, policy frameworks, and best practices from around the world, this study aims to shed light on the opportunities and challenges of energy communities and provide insights into their role in shaping the future of energy.

In the first part of the thesis, the countermeasures taken by world governments to combat climate change will be analyzed. This will include a detailed examination of actions undertaken at the global, regional, and national levels to address the challenges of climate change. Political approaches, mitigation and adaptation strategies, public policies, international agreements, and investments in clean energy and environmental sustainability will be scrutinized. Additionally, the role of multilateral institutions, such as the United Nations and the European Union, in coordinating international efforts and promoting cooperation among countries will be assessed. This in-depth analysis of governmental countermeasures will provide a comprehensive overview of the policies and strategies implemented to address climate change and their implications on a global scale.

Afterwards, a comprehensive introduction to energy communities is presented, elucidating their conceptual framework, operational mechanisms, and potential contributions to the ecological transition. This encompass a detailed examination of how energy communities empower local stakeholders to collectively participate in renewable energy generation, distribution, and consumption, thereby fostering community resilience, promoting energy democracy, and advancing sustainable development goals. Subsequently, the focus shifts towards an analysis of the current landscape of energy communities in Europe and Italy, encompassing an overview of existing initiatives, policy frameworks, regulatory landscapes, and social-economic contexts. By delving into the specific challenges and opportunities faced by energy communities in these regions, this section aims to provide valuable insights into the dynamics shaping the evolution and expansion of community-based energy initiatives within the broader context of the ecological transition.

Energy communities are closely intertwined with governmental authorities, necessitating a de-

tailed overview of the laws regulating this new entity in this thesis. This will involve a comprehensive examination of the legal frameworks, policies, and regulations at the international, regional, and national levels governing the establishment, operation, and governance of energy communities. By exploring the legal landscape surrounding energy communities, including aspects related to energy market regulations, grid connection procedures, community ownership models, and financial incentives, this analysis aims to provide a nuanced understanding of the legal complexities and challenges faced by energy communities in navigating regulatory frameworks and fostering their growth and sustainability.
The analysis proceeds by examining in detail the ordinance issued on 24 January 2024, which is fundamental for the establishment of communities in the Italian territory. Specifically, incentives for founding a community are scrutinized. This entail a thorough examination of the provisions outlined in the ordinance, including any financial incentives, regulatory frameworks, and support mechanisms provided by governmental authorities to encourage the establishment and growth of energy communities.
After all this generalities it is possible to start with the project that consists in identify the best number of users to start a REC. In particular there is the project to build a photovoltaic plant with the power of 1 MW in Motta di Livenza (Northern Italy) and, by having the data of the typical consumers of the zone, it is possible to find how many of them could ”share” the energy produced by the plant. To do this a general Matlab script that could be used also in other situations by changing the input data is created, so basically this acts as an optimizer. The working principle is: give as input the production and consumption profiles of the plants and of the users, calculate all the possible combinations that maximizes the benefits by using mathematical equations and in the end it should be obtained as output the best configuration of users.
The last part consists in analyzing some systems, proposed by Italian companies, that aims to further optimize the community. The goal is to superimpose as max as possible the production with the consumption by installing a massive grid of sensors that can take precise measures basically at each instant. Then by having a simple smartphone it shall be possible to monitor the community and understand earlier the moments at which consuming is better.

2 The climate change problem

2.1 Kyoto protocol

Kyoto protocol was an international treaty which extended the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that commits state parties to reduce greenhouse gas emissions, based on the scientific consensus that global warming is occurring and that human-made CO_2 emissions are driving it. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005. There were 192 parties (Canada withdrew from the protocol, effective December 2012) to the Protocol in 2020.

The Kyoto Protocol implemented the objective of the UNFCCC to reduce the onset of global warming by reducing greenhouse gas concentrations in the atmosphere to "a level that would prevent dangerous anthropogenic interference with the climate system".

The Protocol was based on the principle of common but differentiated responsibilities: it acknowledged that individual countries have different capabilities in combating climate change, owing to economic development, and therefore placed the obligation to reduce current emissions on developed countries on the basis that they are historically responsible for the current levels of greenhouse gases in the atmosphere.

The Protocol's first commitment period started in 2008 and ended in 2012. All 36 countries that fully participated in the first commitment period complied with the Protocol. However, 9 countries had to resort to the flexibility mechanisms by funding emission reductions in other countries because their national emissions were slightly greater than their targets. The financial crisis of 2007–08 reduced emissions. The greatest emission reductions were seen in the former Eastern Bloc countries because the dissolution of the Soviet Union reduced their emissions in the early 1990s. Even though the 36 developed countries reduced their emissions, the global emissions increased by 32% from 1990 to 2010.

The Kyoto Protocol's mechanisms included Emissions Trading, the Clean Development Mechanism (CDM), and Joint Implementation (JI), allowing countries to earn and trade emission reduction credits. These mechanisms were designed to help countries meet their targets cost-effectively while promoting sustainable development and technology transfer. Despite the mixed success of the Protocol, it laid the groundwork for future international climate agreements by establishing a structured, legally binding framework for addressing global warming.

A second commitment period was agreed to in 2012 to extend the agreement to 2020, known as the Doha Amendment to the Kyoto Protocol, in which 37 countries had binding targets: Australia, the European Union (and its then 28 member states) stated that they may withdraw from the Kyoto Protocol or not put into legal force the Amendment with second round targets. Japan, New Zealand, and Russia had participated in Kyoto's first-round but did not take on new targets in the second commitment period. Other developed countries without second-round targets were Canada (which withdrew from the Kyoto Protocol in 2012) and the United States (which did not ratify). If they were to remain as a part of the protocol, Canada would be hit with a 14 billion dollars fine, which would be devastating to their economy, hence the reluctant decision to exit. As of October 2020, 147 states had accepted the Doha Amendment. It entered into force on 31 December 2020, following its acceptance by the mandated minimum of at least 144 states, although the second commitment period ended on the same day. Of the 37 parties with binding commitments, 34 had ratified.

Negotiations were held in the framework of the yearly UNFCCC Climate Change Conferences on measures to be taken after the second commitment period ended in 2020. This resulted in the 2015 adoption of the Paris Agreement, which is a separate instrument under the UNFCCC rather than an amendment of the Kyoto Protocol.[1]

2.2 2015 Paris agreements

The Paris Agreement stands as a pivotal milestone in the global fight against climate change, representing a legally binding international treaty adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. Its ratification culminated in its entry into force on 4 November 2016. At its core, the agreement seeks to address the pressing issue of climate change by aiming to limit the increase in the global average temperature to well below 2°C above pre-industrial levels, with an aspiration to cap the temperature rise at 1.5°C.

In recent years, there has been a growing recognition among world leaders regarding the necessity of striving to limit global warming to 1.5°C by the end of the century. This acknowledgment stems from the findings of the UN's Intergovernmental Panel on Climate Change (IPCC), which underscore the heightened risks associated with surpassing the 1.5°C threshold. Crossing this threshold could unleash more severe climate change impacts, including heightened frequency and intensity of droughts, heatwaves, and rainfall patterns. Additionally, exceeding 1.5°C could have catastrophic impacts on biodiversity and ecosystems, potentially triggering feedback loops that accelerate global warming.

To achieve the ambitious goal of limiting global warming to 1.5°C, the Paris Agreement emphasizes the urgency of action. It highlights that greenhouse gas emissions must peak before 2025 at the latest and decline by 43% by 2030. This necessitates rapid and substantial reductions in emissions across various sectors of the global economy. Moreover, it calls for enhanced efforts in developing renewable energy sources and improving energy efficiency, as well as measures to curb deforestation and promote sustainable land use practices.

One of the distinguishing features of the Paris Agreement is its inclusivity. For the first time in the multilateral climate change process, it brings together all nations, regardless of their level of development or historical contributions to greenhouse gas emissions. This aspect is crucial as it acknowledges the shared responsibility of all countries in addressing climate change while recognizing the differing capacities and vulnerabilities among nations. The agreement also recognizes the principle of "climate justice," emphasizing that climate actions should consider equity and the right to sustainable development.

The Paris Agreement operates on a five-year cycle, wherein member countries are expected to submit increasingly ambitious climate action plans known as Nationally Determined Contributions (NDCs). These plans outline each country's commitments to reduce emissions, adapt to the impacts of climate change, and support climate-resilient development. The agreement encourages countries to regularly enhance their NDCs to reflect their evolving circumstances and capabilities.

Furthermore, the Paris Agreement fosters international cooperation and support mechanisms to assist developing countries in their climate mitigation and adaptation efforts. It establishes frameworks for financial assistance, technology transfer, and capacity-building initiatives to enable these nations to transition towards low-carbon and climate-resilient pathways. The Green Climate Fund, established under the agreement, plays a key role in mobilizing resources for these purposes, ensuring that developing countries have access to the necessary tools and funding.

Looking ahead, the Paris Agreement offers a roadmap for global climate action, with the potential to drive transformative change across economies and societies. By 2030, zero-carbon solutions could become competitive in sectors representing over 70% of global emissions, signaling a shift towards a more sustainable and climate-resilient future. However, fulfilling the promise of the Paris Agreement requires unwavering commitment, collaboration, and urgency from all stakeholders, from governments and businesses to civil society and individuals, to effectively address the existential threat of climate change and safeguard the planet for future generations.[2]

2.3 COP 28 Dubai 2023

COP stays for Conference Of Parties, where the parties are the 198 countries that participates. The conference resumes the objects of the previous COP 27 and the Paris agreements. There are some crucial actions to take immediately, here a summary:

- Triple the renewable energy production within 2030 in global terms, and multiply the measures in optic of energy efficiency.
- It was used the word ”transition away” for the fossil fuels with the purpose to totally eliminate them in the right and equal way within 2050.
- Increase the nuclear energy production and develop CCS systems.
- Starting a massive production of green hydrogen.
- Reduce all the other emissions within 2030, in particular methane.
- Accelerate the reduction especially in the transport sector by using different technologies.
- Eliminate any type of incentive for fossil fuels.

For the first time all the countries agree, in written form, in the total elimination of the fossil fuels and not just the reducing, it is an historical result since the first COP of 1995. However the conference was strongly criticized because the host country and the conference president are strongly related to the fossil fuels industry, so there could have been some interest conflicts.

2.4 Actual situation and scenarios

Since 2016, as consequence of the Paris agreements, there has been a concerted global effort to mitigate greenhouse gas emissions, driven by growing recognition of the urgent need to combat climate change. While many nations have committed to various agreements aimed at reducing emissions, it’s evident that not all countries are fully adhering to these commitments. Nevertheless, European countries have emerged as leaders in this endeavor, demonstrating a strong commitment to reduce their carbon footprint and transit towards more sustainable practices.

The results of these efforts are multifaceted and vary across regions and sectors. In Europe, substantial progress has been made in several key areas. Investments in renewable energy sources such as wind, solar, and hydroelectric power have surged, leading to significant reductions in carbon emissions from electricity generation. Additionally, policies promoting energy efficiency in buildings, transportation, and industry have helped to curb overall emissions.

However, challenges remain, particularly in sectors with entrenched carbon-intensive practices, such as heavy industry and transportation. Additionally, the global nature of climate change means that efforts by individual countries, no matter how substantial, must be complemented by coordinated action on a global scale to truly address the issue.

As it is shown on figure 1 the 2020 target were reached without changing the energy consumption, this is synonym of higher energy efficiency and increasing of renewable energy technologies. An important role was also played by the ”help” of the COVID-19 pandemic that surely impacts on CO_2 emissions, however the estimation are not optimistic on 2030 and even less on 2050, thus a more strong effort is required from all the member state. The situation is even worse in other parts of the world, but after COP 28 some changes are expected.

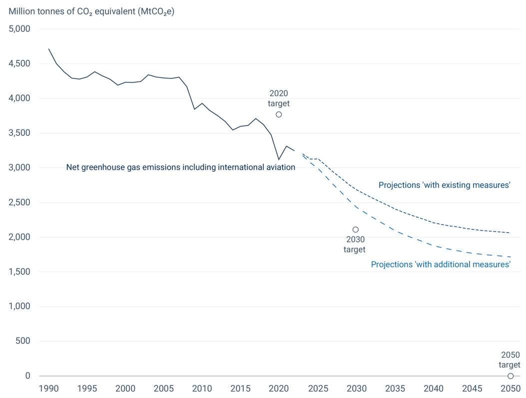
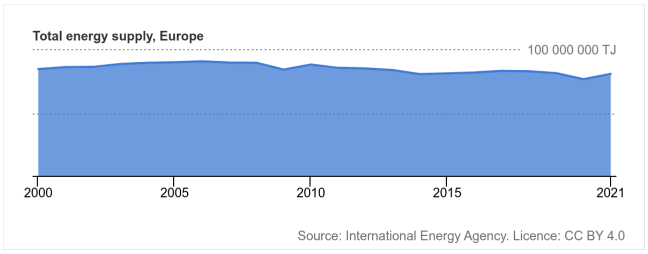


Figure 1: Emissions trend from 1990 to 2050 [3]

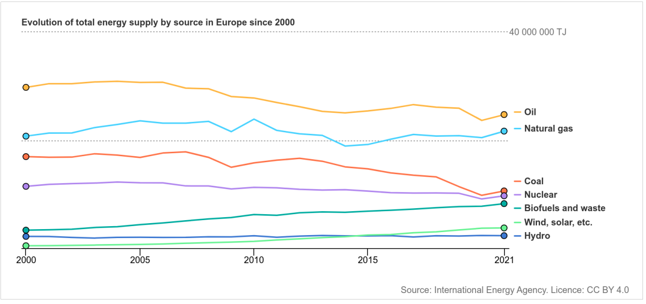
In the context of energy consumption in Europe (figure 2), there's been a notable trend of relatively stable demand over recent years. However, the focus has shifted towards transforming the energy supply from fossil fuel sources to non-fossil alternatives (see figure 3). This transition is essential for addressing climate change and reducing greenhouse gas emissions, aligning with broader efforts to achieve sustainability and mitigate environmental impact.

Hence RECs play a crucial role in this transition, serving as valuable instruments for all sectors, including the domestic one. They are essentially a proof that a certain amount of electricity has been generated from renewable sources, such as solar, wind, hydroelectric, or biomass. They provide a mechanism for tracking and incentives the production and consumption of renewable energy.



Source: International Energy Agency. Licence: CC BY 4.0

Figure 2: Total energy supplied in EU [4]



Source: International Energy Agency. Licence: CC BY 4.0

Figure 3: Energy source evolution in EU [5]

3 The Italian energy sector

3.1 History and future scenarios

Italy's energy sector has evolved significantly over the years, reflecting changes in technology, policy, and global energy trends. Here's a narrative overview of its history: Italy's energy journey began in the late 19th century with the rise of industrialization. During this period, coal emerged as a primary energy source, fueling the growth of factories and railways. However, Italy's abundant water resources soon led to investments in hydroelectric power generation, which became a major contributor to the country's electricity supply. Following World War II, Italy underwent a period of reconstruction and economic expansion. This spurred increased energy demand, leading to the development of domestic oil and natural gas resources as well as significant imports. State intervention in the energy sector became prominent during the 1960s and 1970s, with the nationalization of key assets and the creation of state-owned companies like Eni and Enel. Nuclear energy also entered Italy's energy mix during this period, but faced strong public opposition, culminating in a 1987 referendum that resulted in the closure of existing nuclear power plants and a moratorium on new ones. This event marked a turning point in Italy's energy policy, shifting focus towards other sources such as renewables. In the 1990s and 2000s, Italy implemented liberalization and market reforms in its energy sector, introducing competition and privatizing state-owned assets. This period also saw a growing emphasis on renewable energy, particularly solar and wind power, supported by government incentives and EU directives aimed at reducing greenhouse gas emissions. Today the sector has reached the maturity in terms of energy demand, that is almost constant every year. And the purpose is now to convert the actual production park into renewable. According to IEA (International Energy Agency)*"Italy aims for carbon neutrality by 2050 and is on track to reach its 2030 targets for emissions reductions and energy efficiency, aiming to reach 30% of renewables in total energy consumption and 55% of renewables in electricity generation. The country has experienced notable growth in the renewable energy sector and has successfully integrated large volumes of variable renewable generation. Natural gas is a major source for electricity and heating, therefore Italy has strengthened its energy security by diversifying natural gas supply, making use of the pipeline and LNG infrastructure that it has built up over the last decade. Reducing overall demand for natural gas through an accelerated shift to alternative energy sources and a stronger focus on energy efficiency, especially in buildings, will not only further strengthen energy security, but also help the country meet its climate targets."*[6] About Italy, this is a summary of the actual situation:

- 80% of energy is still produced by fossil fuels
- 30% less emissions of CO2 since 2000
- 21% reduction of demand since 2000
- 3% less NG since 2000
- 44% less oil since 2000
- 41% less coal since 2000
- moreless 280 GWh/year of total energy demand
- 266% increasing of renewable since 2000

It is clear that strong improvements have been made but they are not enough to respect the agreements. However, the most important part of electricity is still produced by fossil fuels even if the renewable increases every year.

Regarding consumption, the main part is required by industries and residential users, this is important because it is here that renewable energy communities will act the most (figure 5).

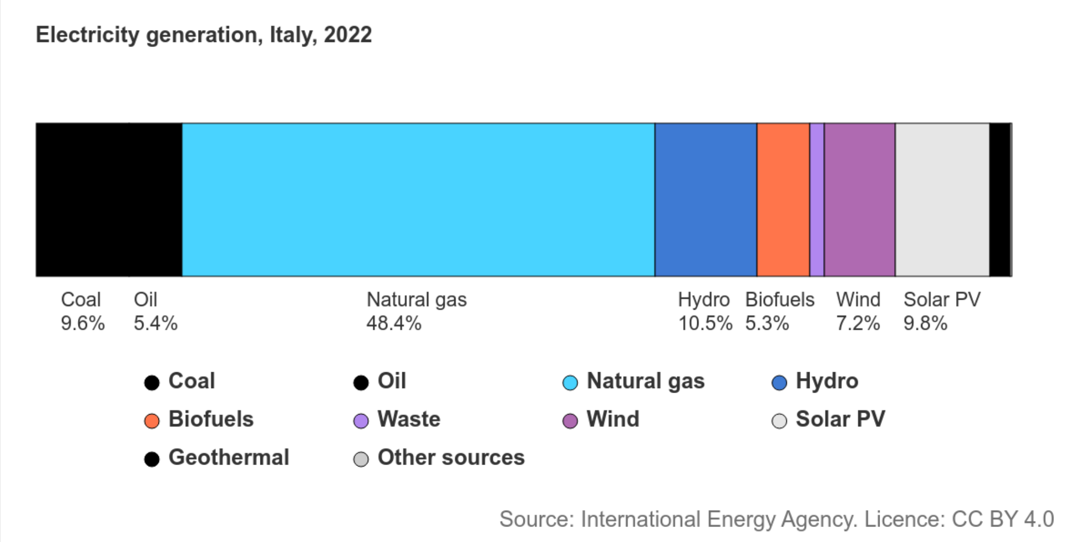


Figure 4: Italian electricity production [7]

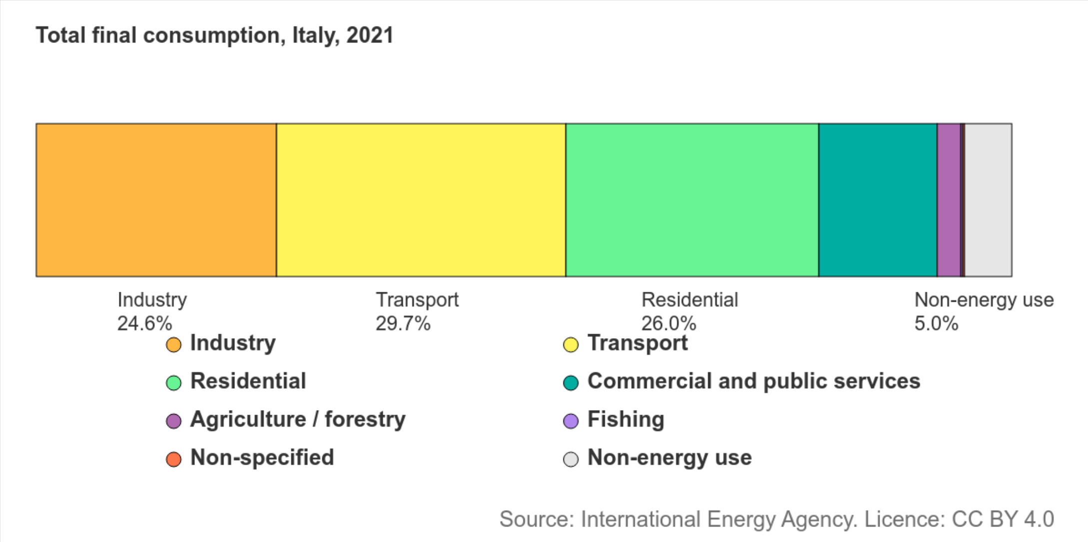
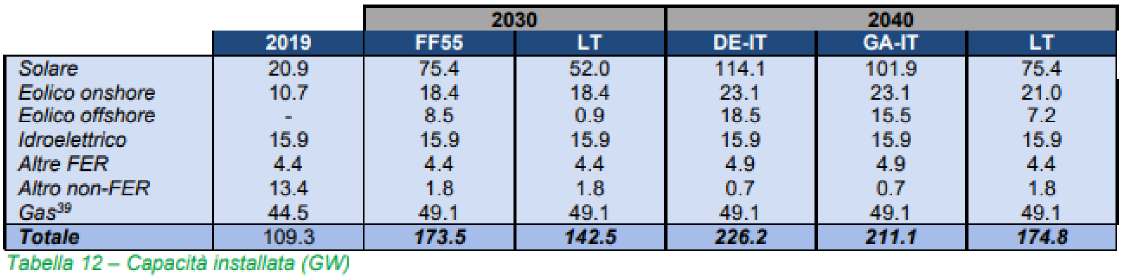


Figure 5: Italian electricity consumption [8]

For the future, the road is already marked by the EU energy roadmap, a document made by the member states to define the targets and consequently the policies to adopt in order to achieve the 0% CO_2 emissions within 2050. Currently there are several scenarios, even if they are valid for all the Europe, the trend of Italy is almost the same so it is possible to generalize. According to Terna [9] there will be an installation of 70 GW in solar and eolic sources within 2040, all the fossil fuels will be deleted within 2050 with the exception of natural gas that will maintains his actual power of more less 40 GW. On figure 6 it is possible to see different scenarios based on different assumptions, however the trend is the same in all the cases.



		2030		2040		
	2019	FF55	LT	DE-IT	GA-IT	LT
Solare	20.9	75.4	52.0	114.1	101.9	75.4
Eolico onshore	10.7	18.4	18.4	23.1	23.1	21.0
Eolico offshore	-	8.5	0.9	18.5	15.5	7.2
Idroelettrico	15.9	15.9	15.9	15.9	15.9	15.9
Altre FER	4.4	4.4	4.4	4.9	4.9	4.4
Altro non-FER	13.4	1.8	1.8	0.7	0.7	1.8
Gas[39]	44.5	49.1	49.1	49.1	49.1	49.1
Totale	109.3	***173.5***	***142.5***	***226.2***	***211.1***	***174.8***

Tabella 12 – Capacità installata (GW)

Figure 6: Scenarios for Italy energy production [9]

As we see the photovoltaic could be the "motor" of the ecologic transition for Italy. In order to improve the efficiency of the photovoltaic systems, REC will be crucial, and in the next chapter it is explained better what is a REC and how it works.

4 Renewable energy communities

4.1 Definition

Renewable energy communities are groups of individuals, households, businesses, or local entities that collectively produce, consume, and often share renewable energy within a specific geographical area. These communities harness various renewable energy sources such as solar, wind, hydro, or biomass to generate electricity, heat, or both, for their own consumption or for sale to the grid.

Note that there is a big difference between REC and collective self consumption. Renewable energy communities consist in connected users who share a cable infrastructure for their energy needs. In contrast, self-consumption groups typically involve individuals within a single building utilizing renewable energy sources for their own consumption, so their working principle is the same, but the fact that a community use the grid to share energy makes it more complex. They are structured as legal entities with distinct roles for members, shareholders, final customers, and producers. Conversely, self-consumption groups are simpler associations formed by individuals. The coverage area of a REC encompasses Points Of Delivery (POD) and renewable energy plants within the same segment of voltage network. On the other hand, a self-consumption group's scope includes only the POD and renewable energy installations within a specific building or condominium.

Both aim to achieve several objectives, including reducing greenhouse gas emissions, increasing energy self-sufficiency, promoting local economic development, and empowering citizens to participate actively in the energy transition. Members of these communities often cooperate through collective ownership or management of renewable energy installations, such as solar panels on rooftops, wind turbines, or community-based solar farms.

Moreover, renewable energy communities often employ innovative business models, such as energy cooperatives, community-owned utilities, or peer-to-peer energy trading platforms, to facilitate the sharing and distribution of renewable energy resources among participants. These models enable members to benefit from cost savings, revenue generation, and increased resilience to energy supply disruptions while contributing to the transition to a more sustainable and decentralized energy system.

As it was said, an important aspects of REC is the fact that the people that are members must find themselves into the same geographic area, referring to the same secondary cable at low/medium voltage. Otherwise recently it is added the possibility to be in the zone of the primary cable with medium/high voltage.

4.2 Components of a REC

- Producers: entities responsible for generating renewable energy within the community, such as solar, wind, or hydroelectric power producers, often through installations like solar panels or wind turbines.
- Consumers: members of the community who utilize renewable energy for their energy needs, either through self-consumption (prosumers) of locally generated clean energy or through purchasing renewable energy from community-owned facilities.
- Authorities: government agencies responsible for overseeing energy regulations, permitting processes, and compliance requirements for renewable energy projects within the community, in this case the GSE.

4.3 REC in Italy

In the context of Italy, the concept of Renewable Energy Communities traces back to the early 2000s, reflecting a growing interest in sustainable energy practices.
Italian RECs typically consist of small communities characterized by power capacities ranging from 20 to 50 KWp, but in this period their presence is exponentially increasing and bigger RECs has already been thought, so this data is going to change within the next year. However they are primarily composed of photovoltaic plants and storage facilities, these communities operate as autoconsumers groups, aiming to maximize self-sufficiency and minimize reliance on traditional energy sources.
Compared to other European Union countries, Italy faces particular challenges associated with the bureaucratic intricacies involved in establishing and operating RECs. Additionally, conducting a precise economic analysis of these communities proves challenging, further complicating citizen engagement. The complexity inherent in understanding the tangible benefits and operational mechanisms of REC participation often deters citizens from embracing this novel energy paradigm.
In response to these challenges, the GSE (Gestore dei Servizi Energetici) has recently introduced initiatives aimed at incentives participation in RECs. These measures seek to provide financial rewards to participants, thereby offsetting initial hesitations and fostering greater uptake. Through these initiatives, GSE endeavors to underscore the economic viability and societal benefits of REC involvement. In practice the members of a REC can earn by selling or sharing their energy:

- Energy produced in excess can be sold to the grid at a well defined price.
- The shared energy inside the community has an incentive.

The government started to strongly push on renewable energy and thus on REC, so it is expected that their number and the energy produced will raise exponentially during next years. According to reports from the local journal ”La Tribuna,” it is anticipated that the number of RECs in regions like Veneto will experience exponential growth. Specifically, projections suggest that the Veneto region alone could host approximately 100 RECs by the end of 2024.

4.4 Laws and regulation

The policies developed from the European Union aim to satisfy the Paris agreements, first of all, directive were made to improve buildings performances, energy production and emissions rates. The main are [10]:

- Directive 2001/77/EC on renewable energies: adopted in 2001, this directive set national targets for the promotion of electricity produced from renewable sources by 2010.
- Directive 2009/28/EC on renewable energies: one of the most significant laws, this directive, adopted in 2009, established binding targets for the share of renewable energy in the EU by 2020, along with support measures and incentives to promote their development.
- Directive 2010/31/EU on the energy performance of buildings: this directive, approved in 2010, introduced minimum energy performance requirements for buildings and promoted the use of renewable energies in the building sector to reduce overall energy consumption.

- Directive 2012/27/EU on energy efficiency: adopted in 2012, this directive set binding energy efficiency targets for the EU and introduced measures to promote energy efficiency in various sectors, including buildings, industry, and transportation.
- directive 2018/2001/EU on the promotion of the use of energy from renewable sources (RED II): this directive, also known as the recast Renewable Energy Directive, was adopted in 2018 to update and extend the EU's renewable energy policy framework beyond 2020, setting new targets for renewable energy deployment by 2030.
- "Clean Energy for All Europeans" Package (2016-2019): this legislative package included several directives and regulations, including the revision of the Renewable Energy Directive and the Energy Efficiency Directive, aimed at promoting a transition to a cleaner, more sustainable, and efficient energy system.

Especially from that packages, for the first time EU opens the energy market even at the single citizen, putting in this way the first brick to create a real energy system composed of RECs. And it defines very well, especially with the Directive 2018/2001, what is an energy community, what are their purposes. In particular some summarized samples: [11]

- COMMA 26: member States should ensure that renewable energy communities can participate in available support schemes on an equal footing with large participants. To this end, Member States should be allowed to adopt measures, including the provision of information, the provision of technical and financial assistance, the reduction of administrative burdens,and include the possibility for such communities to be remunerated through direct support when they meet the requirements of small-scale installations.
- COMMA 70: the participation of local citizens and authorities in renewable energy projects through renewable energy communities has provided significant added value in terms of local acceptance of renewable energies and access to additional private capital, resulting in more investments at the local level.
- COMMA 71: member state must avoid abuse and differentiation between big competitors and communities, by providing apposite instruments.

Italian government must recognise these laws on his territory and apply them. In particular since RED II, some ordinances has been sent out, under here the most important:

- DL 162/19: it is the first acknowledgment of the EU 2018/2001 and begin a first series of rules that REC must respect:
    1. The plants that participates on REC or self consume must have a max power of 200 kW.
    2. The relationship between consumers and producers must be done by elect one responsible for all the REC that interface with the GSE.
    3. The source and the user of the energy must be under the same mid/low voltage cable.
    4. Incentives are based on the installed power.

- DLgs 199/2021-210/2021: this is an empowerment of the previous laws:
    1. Laws recognized REC as legal entities.
    2. The max power is now 1 MW.
    3. Definition of incentives.
- DL 13/2023: introduces urgent measures for implementing the National Recovery and Resilience Plan (PNRR) such as:
    1. Energy efficiency: incentives to improve the general efficiency of the buildings independently of their types.
    2. Energy infrastructure: start the construction of a strong mobility grid charging system and grid upgrades to adapt to the ecological transition.
    3. Increasing of investment: other incentives for the implementation of renewable energy plants and streamline the bureaucratic issues.
- DL 24 January 2024: It is the most recent and important ordinance about REC, it well defines the incentives and the ways to be part of a REC.
  Since it is fundamental it has a dedicated chapter.

5 Incentives and relationship with the authorities

5.1 Ordinance 24 January 2024 for REC

The text identifies two avenues to promote the development of renewable energy communities (RECs) in the country: a non-repayable grant of up to 40% of eligible costs, financed by the National Recovery and Resilience Plan (PNRR) and aimed at communities whose installations are located in municipalities with fewer than 5000 inhabitants, supporting the development of a total of 2 GW, and an incentives tariff on renewable energy produced and shared throughout the national territory. The benefits are cumulative. Through the measure, the development of a total of 5 GW of renewable energy production facilities will be promoted. Note that this statement is valid for the REC, but also for groups of autoconsumers and for the "remote autonsumers".
Moreover the GSE makes available on his site documents and informative guides, as well as dedicated support channels, to assist users in establishing RECs and during april GSE and Arera also released their own REC simulator in order to encourage the participation with concrete numbers. Authorities, in coordination with the Ministry of Ecological Transition, will also launch an information campaign to raise awareness among consumers of the benefits associated with the new mechanism: the first "step" is already online and consists of some "FAQs" to start orienting citizens, small and medium-sized enterprises, institutions, cooperatives, and all other recipients of the measure. So let's see some of them in order to have a clear idea. [12]

- What is a REC ?

  Renewable energy communities are groups of citizens, companies, local authorities that share energy product in a renewable way from their own plants. The energy can be shared between all the members inside a well defined geographic perimeter by using the national grid.

- What is the target of a REC ?

  The target is to provide social, economic and environmental benefit to the citizens by using autoconsume and providing incentives.

- How a REC is built ?

  First of all is necessary to identify the area on which the plants can be built, then is possible to legally create the REC. In this way each of them will have an own juridic autonomy. It is not mandatory to join a REC when it is established.

- Are there limitations on the furniture of electrical energy for who join a REC ?

  No, everybody keep their duty to be a client for the furniture of electrical energy from the grid as all the other citizens.

- What are the requirements of the plants ?
    - The maximum power must not exceed 1 MW and the source must be renewable.
    - The plant must be new or at least it had started working after the 16 December 2021 (date of a previous ordinance) and in this case his contribution to the total production cannot exceed the 30% of the total.
    - All the user of the energy supplied by a certain plant must be inside a determined geographical zone, delimited by the cable.
    - More than one plant is allowed inside a REC.
- Which kind of plants can be used ?

  There is not an exclusivity for photovoltaic, also eolic, biomass and all other renewable energy sources plants are accepted.
- What is the meaning of "remote autoconsume"?

  Basically anyone who is inside the geographical zone of a REC can use the energy produced, by using the grid connection. GSE has the task to calculate the amount of this consumes and then evaluate the respective incentives.
- What are the geographical zone to respect ?

  GSE has recently posted a map with all the areas under the primary cables, that are the zones. It is possible to find them here :
  https://www.gse.it/servizi-per-te/autoconsumo/mappa-interattiva-delle-cabine-primarie
- Can someone belong to more than one REC ?

  No, it is impossible. But for example one person can be the owner of more PODs, and in this case the PODs can belong to different communities.

5.2 Incentives

Here in order to have a better understanding of the situations is possible to look at other FAQs, but an article of Qualenergia.it summarized well the most critical aspects. [13] There are basically 3 kinds of possible targets, all of them can have the benefit of the premium tariff from GSE, but just the groups B and C can require also the PNRR incentive.

A) Individual remote consumer, that use grid to connect to a REC

B) Group of autoconsumers that acts together

C) Renewable Energy Community

The money recognised from the GSE for the following 20 years of activity of the plants are shown on Table 1 but note that they are referred on incentived energy, so it is necessary to well define what GSE means with "incentived" especially in the case C, that comprehend the study case. For this reason a list of all the definition to know in order to comprehend the incentivisation procedure is provided.

- E_{sh} = energy shared, the minimum between the production and consumption of the energies inside a REC. It is obvious that if production > consumption all the energy used comes from the plants so it is shared, otherwise if the production < consumption all the produced energy will be shared. To have a better overview look at figure 7.
- E_{ac} = energy autoconsumed, it is a subassembly of E_{sh} but basically it is the same thing applied under a precise geographic area.
  - E_{rem} = it is the the energy autoconsumed but from remote, so it is necessary to use the grid to have access to it. Here the reference is of users that are not directly connected, but use the grid to share energy, for this reason the terms "autoconsumers" takes the meaning for the whole REC and not for the single user. This energy will be the one subjected to the incentive.
  - E_{loc} = it is the energy autoconsumed locally, directly from the user, it does not need the grid and it brings a save on the bills, moreover it is paid 10.57 €/MWh for the fact that the grid is not used, this incentive is called "valorization contribution".
- E_{inc} = it is the E_{ac} energy that respects the characteristic to be eligible for incentives, in our case $E_{inc} = E_{rem}$ because all the plants are up to standards. It is paid as described on Table 1.

Power of the plant	Incentive tariff
< 200 kW	80 €/MWh + (0÷40 €/MWh)
200 kW < Power < 600 kW	70 €/MWh + (0÷40 €/MWh)
> 600 kW	60 €/MWh + (0÷40 €/MWh)

Table 1: Incentives for the plants based on their size

Notice that there are 2 terms, one fixed and one variable. If photovoltaic plants are considered, for them a supplement of 4€/MWh is added for the center and southern regions while 10 €/MWh for the northern regions, this is done for the fixed part. The difference in this numbers are due to the fact that the same plant located in the southern part of Italy will produce more. Variable part is function of the electricity market price, with the increasing of the electricity price the incentive will decrease and vice versa, nowadays it is set at 20 €/MWh.
To be eligible for the incentive, the facility owner must contact the GSE within 120 days from the start of the facility's operation. Subsequently, within 3 months, the application is processed if all requirements are met. At any time, the GSE reserves the right to withdraw the incentive if any of the listed criteria are not met.
Moreover the amount of the premium surplus tariff is intended for solely for consumers, different from businesses, and/or used for social purposes with repercussions on the territories where the plants are located for sharing. Differently from the tariff given by the threshold value of the shared energy (55% or 45% in the case of capital financing). Nowadays is still difficult to understand how to calculate those percentages since the directive isn't so clear and there are not appropriate way to take the measures. To better explain this part, just the 55% or 45% of the incentive is spread by all the members of the REC, the other part is available just for citizens or social purposes to perform on the local territory. About the precise division of the money there are not rules, it is up to the member of the REC decide how to split the money, especially about the 55% available to all the members. It is important to underline that if the available energy is too much, the part shared will be the one provided by the plant that

firstly start the operation or that are smaller, hence having a big plant could be a risk if the community is not well sized because it can happen that a lot of energy instead of being shared, is just injected to the grid. To avoid this situation the community must be well sized and a precise document regarding the money division must be done internally by the members.
Another very important concept is the fact that this incentive is not related to all the produced energy but just on the shared, for each hour the production is sold to the grid at a very low price without the possibility to get the benefit, thus is very important to try to consume the energy when it is produced, even at distance.

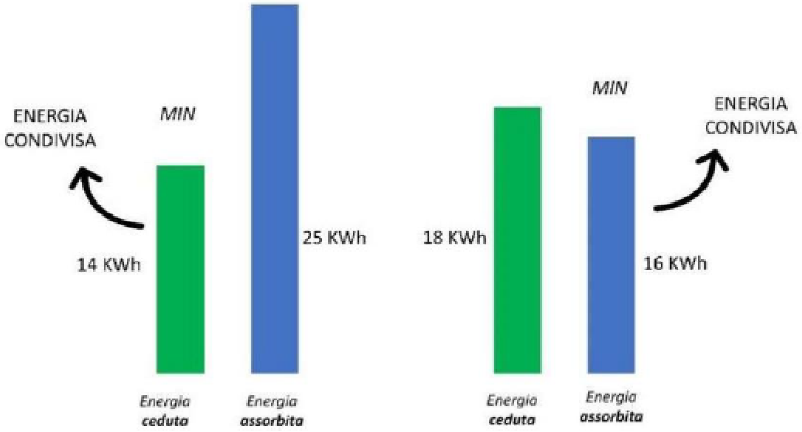


Figure 7: Shared energy principle

Since the initial investment can be very expensive, the state can finance companies or citizens in order to start a REC by using the PNRR funds (Piano nazionale di resistenza e resilienza), but in this case the incentives are scaled up, in particular they varies with the formula I=I(1-F) where I=incentive or premium tariff and F is a parameter function of the amount of the contribution given by the state, that varies linearly with it. Note that this possibility is valid just for the municipalities with less than 5000 people otherwise the whole cost must be covered by privates. Under here the values of F:

- 0 if there is no contribution
- 0.5 if the contribution is 40% of the total investment (max contribution)

After getting F, can be easily calculated the final premium tariff. The contribution must be used to cover the following costs, and the amount of money available is shown on Table 2.

- Realization of renewable energy plants
- Assembly and supply of storage systems
- Buy hardware and software used to manage the plant
- Connection to the electrical grid
- Cover the necessary civil works
- Feasibility study and projects

These are not the unique incentives available, in fact it exists the possibility to couple them with capital contribution from other sources, or to obtain a tax deduction (see article 16-bis comma 1 1986). For both this cases the incentive decreases.

Power of the plant	Contribution
20 kW	1500 €/kW
20 kW< Power < 200 kW	1200 €/kW
200 kW < Power < 600 kW	1100 €/kW
600kW < Power < 1000 kW	1050 €/kW

Table 2: Statal contribution based on new renewable energy plants

5.3 GSE Simulator

The GSE Energy Community Simulator is a comprehensive tool designed to facilitate the creation and management of energy communities. This simulator allows users to assess the feasibility of establishing an energy community in a specific area by taking into account factors such as the availability of renewable resources, local energy demand, and existing infrastructure.

Through the GSE Energy Community Simulator, users can design energy systems by simulating various configurations of production plants, including solar panels, wind turbines, and biogas plants, as well as energy storage systems. This process helps to optimize the installed capacity based on the unique needs of the community.

In addition to system design, the simulator evaluates the economic and environmental benefits of the proposed energy community. It calculates cost savings from self-production and self-consumption of energy, as well as the environmental advantages in terms of reducing greenhouse gas emissions. Users can also develop energy management strategies to maximize efficiency and self-sufficiency. These strategies include the use of demand management systems and integration with the electrical grid.

The GSE Energy Community Simulator is designed to be user-friendly, making it accessible even to individuals without expertise in engineering or energy. It supports informed decision-making for designing and managing energy resources within communities. By providing accurate simulations using advanced mathematical models, the simulator offers precise estimates of expected outcomes. Additionally, it serves as an educational resource, raising awareness about the benefits of renewable energy and sustainable energy management.

To access the simulator, visit www.autoconsumo.gse.it and begin the simulation process. The portal requires users to enter the site where the community will be established, specifying the location of the facility. Next, the total consumption of the users connected to the facility must be entered. Following this, users will be asked legal questions regarding the responsible entity. For a more precise simulation, users can input individual consumption data for each user and provide detailed descriptions of the facility, including the exact location, tilt angle, and power of the panels, as well as other characteristics such as an energy storage battery.

Once all data related to production and consumption are entered, users will be asked to allocate consumption across various hourly periods. At this stage, except for specific cases, data entry will be complete. Additional economic parameters will then be requested to enable a thorough economic simulation.

After this step, numerical results and graphs will be generated based on the input data. Figure 8 illustrates the energy flows, and figure 9 demonstrates the feasibility of the initial investment, which is essentially the same as in figure 20. These visualizations help users understand the projected performance and financial viability of the energy community [14] .

As this is a simulator intended for use before the construction of the community, obtaining precise consumption data before identifying users can be challenging. Consequently, results may be based on statistical analysis and could differ significantly from actual outcomes. Nonetheless,

the simulator provides an approximate estimate of potential gains and a clear understanding of the bureaucratic requirements, which can sometimes be misunderstood.
While other companies have developed their own simulators, the GSE Energy Community Simulator stands out for being free and easy to use. It can be effectively coupled with the optimizer described in the next chapter, which can suggest precise configurations of users.

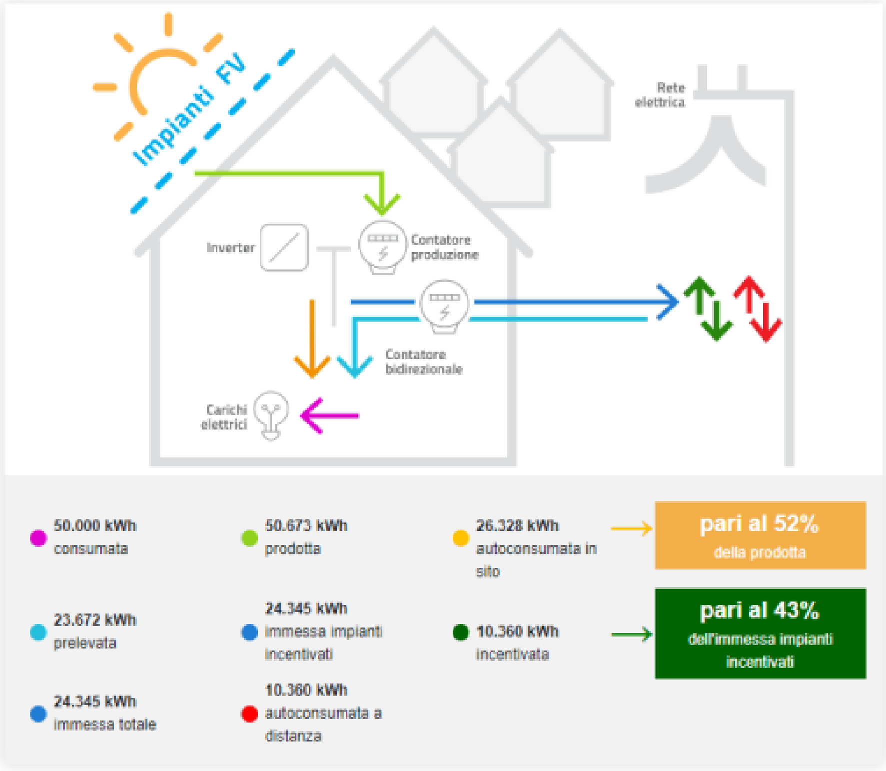


Figure 8: Energy flows from GSE simulator [14]

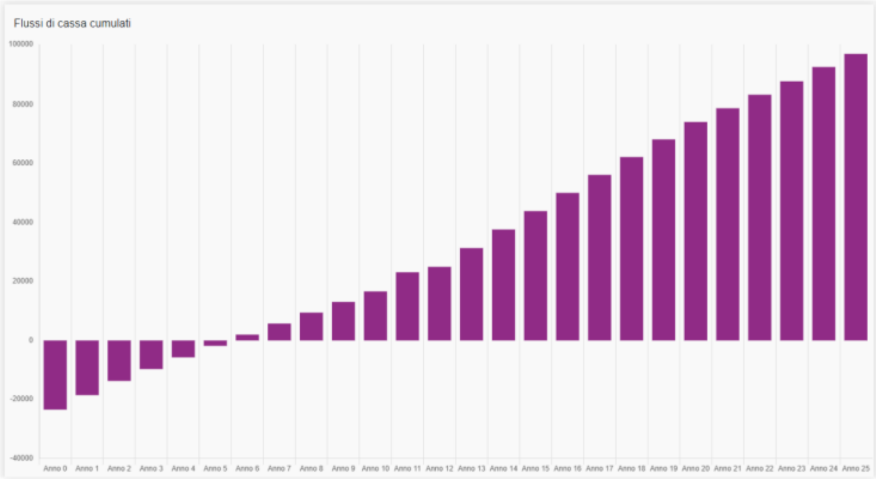


Figure 9: Cash flow from GSE simulator [14]

6 Study Case

As anticipated the project consists in evaluating the feasibility of a photovoltaic plant of 1 MW placed in Motta di Livenza (TV), Italy. It has the target to be one of the main energy sources for a future REC. This thesis tries to understand which are the possible users of the energy and how they can get benefit in being part of the community. At the same time it analyzes if for the owner of the plant, is convenient to start a REC considering all the economical parameters and the new incentivisation methods. To do this work data have been taken from residential users, companies and public administration buildings in order to create a sort of "medium user" of the zone, and then elaborate them with a Matlab script that performs optimization and economic analysis. Note that the area where the data come from is well defined by the GSE map, in particular it refers to the area under the primary cable AC001E00853.

It's important to specify the optimization criterion used. Remember, if the goal is simply to maximize the incentive, it would be sufficient increase the number of consumers until all the energy is shared. This would be the best scenario for the producer, who would earn more converting all his production into shared energy. However, the portion of incentives that would belong to consumers would have to be divided among too many users, resulting in negligible profits.

For this reason, finding a balance point is important. Anyway, since each REC has its own independent statute and rules for spreading the earnings, the "equilibrium situation" cannot be found by a mathematical model.

Hence, optimization has been pursued not in terms of money, but rather in terms of energy. The goal is to find combinations that minimize excess of production or purchased energy, essentially all the energy that is not shared. It should be noted that the latter situations are not necessarily the best economically but rather a compromise. Each REC is then free to distribute profits as it prefers, remembering the rule that maximum 55% can be for the companies, so especially in this case where the producer has to sustain a big investment it is possible to think in a division 55/45, meanwhile in other cases, for example where all the members are "small", it has been proposed fixed part for consumers and variable part for producers but it's up to the members, however this partition can change a lot the attractiveness in joining a REC and it must be specified before the optimization.

6.1 Photovoltaic project

The project has been made from an external company specialized on this, the data are the same, a plant with the power of 1 MW located in Motta di Livenza (TV), Italy. They propose 2 solutions, one with just one plant of 1 MW and another with 5 plants of 200 kW each, since the second options seems to be worse I analyzed just the first. Someone can context that if the plants are smaller the incentives will be higher as represented on Table 1, but in reality GSE takes into account the total power so this trick won't work because 5 plants of 200 kW are considered as one of 1 MW.

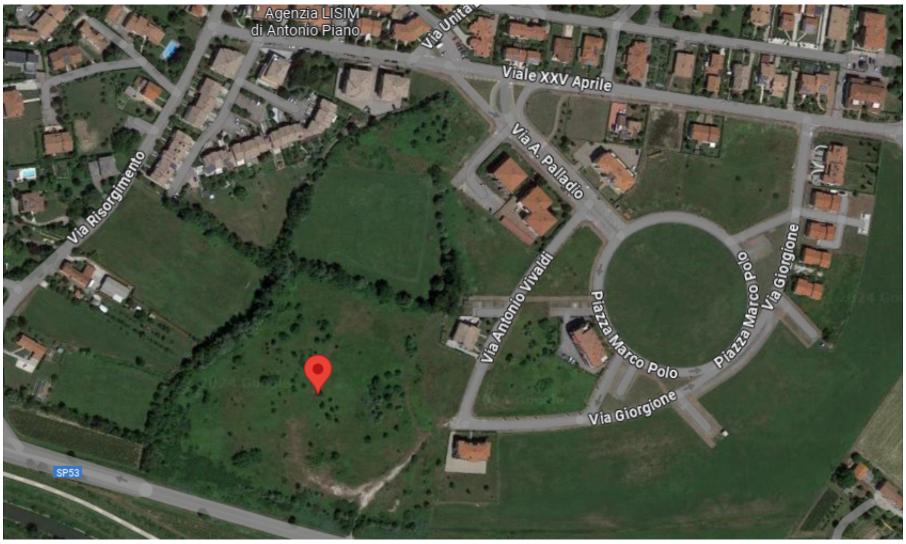


Figure 10: Area of installation

Under here the main results, considering a shading coefficient of 1 and a $\eta_{BOS} = 0.7497$ (basically it is a parameter that takes into account the losses of all the systems, comprehending the inverter). The panels are installed at optimized Azimuth angle = 0° and optimal slope = 39° since the area hasn't any obstacle. (The trees are not there anymore).

- Number of modules: 2500
- Total area of the panels: 5017.5 m^2
- Power of one panel: 400 Watt
- Datasheet of the panel is not available due to a disclosure agreement
- Annual irradiation on horizontal plane: 4728 MJ/m^2
- Total annual production: 1096 MWh
- Total costs: 800k + 13.5 €/MWh produced

Since the company has done just a monthly estimation of the production, in order to have a clearer production curve (in hour base) a part of the script is dedicated to the precise calculation of the production, this step is done considering the climate data from 2018 to 2021 provided by PVGIS, and the results are similar with the one calculated by the external company, in terms of total production in a year, 1197 MWh/year are obtained so the difference is of the 8.5%, acceptable considering the climate conditions.

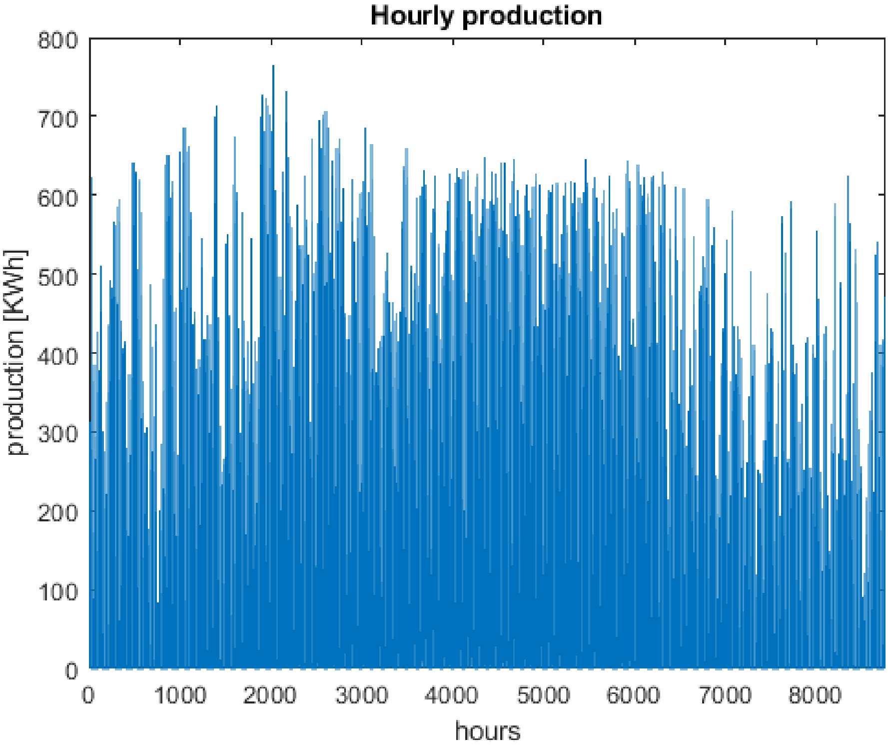


Figure 11: Hourly production of the photovoltaic plant

6.2 Loads

Now that the power curve of the plant is available, some kinds of load profiles are analyzed belonging to potential customer for the REC. Not all of them are just consumers, but there are also prosumers so the profiles will be very different based on the type and amount of users, if they produce or not, if they use boilers or heat pumps....
Note that these profiles are not completely real, but are extracted from a sample of potential customers that gently provided the access to their consumption and production data and some other client of the company. The data are "averaged" from their PODs and then grouped in 6 macro categories with the medium values of consumption and production. On figure 12 it is possible to see the hourly profiles considered, in blue there is the consumption and in orange the production. It would have been possible to use statistical data based on a bigger database, but since the community will be in a certain zone and some customers have already agreed in joining, it has been preferred to do a more specific work. However independently from the input data the reasoning's are the same.

Users tipology		Consumption	Production
		[kWh/year]	[kWh/year]
Domestic	Consumer	4298	//
Domestic	Prosumer	4026	3370
Industry	Consumer	64176	//
Industry	Prosumer	66115	127880
Office	Consumer	25895	//
School	Prosumer	50407	8978

Table 3: Load profiles

Obviously the algorithm can work with more than 6 profiles, this could be very useful for large scale when the utilities are a lot and very different from each other, however they were enough to test it.

On the script there are matrix that represents hourly production and consumption of each load, the size of the matrix is [24 x 365] where 24 are the hours of the day and 365 are the days in a year. This passage is crucial since it must be remembered that even if the production is high, it is not sure that the consumption is covered at each hour, and moreover the incentives are given on hourly base. Note that the superimposition is not guaranteed for every hour.

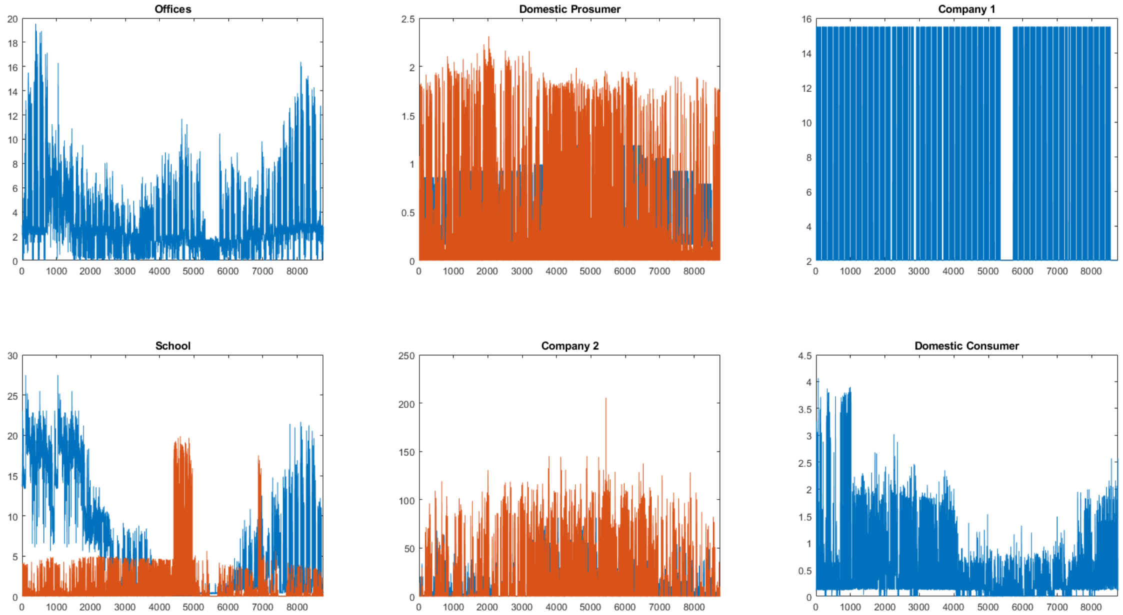


Figure 12: Load profiles

Let's better describe the 6 profiles involved with their peculiarity:

- Domestic consumer and prosumer: they are the most common type of user. Since their consumption is relatively low compared to the 1 MW plant production, it is necessary to significantly increase their number to utilize a substantial amount of energy. For this reason, especially with their involvement, the reliability of the model will play a crucial role given the limited data and the fact that the domestic sector has the most varied consumption distribution. Since the 1 MW plant provides a significant amount of energy, prosumers will likely be needed more to overlap consumption and production profiles, so the code is not expected to favor their number.

- Industrial consumer and prosumer: they are not as common as domestic users, but they consume much more energy. Due to their work-related nature, their consumption is concentrated during the day, a characteristic that aligns well with the 1 MW plant. Therefore, it is expected that these profiles will ensure the best overlap between consumption and production. It's worth noting from table 3 that in this case prosumers are also very capable producers themselves, so the number of consumers is expected to be much greater than the number of prosumers.

- Office: this profile is a sort of mix between domestic and industrial because it is affected by the work time, but surely the consumption are not so high as the industrial. It will not be possible to have a scenario with just offices because they are not so common, however they can have a role coupled by other types of users.
- School: it is a particular profile since it do not consume nothing during summer, however their number is not supposed to be bigger than 1, so it will not have a big impact on the optimization.

Thus, by having this classes of customers it has been chosen to analyze the configurations below. The ones with prosumers could theoretically work also without the presence of the plant, thus it has been decided to make also the scenarios like the community is autonomous when possible:

1. Just domestic consumers
2. Domestic consumers + prosumers
3. Just industrial consumers
4. Industrial consumers + prosumers
5. Mixed

7 Matlab Code

7.1 Model

The processes performed into the code simulate accurately what happen inside the general model described on figure 13. It is clear that the community is not completely autonomous and it must be connected to the grid, not just to share energy but also for buying it during the low production hours. Let's analyze this model from all the point of view:

- Renewable user: it has its own plant and his main target is maximize the autoconsume in order to not pay the bills and get the contribution of valorization, it does not care to inject energy into the grid since the save on the bills will be higher than the incentive gained from the sharing, moreover it is not assured that if the energy is sent to the grid it will be shared. At the same time, when its plant cannot satisfy the consumption it is constrained to buy from the grid, here there are 2 ways, one satisfied by the energy produced by another plant and thus shared, or buy directly from the grid.
- Not renewable user: in this case it is quite simple to understand that all the energy must be bought, then if the other plants on the community are good there will be incentives because the consumption is "shared" otherwise there will be no incentive.
- 1 MW Plant: the only target is to produce as much as possible to satisfy the consumption inside the community, his role is basically the same of the grid, it must be the big source of electricity of the whole community. Due to its nature, on night and on rainy days the community suffers and it is constrained to buy energy, so some kinds of storage can be thought and the use of the grid must be integrated.
- Grid: the purpose of the grid is to distribute the energy from a user to another, in this case it acts as a service and not as a provider. Different situation when the energy is in excess, because it absorbs this quantity avoiding wastes, or when the energy is in lack where it provides the remaining part.

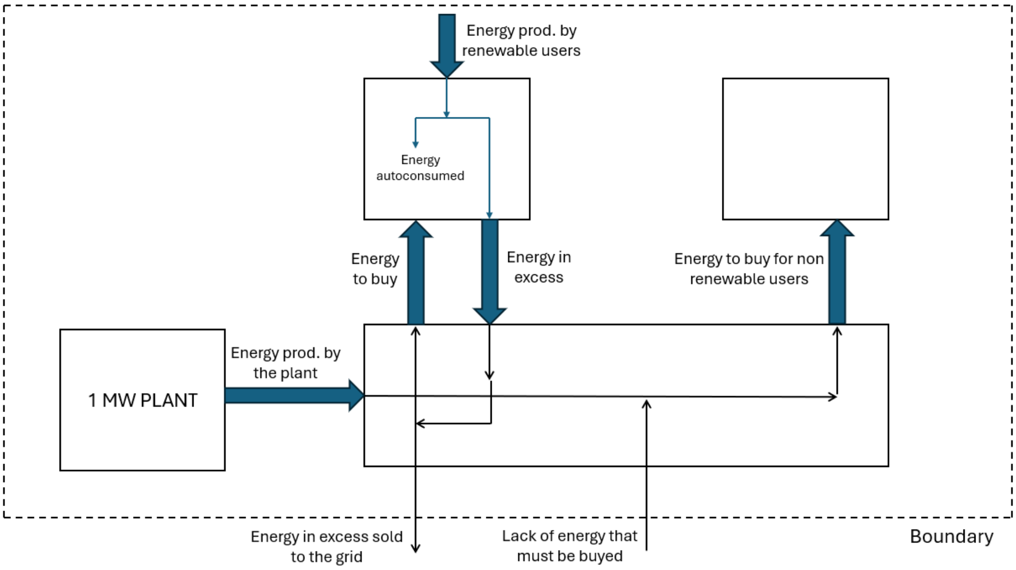


Figure 13: General model that represents the community

After the importing of all the consumption and production data in a matrix form of
[24 × 365], all the prices are set and these will be the inputs.

- Incentives for the plant and for users: table 1
- Money for the injection on the grid (Ritiro Dedicato) = 0.044 €/kWh [15]
- Contribution for valorization = 0.01057 €/kWh [16]

Then it is possible to start with the core of the code, a sextuple "for" cycle is built, where each section represents a type of user. For example if there are 10 domestic consumers and 10 industrial consumers the analyzed configurations will be 10 × 10 = 100, covering all the possible combinations of users, by adding other profiles the number of combinations increase making this process computationally demanding, also for this reason just 6 profiles are used.
For each configuration, matrices [24 × 365] representing each kind of energy are calculated for producers and consumers (see nomenclature).

$$E_{\text{prod}} = \sum_{n=1}^{N} E_{prod_n} \tag{1}$$

$$E_{\text{cons}} = \sum_{n=1}^{N} E_{cons_n} \tag{2}$$

$$E_{\text{loc}} = \sum_{n=1}^{N} E_{loc_n} \tag{3}$$

$$E_{\text{prod pros}} = \sum_{n=1}^{N} E_{\text{prod pros}} \tag{4}$$

$$E_{sh} = min[(E_{prod}), (E_{cons})] \tag{5}$$

$$E_{\text{no sh}} = E_{prod} - E_{cons} \tag{6}$$

$$E_{inj} = E_{\text{no sh}}(> 0) \tag{7}$$

$$E_{buy} = E_{\text{no sh}}(< 0) \tag{8}$$

Basically when the production is higher than the consumption there is injection on the grid without sharing, from there the choice to extract the components greater than 0 to have the excess, it is the contrary for the energy to buy. Remember that all these matrices are actually [24 × 365].
The following passage consists in creating [1 × N] vectors for each kind of energy, where for every energy matrix [24 × 365] is calculated the sum of all the values inside, in this way the content is summarized into the quantity for all the year, N is just the number of iterations. Each iteration represents a configuration analyzed.
By having this vectors it is easy to calculate the incentives and also the gains for the injection on the grid, the next part of the cycle do this. It is supposed a division of incentives with 55% for the producer due to the big initial investment and the remaining 45% for the consumers and prosumers, surely it is possible to change that division and on the final results there will

be comparison to see the benefit for producers and consumers. The tariffs derives from Table 1.

$$
\begin{align}
Inc_{cons} &= E_{sh} \cdot 0.11 \cdot 0.45 \tag{9}\\
Inc_{plant} &= E_{sh} \cdot 0.09 \cdot 0.55 \tag{10}\\
Inj_{pros} &= E_{\text{prod pros}} \cdot 0.044 \tag{11}\\
Inj_{plant} &= E_{\text{prod plant}} \cdot 0.044 \tag{12}\\
Val &= E_{loc} \cdot 0.1057 \tag{13}
\end{align}
$$

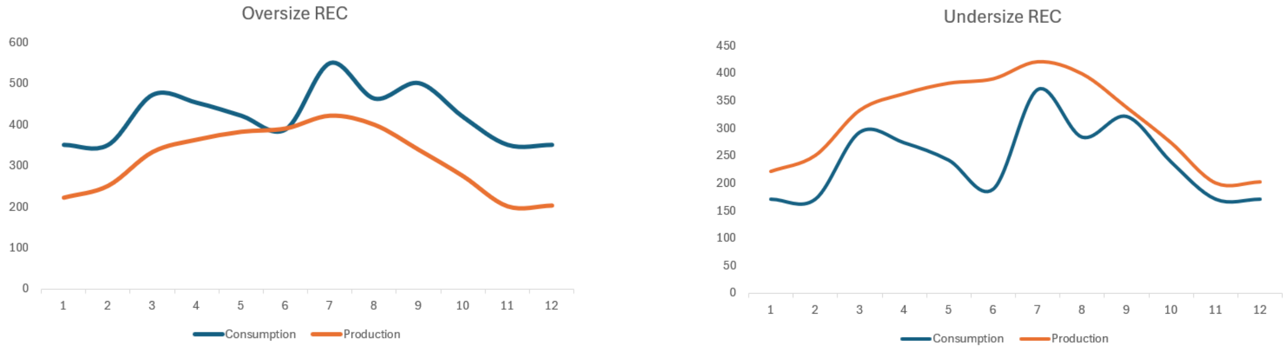
Thus there will be $[1 \times N]$ vectors that represent the money for each combination, at this point it is easy to calculate the gain for each kind of user:

$$
\begin{align}
G_{cons} &= Inc_{cons} \tag{14}\\
G_{pros} &= Val + Inj_{pros} \tag{15}\\
G_{plant} &= Inc_{plant} + Inj_{plant} \tag{16}
\end{align}
$$

Notice that Gains prosumer is intended as an adding to Gains consumer since each prosumer is also a consumer but they will earn more because of the valorization and injection, moreover also the save on the bills should be considered but whereas it is not a real gain it is not on the calculation.

7.2 Optimization criterion

At the end of the for cycle, an Excel table with N rows and 17 columns is created where for each combination the results related to energy and earnings are listed.
Once this is done, the top 50 results are extracted, but it is very complicated to determine which ones they might be because there are many factors involved. Additionally, it should be noted that the distribution of incentives is renegotiated by each individual REC, so optimization based on balancing gains between consumers and producers is not possible, also because it won't take into account investments for plants or other utilities.
Neither maximizing the incentives would be a good idea, because this would simply lead to an increase in shared energy and consequently the number of users until reaching saturation as it is shown in figure 14a. In this condition the REC would be oversized, and the specific gain for each user would be too low to justify participation. For these reasons, it has been decided to focus and optimize for the minimum of not shared energies, which is the sum of purchased energy and excess energy. In this way, the script will find the configurations where the production/consumption overlap is optimal. This strategy will certainly lead to the best configuration from an energy standpoint but not necessarily from an economic one. This is because producers would like to saturate their production to obtain the maximum incentive, but this situation is disadvantageous for consumers, who would be too many, as previously mentioned. Conversely, consumers would prefer to be few so that all their consumption is met and they achieve the highest specific gain as described by figure 14b. So by using this criterion it is expected to reach a good sizing of the whole community. Obviously this reason is valid just because nowadays the profiles of production and consumption are very different, if absurdly the profiles are exactly the same, saturation should be the best configuration, but it is basically impossible.
Also the usage of Python gurobi or the Matlab optimization toolbox were considered, but the fact that this work is done on the discrete domain and not continuous makes me choose the "forced optimization" method. Certainly it is more demanding from a computational point of view, but easier to manage.



(a) Oversize community

(b) Undersize community

Figure 14: Consequences of different REC sizes

Thus basically what we want ideally is having 0 energy to buy and 0 energy in excess, if we plot a chart that represent it for each combination something like this is obtained.

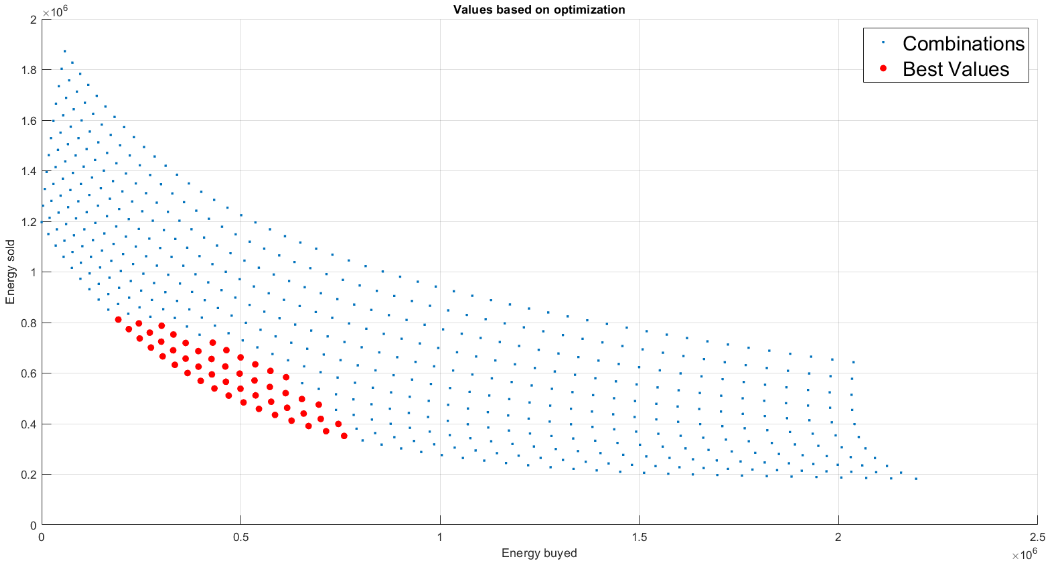


Figure 15: Example that shows the 50 best combinations

In order to understand the best combinations, that basically are the points closer to the origin (nearest to 0 buy and 0 excess that is the ideal situation), it is possible to simply use the Pytagorean theorem for each point, and the 50 closer to the origin will represent the best configurations. On the chart there is energy bought on x-axis and energy sold on y-axis [MWh], each combinations will provide a point and the 50 best are highlighted in red. By taking a careful look of the chart it is possible to see that when the energy bought is 0 (no users) the sold is exactly the quantity produced by the plant of 1 MW plus the amount coming from prosumers.

7.3 Plots

Moreover to the chart cited before, which is done more to increase understanding rather than for actual utility, the script generates other significant plot, in particular on figure 16 are shown the total gains of consumers, prosumers and owner of the plant. On the x-axis there is the corresponding combination of users starting from domestic consumer at the lower row, while on y-axis simply the money for each year.
Then, if there are consumers and prosumers of the same type, is possible to calculate their specific gains shown on figure 17, this data is very important since it can encourage and support by numbers the convenience in joining a REC. Here it must be specified that the gain for prosumers is to intend as an add of the one of consumers since each prosumer is also a consumer.
Last but not least a 3D chart that shows for each hour the trend of consumption and production, this is related to the best configuration but is possible to plot it with every combinations (figure 18). By viewing it from the top, 2 heatmaps are created on figure 19, one for production and the other for consumption and it is possible to clearly see the periods when there is more difference between them.

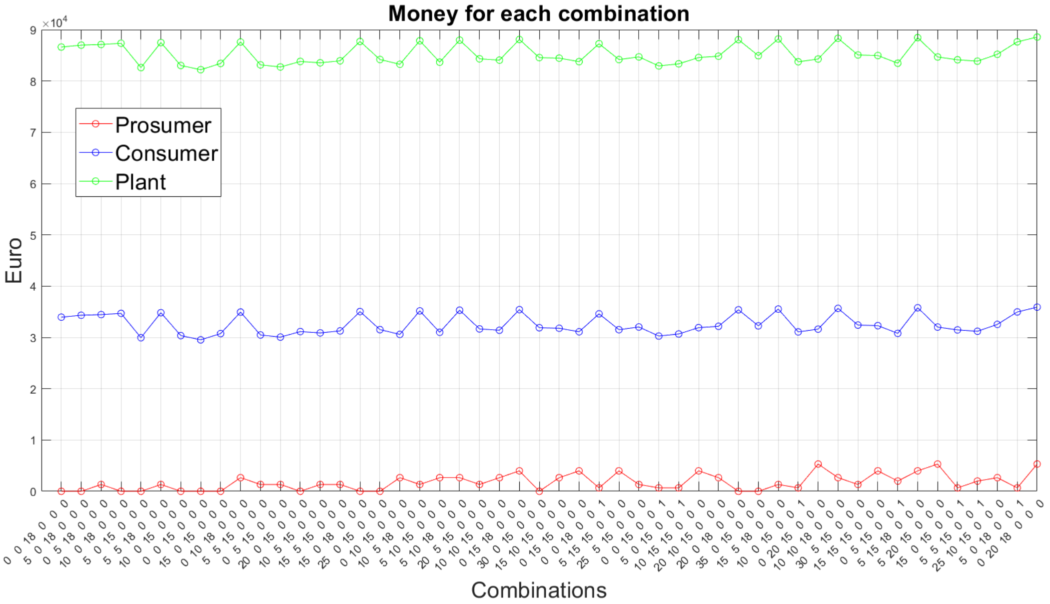


Figure 16: Total Gains for the 50 best combination

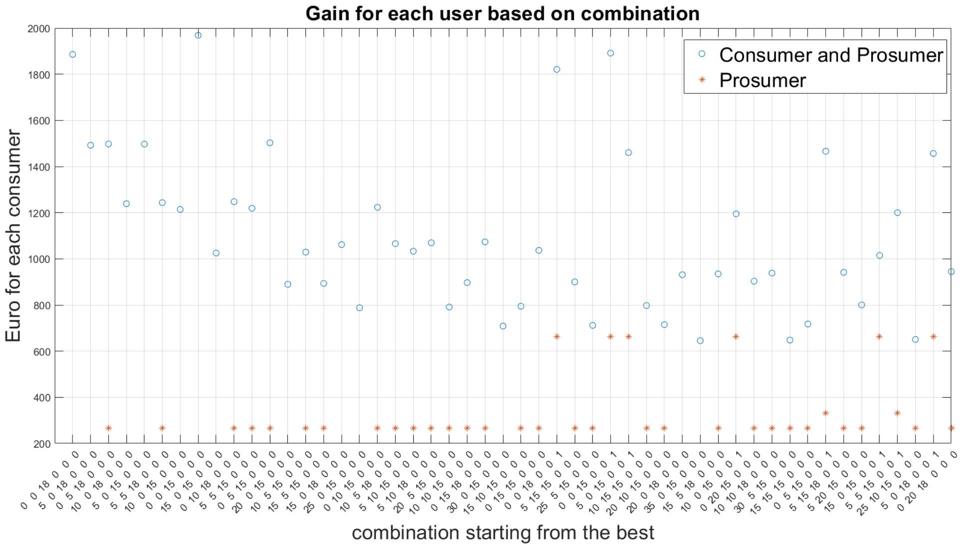


Figure 17: Specific Gains for the 50 best combination

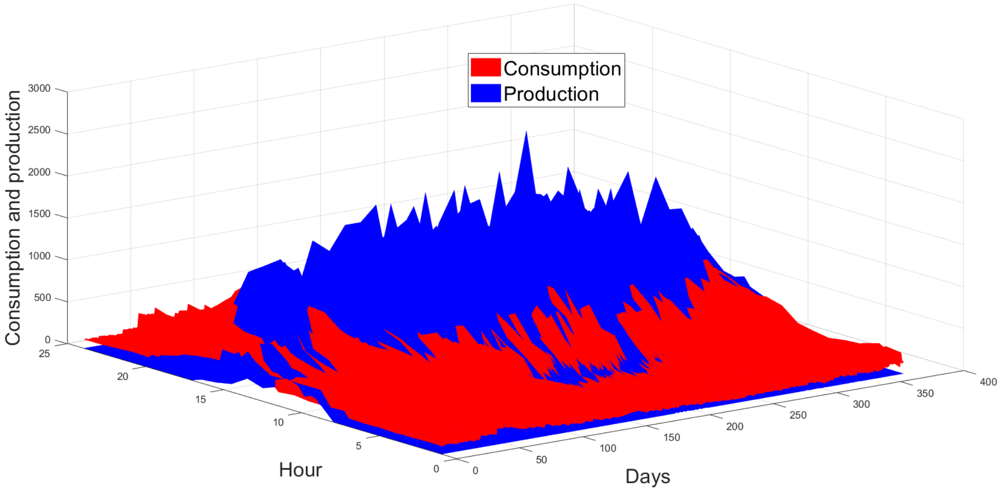
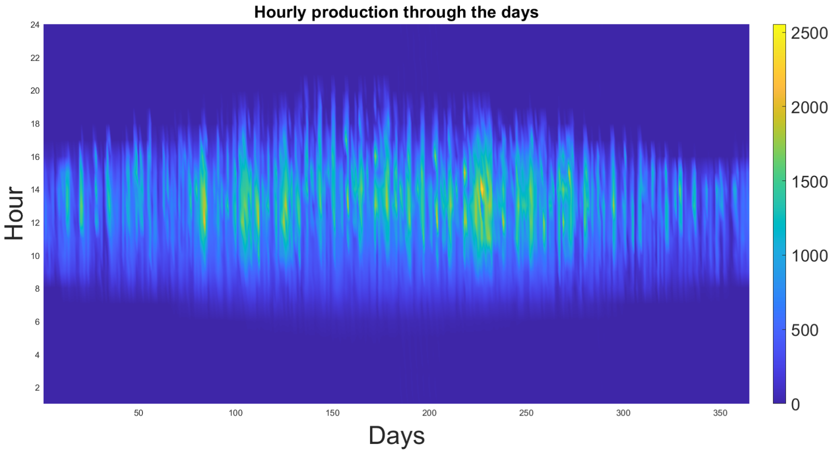
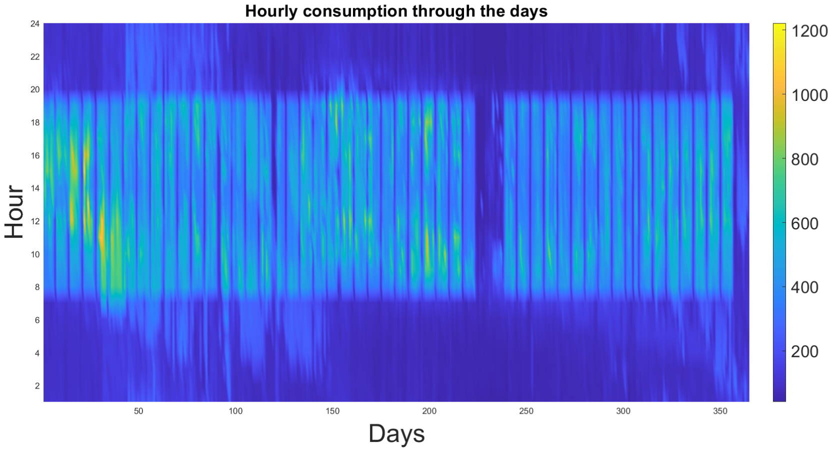


Figure 18: Superimposition of production and consumption



(a) Heatmap of production



(b) Heatmap of consumption

Figure 19: Heatmaps

7.4 Reliability of the model

Since the users profiles are based just on a little sample of potential customers, even a little change on the habits of the users could have big effects on gains.

It is true that the profiles are based on real data from people who have expressed interest in joining REC, but it cannot be ruled out that in the future someone else may enter or leave. Therefore, an analysis of reliability is important. This analysis is carried out using the Monte Carlo method. Monte Carlo method is a powerful statistical technique that uses random sampling to obtain numerical results for mathematical problems that might be deterministic in principle.

To begin with, let's understand how it works. The Monte Carlo method involves generating a large number of random samples from a probability distribution. These samples represent possible states or outcomes of the system being studied. For each random sample, the function or model of interest is evaluated, performing calculations based on the sampled values. The results from these evaluations are then aggregated to provide a statistical estimation. As the number of samples increases, the estimation converges to the true value. The law of large numbers ensures that the average of the results from many samples approximates the expected value of the function.

The central limit theorem supports the Monte Carlo method by indicating that the distribution of the sample mean approximates a normal distribution as the sample size becomes large, regardless of the original distribution of the population. This theorem helps in estimating the accuracy and reliability of the simulation results.

So, using this method, it is possible to estimate the reliability of the model by starting with and using the production and consumption matrices [24 x 365] as input. The steps are clearly explained below:

1. Input retrieval: the total production and consumption matrices [24 x 365] are called from the previous code.

2. Calculation of standard deviation and mean: the means and standard deviations are calculated for each hour of the day among the year regarding energy production and consumption, note that it is intended not for each hour, so not for the 8760 hours in a year, but there will be the mean of the 365 values regarding hours between 00.00 and 01.00 and so on with the other hours. This process generates [24 x 1] matrices for each of the following quantities:

    - Average production per hour
    - Standard deviation of production per hour
    - Average consumption per hour
    - Standard deviation of consumption per hour

    Separating the means and standard deviations by hour allows the model to account for significant variations in production and consumption that can occur throughout the day.

3. Generation of random scenarios: using the mean and standard deviation obtained earlier, N scenarios are generated using the "normrnd" command, assuming a normal distribution. Each iteration (one per scenario) will provide a matrix, resulting in N matrices of size [365 x 24]. These matrices essentially contain random variants based on the input data. From these matrices are obtained the shared energy, energy to be purchased, and excess

energy for each scenario using the functions described on paragraph 7.1. For simplicity and to obtain a good convergence N=5000.

4. Calculation of the notable energies distribution: here the calculation of average and std. deviation for shared, excess, bought energy are calculated and it is obtained a value for each scenario [1 x 5000], then they are averaged and the result will contain information about all the scenarios.

5. Calculation of the CV coefficient: this parameters is referred to the reliability of the results, it is expressed as $\frac{std.dev}{average}$, it represents the stability in case of changing the inputs.

CV results are quite good, if the configuration is optimal they are between the 1% and 3%, except for the bought energy where CV it is around 5%. As long as the optimal configuration is not respected the CV increase until more less 12% on the worst cases.
In general the results can be considered quite good since usually the energy consumption profiles does not change a lot during the years and moreover by having a monitoring system each user should be able to regulate.

7.5 Economic Analysis

When the previous code has finished working, an economic analysis of the investment is needed to assess the economic feasibility of the plant.
This part is separated from the previous one for simplicity and it is interactive. The user is asked to input the expected annual profit that will represent the cash flow for each year (easily derived from the tables and charts generated by the previous script). Once this is done, all costs to be incurred, including technical and bureaucratic management costs of the community and a fixed discount rate, are taken into account precisely:

- Gain: Asked to the user
- Initial investment (I_0): 800000 euro based on a quotation of an external company, note it doesn't include the price for the land since after 20 years it will still be a capital.
- O&M costs: 13.5 €/MWh produced by the plant, this value encompass inverter substitution, modules washing, periodic maintenance and controls.
- Management costs: 2000 €/year , for the systems that manage the community and all the bureaucratic issues, this cost is now fixed but it can vary depending on the plant owner choice.
- Insurance costs: 5000 €/year, usually an insurance is required for big plants due to faults or some extreme events that can damage the modules for example hailstorms.
- Discount rate (k): fixed at 3% to take into account inflation and more in general the time value of the money, it is possible to automatic change this value.
- Net: simply what the user will earn each year thus equal to: Gain - O&M - Insurance - Management costs.
- Residual: this is a vector with one component for each year of operation hence it is calculated as -$I_0 + Net \times Years$.

At this point, a bar chart showing the plant's residual investment for 20 years is plotted, an example is on figure 20. Finally, the main economic parameters are calculated and displayed on the screen.

$$ROI = \sum_{n=1}^{Years} \frac{Net_n - I_0}{I_0} \tag{17}$$

$$NPV = \sum_{n=1}^{Years} \frac{CashFlow_n}{(1+k)^n} - I_0 \tag{18}$$

$$LCOE = \sum_{n=1}^{Years} \frac{I_0 + Costs_{tot}}{(Energy_n)} \tag{19}$$

$$PB = \frac{I_0}{Net} \tag{20}$$

Also IRR is calculated by using the default matlab function 'irr', however based on these values, the feasibility of the plant can be assessed.

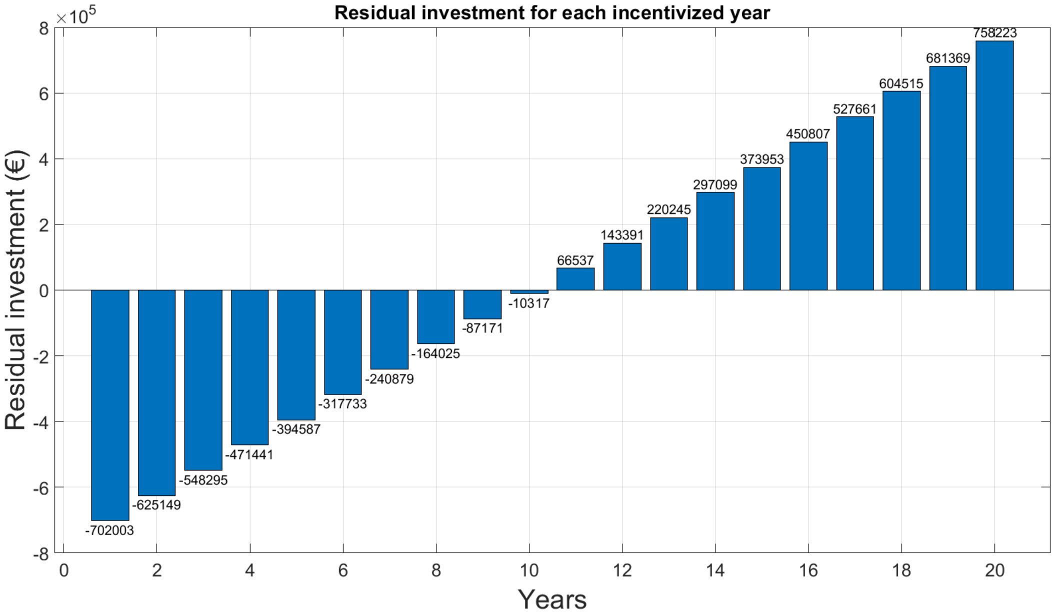


Figure 20: Bar chart of the residual investment

8 Results

Now that the operation of the model has been described, the next step is to execute it by applying it to the profiles described at the end of paragraph 6.2. In this way, it will become clear who the best users are and how many of them there should be. Moreover it will be possible to see periods where there is lack of production and consumption and eventually directly act on the users habits to superimpose as much as possible production with consumption.

In this chapter the results are expressed by using tables and charts in order to have a clear and quick comparison between them. Then some considerations will be made on the values, moreover it is important to remember that the optimization is done on the "minimum of the not shared energy", thus often it could happen that the best solution in economic terms is not the best in terms of energy.

The script outputs the total money to be distributed among consumers and prosumers. When the type of users is almost identical (either all industrial or all domestic), it is assumed that this money is divided equally. For example, if there is a total of 10000 € and 10 domestic users, each of them will receive 10000/10 = 1000 €. Since each prosumer is also inherently a consumer, their earnings will be the sum of the consumer's gain plus an equal division of the prosumers' one that corresponds to valorization and grid injection. To make a clear example, suppose a combination with 100 consumers and 50 prosumers who respectively earn 20000 € and 30000 € in total. The consumers' earnings will be 20000/100 = 200 €, while the prosumers' earnings will be 200 + 30000/50 = 800 €.

It's a different story when the types of users are not the same. In this case, an equal distribution of incentives is not applicable because it is clear that an industry will share much more energy than a domestic user. Therefore, in this scenario, the values provided directly by the code are left in their total form. Various hypotheses can be made about the precise distribution of money for each individual user, but it is pointless to enforce one as each community will have its own regulations. In any case, it should be remembered that consumers' earnings must also be shared with prosumers. Anyway, tables are organized with columns that contain notable values for the comparison such as:

- N: number of users, it will be specified at which one of the profiles they belong.
- Notable energies: with these values there is a quick look on all the energy flows inside the system.
- Gains: the money deriving from incentives and in the case of prosumers also with the valorization and injection, I decided to not insert also the single value of the incentives in order to have a slimmer table.
- Economic parameter: some of the calculated parameter will be added in order to access the real feasibility of the plant. Note that all of these values are calculated on 20 years after the initial investment.

8.1 Domestic consumers

Domestic consumer is a very common type of user so the optimization is done without limits of customers.
Results expressed on table 4 are not very good from an economic standpoint. It is particularly noticeable that the plant owner has very long payback periods. Therefore, it was decided to carry out all the simulations with a 55/45 split of incentives (55% for the plant owner and 45% for the users) that is the maximum allowed by the rules, otherwise the feasibility would be irrevocably compromised.
The reasons for these results are certainly due to the fact that the 2 profiles do not resemble each other much as shown on figure 21, it is clear that for a lot of time consumption overcome production especially in winter and during the nights (note that if sometimes there is blue also on night it means that the consumption is null), those charts are obtained from a potential good configuration and it is the upper view of image 18.
However, by knowing and analyzing the moments of highest consumption or production through heatmaps or by using a feedback system, it should be certainly possible to make significant improvements and greatly increase earnings.
Before starting the analysis of the results, it is important to specify that the energy produced is always 1196 MWh and is exactly equal to the energy injected since there is no autoconsume, so those values are constant for each simulation.
From table 4, it is evident that the best energy performance in terms of not shared energy involves only 36 users. Despite a significant percentage of consumption being shared energy, the excess is too high, making economic feasibility for the system owner impossible. Probably this is due to the fact that domestic users often have big consumption during evening or night since along the day people usually are not at home but at work. Therefore, it is necessary to sacrifice energy optimization and consumer profits to support the investment.
It should be noted that increasing the number of users improves the situation, and an acceptable compromise could be around 400 users, the situation does not permit to go over because the earn for the citizens starts to be too low. However, the economic parameters remain unconvincing, and even after improving the profiles as much as possible, through a feedback system or changes in consumer habits, feasibility remains doubtful.
For all these reasons, it is clear that domestic users are not suitable for connecting to such a large-scale system and should likely form their own community with similar prosumers.

N	E_{cons}	E_{sh}	E_{buy}	E_{exc}	E_{nosh}	G_{plant}	G_{cons}	ROI	PB	IRR	NPV
//	MWh	MWh	MWh	MWh	MWh	€	€	%	Years	%	€
36	152	81	71	1115	1186	56694	112.01	-13.85	23.22	-1.38	-279747
100	423	205	218	991	1209	62829	101.64	1.9	19.63	0.18	-188474
200	848	353	494	844	1338	70184	87.60	20.79	16.53	1.87	-79050
300	1272	465	808	733	1541	75600	76.45	34.89	14.85	3.02	1526
400	1695	547	1148	650	1798	79740	67.78	45.33	13.76	3.86	63118
500	2119	613	1506	583	2089	83027	60.726	53.77	13.01	4.5	112021

Table 4: Domestic consumers results

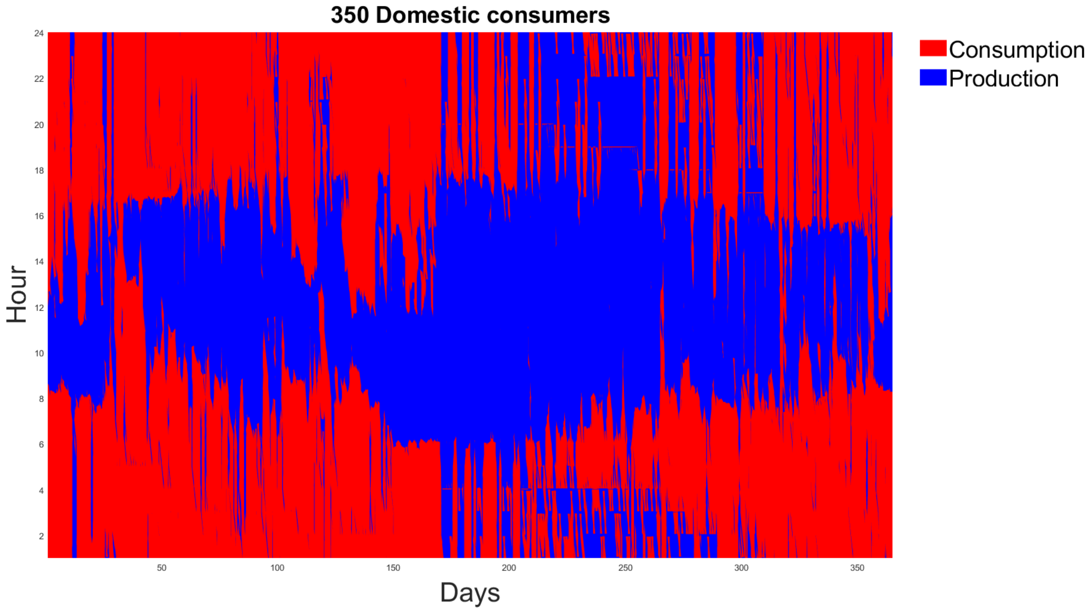


Figure 21: 350 domestic consumer production and production

8.2 Domestic consumers + prosumers

Let's see how the situation change with the insertion of prosumers.
Even by increasing the number of prosumers, the algorithm tends to favor scenarios with only consumers. This is because, with increased energy production, it becomes even more difficult to share, resulting in practically similar outcomes as the previous combination. Therefore, a 55/45 incentive distribution is still mandatory.
It can be observed that the rule imposing the priority of sharing (shared energy comes first from smaller plants) strongly penalizes the 1 MW plant, which sees its profits basically unchanged. In contrast, prosumers derive enormous benefit from this, significantly increasing their earnings because they can share energy acting as consumers and then they can newly share with their production excess.
In order to read table 5 correctly, some clarifications are provided to better explain what has already been stated in the definitions at the beginning of the thesis. Here, energy consumed and self-consumed are distinct categories, so the total consumption will be the sum of these two. Additionally, I would like to remind that the injected energy is the energy that is transmitted to the grid, while the excess energy is the portion that, even after being injected, cannot be shared and is therefore sold. Consequently, the sum of shared and excess energy will be equal to the injected energy. Moreover remember that the autoconsumed energy here is intended as locally and not remote. The best solution under the energetic point of view is still the one with 36 consumers, also here a feasible solution is around the 400 users, but the results are still not good for the plant owner, different situation for the users where the gains slightly increase.
In fact by comparing table 4 with table 5 notice that with the presence of prosumers the gain for the domestic user in general increase a lot, while the one of the plant changes but probably it is more a coincidence due to the fact that the prosumer profile matches better with the production.
Definitively, raising the number of users, in order to improve the gain of the plant owner could be possible but the situation will be the one of an oversize REC, very inefficient from an energetic standpoint thus and still with no enough gains for the plant owner, it is clear that this type of

user is not so suitable for connecting to such a large-scale plant. Moreover managing such a big number of clients will not be easy and can abruptly increase the costs for a feedback systems.

N_{cons}	N_{pros}	E_{prod}	E_{cons}	E_{loc}	E_{sh}	E_{buy}	E_{inj}	E_{exc}	G_{pros}	G_{cons}	G_{plant}
//	//	MWh	MWh	MWh	MWh	MWh	MWh	MWh	€	€	€
36	0	1196	152	0	81	71	1196	1115	0	112.01	56694
30	70	1446	409	133	249	159	1313	1064	208.42	123.71	65035
60	140	1667	818	266	464	353	1401	937	199.68	114.96	74599
100	300	2206	1591	570	805	828	1619	814	184.46	99.73	92557
300	100	1532	1674	190	671	1003	1342	671	167.77	83.04	85879

Table 5: Domestic consumers and prosumers with plant results

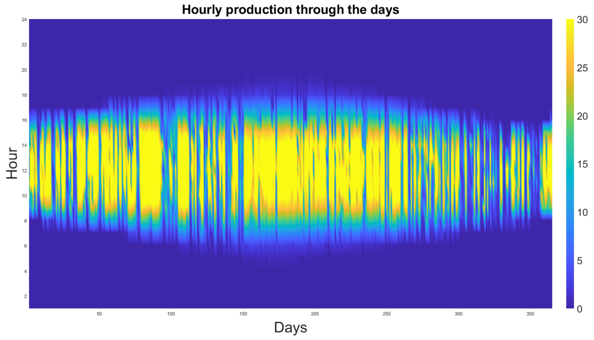
Thus, a simulation is conducted imagining the absence of link with bigger plants. It should be noted that since the script is designed to minimize unshared energy, it proposes a 0 users as best combination with no consumers and no prosumers. In this case, the criterion can be changed by directly analyzing the profits. Here it has no sense to think about the division of gains because there are no laws involved so there are 2 ways: if there are appropriate measurement systems the gains can be precisely allocated, or an equal spread between all the users and this is what is considered. On table 6, an overview is shown.

From the results, it is evident that the earnings for individual users are a bit lower for both the users types, this happens because the energy produced by the prosumers is mainly used as autoconsumed energy and the rest is not sufficient for consumers that are obliged to buy a lot of their demand. However, the percentage of shared energy is quite good, with the E_{sh}/E_{prod} ratio being around 0.3 kept almost constant in all the simulation, this is a sign that means good correspondence between profiles. It is interesting to note from row 1 that prosumers could benefit even more from the community if they collaborated exclusively with each other, further increasing their earnings. By the way in this case the earnings are enough to justify the creation of a REC for both consumers and prosumers, then remember that the money can actually redistributed in other ways.

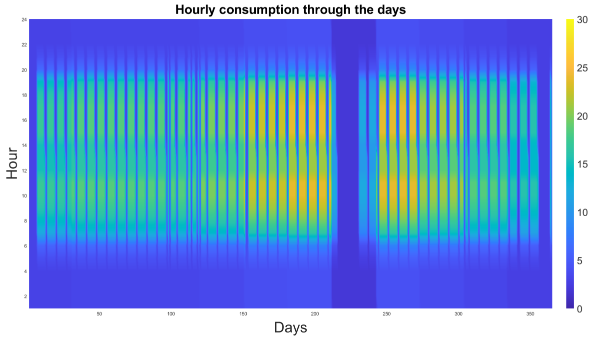
In conclusion, it is clear that for users with such limited consumption that is more evenly distributed throughout the day, connecting to a large photovoltaic plant is not the best solution. Rather, it is advisable for them to form a community among themselves. Indeed, the heatmaps show that there is a good overlap between consumption and production except during the nighttime hours where there is minimal consumption, but production is completely absent.

N_{cons}	N_{pros}	E_{prod}	E_{cons}	E_{loc}	E_{buy}	E_{inj}	E_{exc}	E_{sh}	G_{pros}	G_{cons}
//	//	MWh	MWh	MWh	MWh	MWh	MWh	MWh	€	€
0	20	66.34	80.52	38.02	64.27	29.37	13.13	16.24	174	0
10	10	33.68	82.65	19.01	71.57	14.67	3.59	11.08	145	61
10	20	66.34	122.92	38.02	102.8	29.37	9.25	20.12	158	73
20	50	168.48	286.10	95.04	237.23	73.44	24.57	48.68	161	76
30	70	235.86	409.10	133.07	340.11	102.82	33.80	69.02	160	75

Table 6: Domestic consumers and prosumers results without external plants supply



(a) Heatmap of production



(b) Heatmap of consumption

Figure 22: Heatmaps for 20 prosumers

8.3 Industrial consumers

As mentioned earlier, industrial consumers are certainly those who, in theory, are best suited for a connection with a large plant, since they consume a significant amount of energy and do so during the plant's production hours.

Indeed, notice from Table 7 that the results, considering the connection to industrial consumers, are much better compared to those with domestic users. However, these values are not sufficiently favorable to warrant changing the incentive distribution from the current 55/45 split to a different ratio. Although acceptable economic parameters are shown, they are certainly not great ones.

In this scenario, the ratio E_{sh}/E_{prod} reaches 50% also even with just 15 users. This suggests that while there is definitely space for performance improvements, the potential for enhancement is limited, in fact due to the inconstant nature of photovoltaic systems, it is virtually impossible to exceed a value of approximately 85%. Therefore, it can be deduced that the energy consumption profiles of industrial users align quite well with the production profiles, as described on figure 24. Also despite this alignment, the overall investment does not appear to be particularly promising.

Furthermore, it is evident that the concept of an energy community is likely designed for users who are equipped with their own energy generation systems and whose primary goal is to maximize self-consumption. This indicates that, with the current levels of incentivisation, investing in a system specifically built to power an energy community is not very profitable.

From image 23, it is clear that the best configuration in terms of energy efficiency is the one involving 15 users. However, it is also apparent that the financial gains for consumers and the plant are inversely related. By examining the images, it is possible to deduce that the configurations which maximize the plant's financial gain are the opposite of those which maximize the consumers' gain. Thus, when the plant's gain increases, the consumers' gain decreases, and vice versa.

Even in this context, it is essential to consider the needs of the plant owner more carefully to improve the amortization of the investment otherwise even with the best configuration the situation is better than the one obtained with domestic users. A potential compromise solution could involve around 25 consumers where maybe the energetic performance decreases but they are still quite good, in fact the majority of the demand is still satisfied by shared energy and not by bought energy. This configuration would likely guarantee also acceptable financial gains for both the plant owner and the consumers. It is important to keep in mind that these gains are expected to increase with slight changes in consumption habits. By encouraging more synchronized consumption patterns and optimizing usage, both the plant and the consumers can achieve better financial outcomes within the energy community framework.

N	E_{cons}	E_{sh}	E_{buy}	E_{exc}	E_{nosh}	G_{plant}	G_{cons}	ROI	PB	IRR	NPV
//	MWh	MWh	MWh	MWh	MWh	€	€	%	Years	%	€
15	962	596	366	600	966	82193	1968	51.62	13.19	4.34	99613
20	1283	738	545	458	1003	89207	1827	69.64	11.79	5.66	203963
25	1604	845	759	351	1110	94506	1673	83.24	10.91	6.62	282799
30	1925	921	1004	275	1279	98256	1519	92.87	10.37	7.28	338590
35	2246	968	1277	227	1504	100626	1370	98.96	10.05	7.69	373849

Table 7: Industrial consumers results

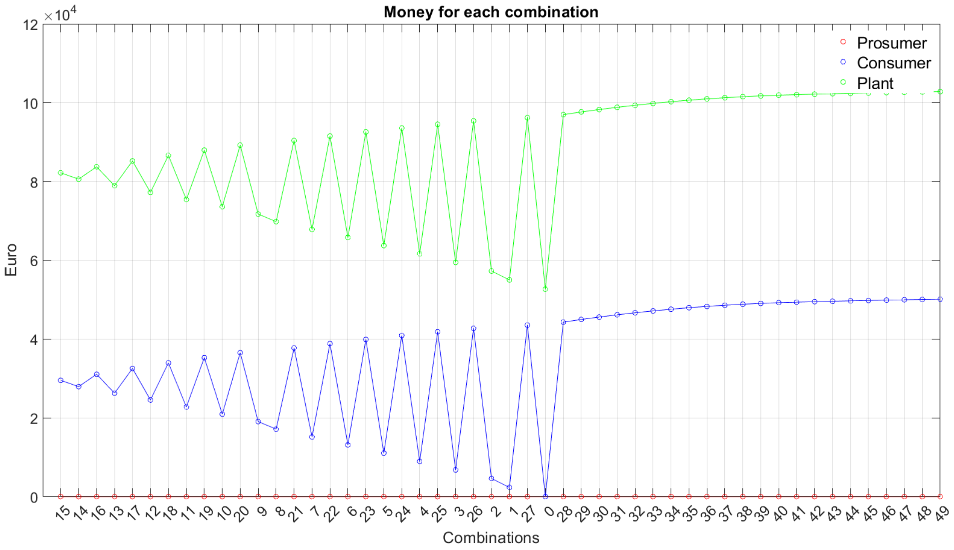
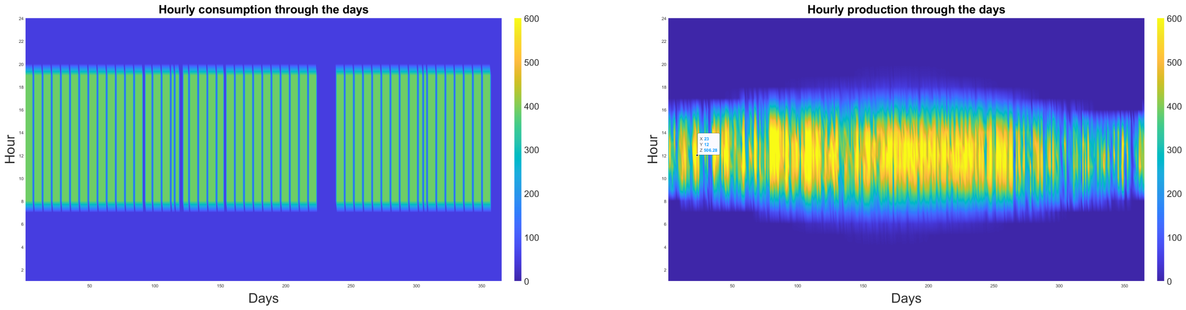


Figure 23: Combinations for industrial consumers



(a) Heatmap of consumption (b) Heatmap of production

Figure 24: Heatmaps for 25 industrial consumers

8.4 Industrial consumers + prosumers

The same reasoning applied to the previous table 6 with domestic prosumers can also be applied to table 8. It has no sense to make a table considering the plant supplying consumers and prosumers of this type because the energy produced by the prosumer in this case is high and thus the code will exclude them from basically all the combinations.
So, it is established that prosumers have a large percentage of the energy they produce which is then self-consumed locally, given their high production that greatly exceeds their consumption. For this reason, it is expected that the best combinations will arise with few prosumers and several consumers.
Analyzing the results, it is evident that prosumers already have a substantial base income from self-consumption, and they manage to add another significant amount by sharing energy with consumers. From the values, note that the code suggest configurations with more prosumers that can supply energy to the consumers due to their high injection. From the excel table generated by the script, the best combination in economic terms is highlighted [16,7] and the 100th best combination [19,14], note that they provide similar gains so there will be a lot of possible good combinations. They shows that the gains are very high for both parties involved and that the $(E_{sh} + E_{loc})/E_{prod}$ ratio is very high. This suggests that this pairing is very promising in almost every configuration. Moreover, it can be further improved with a feedback and monitoring system. Other demonstration of this good match is shown on heatmaps, that are basically identical to the ones of figure 24 with the difference of lower values showed on the legend.

N_{cons}	N_{pros}	E_{prod}	E_{cons}	E_{loc}	E_{buy}	E_{inj}	E_{exc}	E_{sh}	G_{pros}	G_{cons}
//	//	MWh	MWh	MWh	MWh	MWh	MWh	MWh	€	€
5	5	639	428	223	333	416	230	94	5174	1041
5	10	1278	535	446	433	832	730	101	4878	745
5	20	2559	750	863	644	1696	1558	106	4568	465
16	7	893	1177	312	921	581	326	255	5355	1222
19	14	1789	1519	625	1177	1164	822	342	5275	1142

Table 8: Results of industrial consumers and prosumers without plant

8.5 Mixed configuration

This case comprehend all the 6 profiles. This is a variable configuration obtained by using all the available data, obviously it should be improved by using more profiles. Here it is considered that everybody can join the community, but with some limitation on their numbers. For examples school user is set to be maximum one, and offices 10, this due to the fact that they are not so common as industries or domestic users.

As before, due to the presence of the plant, the script tends to refuse prosumers especially the industrial ones that have big production, thus most of the results will not have prosumers included, at the contrary the best user type will always be the industrial due to its profile, in fact it is present in basically all the configuration to guarantee good performance.

In this simulation over 1 million of combinations are generated and on tables 9 and 10 there is a sample with some of them, but note that everyone can watch at the .xlsx file generated by the script and take his own decisions.

The results are selected, specifically, all of them that do not provide at least 90000 euro as gains were excluded since they are not feasible for the plant owner, it has no sense to view them if they are interesting from an energetic point of view, the only exception is done for the best result that is newly with 15 industrial consumers, however this criterion exclude the most part of the combinations.

There are 2 tables in order to improve the reading, on the first it is possible to see the energies and on the second the gains.

From them, it is clear that as the number of users increases, or generally as consumption increases, more energy can be shared, even at the expense of not shared energy. An acceptable balance has been found around 40/50 users with a solid industrial base who, by joining a REC, can achieve good personal earnings and provide adequate compensation to the plant owner, this always with a 55/45 split of incentives.

All configurations are feasible both from an economic standpoint and in terms of the number of users. The economic analysis can guarantee that the investment will be repaid within a maximum of 12 years (similarly to the industrial results, thereby achieving another 8 years of positive cash flow.

In reality also with the domestic and industrial profiles better results could be achieved by simply increasing the number of users, but at least in this way, if this is done, the energetic performance are less ruined since the majority of the consumption is by the way absorbed by the shared energy, but with acceptable gains differently from other configurations. Remember that those are just examples but by looking at the table generated by the script it is possible to have a better view on all the results.

As it was said at the beginning at the chapter, the gains of consumers and prosumers are provided in their total forms and not in specific forms as was done in the previous paragraphs. This is because previously the types of users were essentially identical, so an equal distribution of gains was acceptable.

To better explain here G_{cons} is spread by all the users while G_{pros} just with the prosumers. However, now there are different types of users, and the distribution must be determined in another way, at the discretion of the REC users.

As it was said at the beginning at the chapter, the gains of consumers and prosumers are provided in their total forms and not in specific forms as was done in the previous paragraphs. This is because previously the types of users were essentially identical, so an equal distribution of gains was acceptable. To better explain here G_{cons} is spread by all the users while G_{pros} just with the prosumers.However, now there are different types of users, and the distribution must be determined in another way, at the discretion of the REC users.

Dom. Cons.	Dom. Pros.	Ind. Cons.	Ind. Pros.	Offices	School	E$_{prod}$	E$_{cons}$	E$_{loc}$	E$_{sh}$	E$_{buy}$	E$_{inj}$	E$_{exc}$
//	//	//	//	//	//	MWh	MWh	MWh	MWh	MWh	MWh	MWh
0	0	15	0	0	0	1196	962	0	596	366	1196	600
20	0	20	4	8	1	1533	1661	178	895	765	1355	460
30	10	20	6	0	0	1709	1579	287	915	664	1422	795
0	0	20	0	4	1	1196	1387	0	760	627	1196	436

Table 9: Mixed configuration with plant results (Energies)

Dom. Cons.	Dom. Pros.	Ind. Cons.	Ind. Pros.	Offices	School	G_{plant}	G_{pros}	G_{cons}	ROI	PB	IRR	NPV
//	//	//	//	//	//	€	€	€	%	Years	%	€
0	0	15	0	0	0	82193	0	29520	51.62	13.19	4.34	99613
20	0	20	4	8	1	97533	16784	44888	91.02	10.47	7.15	327833
30	10	20	6	0	0	97697	25649	45302	91.44	10.45	7.18	330273
0	0	20	0	4	1	90860	250	38195	73.88	11.5	5.97	228556

Table 10: Mixed configuration with plant results (Gains)

8.6 Mixed without plant

Here the situation is similar, but without the presence of the plant supplying energy. As a result, it is expected to see more prosumers than before, leading to higher overall gains. Similar to the previous case, the results are provided in their total form for the same reasons.

It is important to note that the presence of some industrial prosumers is always necessary to supply energy to other utilities. It should be possible to replace industrial prosumers with domestic ones, doing so would lead to decreased performance from both an energy and economic perspective.

Watching at table 11, it is confirmed that for individual users, it is always better to be part of a community without the plant, in fact with a rapid calculation it is discovered that the gains are higher for prosumers and similar for consumers. This is because the excess energy is very low compared to the energy produced, indicating good performance. The amount of energy purchased is high, but that is because of consumers are more than prosumers in order to have a good balancing. Moreover prosumers primary goal is always self-consumption rather than injecting energy for sharing thus the value of E_{buy} is less important in this case.

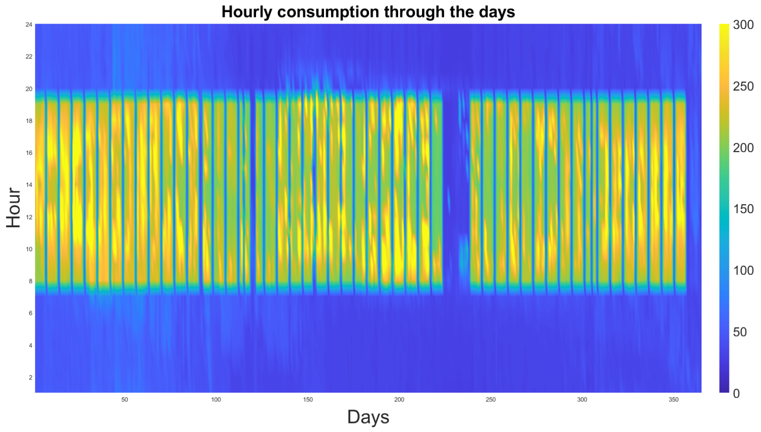
To demonstrate this, one can look at the values of E_{loc} in relation to E_{prod}, which is around 30%. This percentage could be higher if not for the school, which clearly affects the results negatively since it does not consume energy during the summer that is the period at which the plants produce more. Despite this, the performance is quite good, but not enough to be compared to the total industrial configuration. Additionally, when considering the value of the energy shared, the remaining excess energy is very low.

In summary, while the absence of the plant does lead to certain challenges, the overall performance and gains remain favorable, particularly when considering the high levels of self-consumption and the efficient use of produced energy.

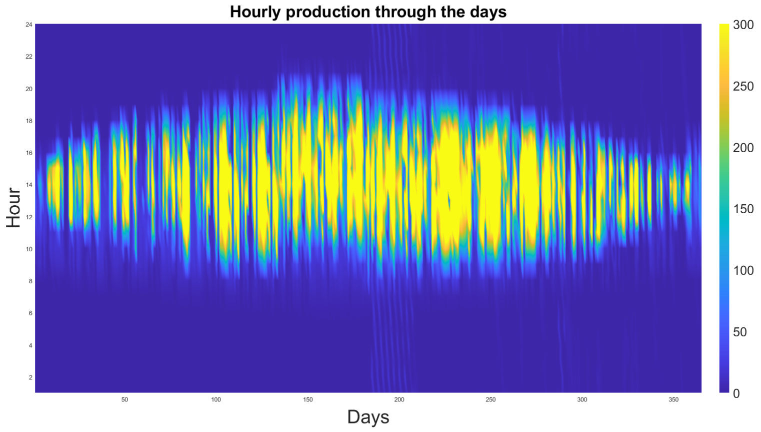
One issue of this model can be the fact that here the rules of the ”priority of sharing” can damage the industrial prosumers, also for this it should be better to choose configuration where the plants are similar and this rule does not impact so much.

Dom. Cons.	Dom. Pros.	Ind. Cons.	Ind. Pros.	Offices	School	E_{prod}	E_{cons}	E_{loc}	E_{sh}	E_{buy}	E_{inj}	E_{exc}	G_{pros}	G_{cons}
//	//	//	//	//	//	MWh	MWh	MWh	MWh	MWh	MWh	MWh	€	€
0	10	20	6	2	1	809	1550	291	305	1245	518	213	25649	32843
10	20	16	6	2	1	843	1376	310	292	1083	533	240	24745	32205
30	30	8	6	6	1	877	1091	329	237	854	548	310	27593	26140
10	10	12	4	2	1	553	1036	201	206	830	352	146	17631	22627

Table 11: Mixed configuration without plant



(a) Heatmap of consumption



(b) Heatmap of production

Figure 25: Heatmaps for 10-10-12-4-2-1 configuration

9 Management and optimization of the REC

This section of the thesis aims to identify the optimal system for keeping the community well-monitored and easily manageable for the designated overseer. The system comprises a combination of software and hardware components. The hardware segment is tasked with consistently and accurately measuring energy flows, while the software must process this data to provide a comprehensive historical record and a clear understanding of "what is happening inside the community".

This setup enables the overseer to readily identify system errors and, if necessary, rectify them or suggest potential changes. Additionally, it would be beneficial if the system could generate the necessary documentation for submission to the GSE to obtain incentives and allocate them to various users based on predefined criteria.

Another feature is predictive capability. The software should be linked to external databases containing not only climatic data but also other relevant information for example historical data. This linkage allows for the advance prediction of the production from various installations. By comparing this forecast with historical consumption data, any mismatches can be detected. In such cases, the software should alert users via notifications to adjust their consumption to times when production is expected to be higher.

Obviously the cost of this system must be covered specially by the referent (plant owner) that will buy the service, but also from the users that often will have to buy apposite measuring systems, in case of autonomous configurations the users can decide together which system adopt or pay some external company to manage the community. Since it has been seen that the earnings are not so high, the costs will be crucial. Remember that the REC can work even without monitor and optimization by using directly the data from GSE that are provided for every month (even if they could arrive with delay) and spread the incentives as decided internally. To do this some crucial characteristics are required:

- High precision of the measures
- Constancy of the measures
- High reliability of the systems
- Automatization
- User friendly interface
- Good coupling software + hardware

The systems considered were all developed by Italian companies and are now available.

At the end it will be done a final comparison between all of them and the best will be identified and suggest to the owner.

9.1 Higeco

Higeco energy srl is a startup from Belluno certified UNI EN ISO 9001, with decades of experience in monitoring and managing the consumption of industry sector and GDO (Grande Distribuzione Organizzata).

Starting from 2008 they started to produce their own monitoring systems composed by hardware and software. Recently they start to adapt their devices for REC. The company focuses on developing and implementing innovative energy systems, including photovoltaic installations,

energy efficiency projects, and renewable energy consulting services. Higeco energy is dedicated to advancing the adoption of clean energy, supporting both residential and commercial clients in reducing their carbon footprint and enhancing energy efficiency.
They propose an energy management software called X-Spector, linked with dedicated meters installed into users' buildings. These devices measure the flow of electricity towards the buildings both in entrance and in exit. The system can be expanded without limitations as long as the user has the meter, which is obviously a significant drawback because it requires a purchase. Additionally, the software is currently not connected to historical databases or weather data to predict consumption or production, so it is effectively just a visualization and management software, but the company assure that they are working on it. Anomalies or potential improvements must be manually identified and then corrected.
The software is very complete, it gives a clear view of all the flows and allocate incentives based on energy or with personalized criterion, but it is quite difficult to use and not so intuitive, thus hypothetically there should be one person inside the office that must learn to use it, and this could be a problem since there are no demo versions, formation program or possibility to try it before the purchase.
The price is around 6000 € per year for the software, plus 10 € for each connected user utilizing their meter, which, depending on usage, can cost between 200 € and 500 €. Another option is to pay 30 € per user while allowing them to keep their existing meters instead of installing the new ones. Hence all the domestic users are basically excluded if this system is adopted, because it will cost around 3 or 4 years of gains deriving by the community joining, and surely the company owner of the plant won't accept the limitation of cannot expand the community if possible and won't pay more for the meter absence.

9.2 Regalgrid

Regalgrid, based in Treviso, Italy, is an innovative technology company specialized in energy management and smart grid solutions. The company focuses on developing advanced software and hardware systems that enable efficient and sustainable energy distribution and consumption. They offers solutions that facilitate the integration of renewable energy sources, such as solar and wind, into local grids, enhancing the stability and reliability of energy networks. By providing tools for real-time energy monitoring and management, Regalgrid empowers both residential and commercial users to optimize their energy usage, reduce costs, and contribute to a more sustainable energy future. Through its cutting-edge technology and commitment to innovation, the company is at the forefront of the transition to smarter, greener energy systems and now they are leader on the sector on the Treviso area.
They propose a POD called "shoku" that interact with a software to monitor and manage the whole community.
PODs must be owned from all the users of the community and they transmit data to a software used to have an overview of the community. Regalgrid gives the possibility to have the meter on loan for domestic users for a certain period before decide and this is very good, moreover the technical assistance is often available and has a dedicated office.
Each user, after the trial period, must buy his meter that costs 120 € for domestic user or 390 € for industrial, then other 1200 € for the software are considered for the plant owner, considering this is relatively cheap.

9.3 Maps

Maps, headquartered in Padova, Italy, is a leading company in the field of data analytics and digital transformation solutions. The company specializes in providing advanced software platforms and consulting services that enable businesses and public sector organizations to harness the power of big data and artificial intelligence. It offers solutions in various domains, including healthcare, energy, and smart cities, helping clients improve operational efficiency, enhance decision-making, and achieve strategic objectives. Known for its innovative approach and expertise, they supports its customers in navigating the complexities of the digital age, fostering innovation, and driving sustainable growth. Through its cutting-edge technologies and deep industry knowledge, it is a key player in advancing digital transformation initiatives in Italy and beyond.

So it is clear that Maps is not properly a company related to the energy sector, but it is a software house that recently starts collaboration with energy engineers in order to create programs for cogeneration and optimization of all kinds of plants. Their softwares are innovative and use machine learning and AI algorithms to perform optimization.

The software destined to the REC is called ROSE, it interfaces with a meter that can be linked to the POD without any changing.

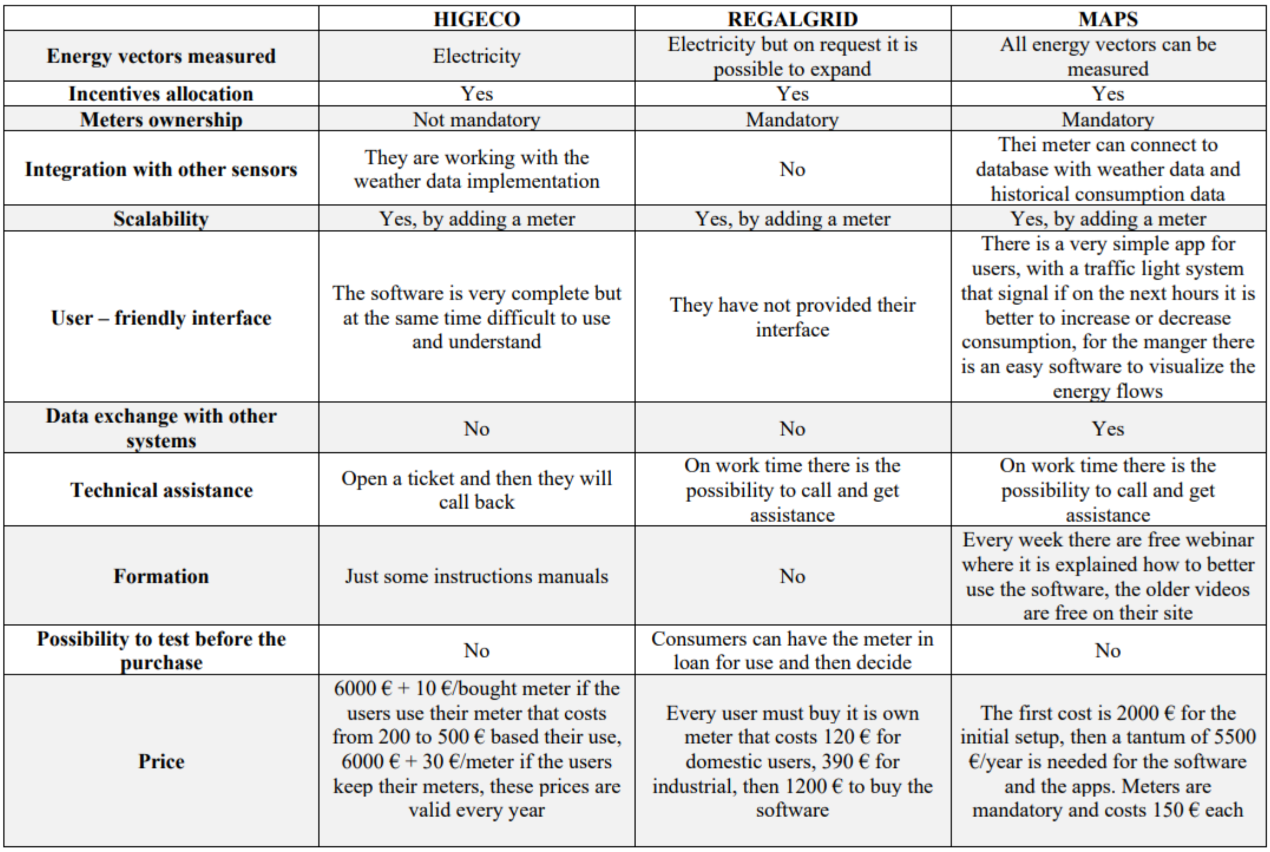
Here, the purchase of meters is also mandatory, but it includes access to a smartphone app. The app uses a traffic light system to indicate to the user whether to increase or decrease consumption in the following hours and provides a simple and clear screen with consumption data. The app is connected to historical data databases of the area and real-time weather data, allowing it to predict the production of the plants and, therefore, suggest actions to the user at the most appropriate times.

The price is 2000 € for the software setup, then 5500 € per year for the license. Additionally, each user will need to purchase a pod priced at 150 € each.

9.4 Software choice

Surely all three choices are valid, however, each of them has its own ”strengths” and ”weaknesses”. For example, Higeco provides a very comprehensive software, although it is not the easiest to use, and will likely implement integration with other data over time. Additionally, it does not require the consumer to purchase the meter, which is very important, especially in the case of residential users, but it is also true that if the customer do not purchase the meter the costs for the software increases thus probably this system is better for community with at least industrial users that can easily pay a meter. On the other hand, it has an even higher price than Maps, which has already implemented an AI system to predict consumption but requires the consumer to buy the meter for 150 € so it can be a sustainable prices for all the users types. Regalgrid, offers a simpler but also more economical solution and also gives the possibility to test the system for a period before deciding, then his meter price is competitive, just 120 € .

Since the price significantly impacts the total earnings of the community, I would personally narrow the choice down to Maps or Regalgrid. The first, if used to adapt consumption and production, can significantly benefit the REC, even though the financial outlay is substantial. The second option is simpler and more economical but more than sufficient to keep the community well monitored. Unfortunately, Higeco offers a middle ground that, at this moment, does not align with the company’s interests in my opinion. Under here on table 26 the main differences are shown, obviously on the table there could be other parameters not mentioned that can be important for the final choice.



	HIGECO	REGALGRID	MAPS
Energy vectors measured	Electricity	Electricity but on request it is possible to expand	All energy vectors can be measured
Incentives allocation	Yes	Yes	Yes
Meters ownership	Not mandatory	Mandatory	Mandatory
Integration with other sensors	They are working with the weather data implementation	No	Thei meter can connect to database with weather data and historical consumption data
Scalability	Yes, by adding a meter	Yes, by adding a meter	Yes, by adding a meter
User – friendly interface	The software is very complete but at the same time difficult to use and understand	They have not provided their interface	There is a very simple app for users, with a traffic light system that signal if on the next hours it is better to increase or decrease consumption, for the manger there is an easy software to visualize the energy flows
Data exchange with other systems	No	No	Yes
Technical assistance	Open a ticket and then they will call back	On work time there is the possibility to call and get assistance	On work time there is the possibility to call and get assistance
Formation	Just some instructions manuals	No	Every week there are free webinar where it is explained how to better use the software, the older videos are free on their site
Possibility to test before the purchase	No	Consumers can have the meter in loan for use and then decide	No
Price	6000 € + 10 €/bought meter if the users use their meter that costs from 200 to 500 € based their use, 6000 € + 30 €/meter if the users keep their meters, these prices are valid every year	Every user must buy it is own meter that costs 120 € for domestic users, 390 € for industrial, then 1200 € to buy the software	The first cost is 2000 € for the initial setup, then a tantum of 5500 €/year is needed for the software and the apps. Meters are mandatory and costs 150 € each

Figure 26: Comparison table between softwares

10 Improvements

The code is still incomplete and can foresee several improvements to be perfected. The first is certainly the language used. In fact, Matlab is not exactly the most widely used software by companies, and converting everything to Python would make it much more accessible. Moreover there are other issues for example:

- Considered profiles: they are just 6, but in reality there will be a lot of other available profiles that, if well combined, can improve a lot the gains. This is not a problem related to the code but on the data availability that is not always banal.
- Time slots F1, F2, F3: the algorithm consider the energy price like there is just one time slot, this can cause some changes on the results especially with users that consume more at night.
- Variation of electricity price: electricity price effects the variable part of the incentives, in this simulations the variable part is set at 20€/MWh but it suppose to change a lot during the year, this can effect the gains, so a sort of dynamic scenario based on the historical data of the electricity price can be implemented.
- Storage possibility: Since the photovoltaic nature makes the production just on the daily hours, it should be thought a storage system, in order to increase the energy shared and thus the incentives. Initially it was not considered as an option by the company, due to the fact that the users were not well defined and the general high price of batteries, but in future it could be a possibility.
- PNRR: it is difficult to well understand who can receive the maximum incentives, because who has already take other kinds of benefits from PNRR could have his incentives decreased.
- Input: input data in this case are not enough to have a very precise results, even if the Monte Carlo method output are promising. This is not properly a problem but a little arrangement to have before the usage of the script.
- Ancillary services: services could be an important part of the community, they can help increasing the energy shared and make the community more attractive for external users. For example think of a charging station for electric vehicle with free energy could help the users that charge their cars, and can increase the energy shared inside the community.
- Computational problem: even with just 6 profiles analyze all the combination takes a lot of time and the calculus is difficult, thus a better defined optimization method that can improve calculations by deleting some results that are obviously useless can be thought. For example on figure 15 the red points are all together near, so maybe there could be a way to directly exclude the blue points and not even do the calculations for those cases.

11 Conclusion

This thesis focused on the development and analysis of energy community for a company that has in program the building of a 1 MW photovoltaic plant located in Motta di Livenza (TV). Furthermore, the relevant and most recent decrees are been reviewed and the incentives available analyzed on the energy communities field. These incentives play a crucial role in the economic viability and attractiveness of such communities, providing financial benefits that can offset initial costs and enhance long-term sustainability.
Then a software tool was built, it takes as input the hourly consumption data of 6 different consumers profiles that I collect, and the production data of the 1 MW photovoltaic plant. The software outputs the optimal configuration to maximize gains from self-consumption and shared energy. Various configurations were created by combining these profiles, and the results were analyzed.
The main problem was founding a compromise the gains of producers and consumers, in fact by increasing the users, it is favored the gain of the plant owner but penalized the one of the normal customer, thus it has been decided to optimize on the energetic point of view, precisely minimizing what is called "not shared energy" that is basically the sum of the energy that is injected and then cannot be shared so in excess, and the bought energy that is simple the quantity needed when the plant production is insufficient. The configurations with the minimum of this quantity are considered the best.
Often happens that those combinations do not guarantee enough gain to the plant owner to cover its initial investment, hence it is necessary to move a little bit from the best results under the energetic point of view.
In general, the analysis revealed that the results are not particularly promising , except for combinations that include a strong industrial base, where the outcomes are acceptable even with good energetic performance due to the fact that the consumption, typical of the daily hours, is well superimposed with the production of the plant, while for the other type of users, to improve the gains it is mandatory to choose other configurations far from the best from the energetic point of view, however they are suggested by the table generated by the script or from the charts. Domestic users are not suitable to the linkage as such a big plant since they do not consume enough and their consumption profiles are more distributed along the day, this facts make the gains of the plant owner quite low, so they should collaborate each other or at least connect to a lower power plant. Regarding the industrial users, they can be connected to the plant but it is evident from the results that their gains shall be higher with an autonomous configuration, since often on industry roofs can be mounted big photovoltaic plants and thus a lot of energy can be produced that can be autoconsumed or shared with other companies that do not have energy sources.
In general, a plant of this capacity, in my opinion, is not suitable as the primary energy source for a community for several reasons. Firstly, the law significantly disadvantages it with the priority sharing rule, which dictates that a plant with these characteristics will always be the last to share energy. Additionally, the incentives provided are very low and even lower with the increasing size of the plant. Note that even in the best scenario where all the produced energy is shared, the revenue would be: $E_{prod} \times (44 + 90) = 160254$ € as max possible gain, resulting in a payback period of 5.69 years, realistically the maximum gains the plant owner could aim at is slightly lower since it is impossible to share all the energy with a reasonable number of users. This suggests that there are far more promising investment opportunities available. Furthermore, individual users would benefit more by managing their own energy needs or seeking smaller plants from which to source energy. Then I think that energy communities are thought

to decrease the amount of energy that let the primary cable and the principle is to use it where it is produced, so it is counter intuitive build a big plant if it is not able to share a lot.
Moreover the intrinsic nature of photovoltaic and the Veneto region characteristics are not so suitable for this kind of systems because often the weather is not favourable and there is a lack of production, probably if this system is implemented by using other sources it could be better, one solution can be the coupling of hydroelectric, that is available in this region, (especially in the higher part) with photovoltaic in order to store water and then use it on the low production period.
It could also be possible to increase the sharing by adding a monitoring systems and by including ancillary services but in that case the plant should act as a sort of help when the autoconsume is unfeasible and not as only supplier.
Another solution can be increasing a lot the users and share more energy, but instead of paying the consumers with the incentives, give them some other benefits for example electric vehicle free charge or lower electricity prices.
Obviously it then depends on the purpose of the community, if it is built just to barely share some energy and get some extra money, all systems can be good, but if the purpose is to use as much as possible the energy inside the area covered by the primary cable, some optimization and more complex reasonings are required, this thesis can be a sort of first little possible improvement to try to optimize as much as possible the role of the renewable energy sources.
At the end the results underlines that energy communities are more suitable for individuals who aim to maximize their self-consumption and then share the energy in excess, rather than having a dedicated plant built specifically to supply the community. This is because the incentives are not so high, especially for big plants that requires huge investment costs and because little plants are favored by the law in sharing energy, this leads to very high payback times that do not make the investment attractive.
Hence autoconsume is still the best solution for all the users since potentially it can set at 0 the bills and sometimes they can also be in credit due to the valorization and injection contribution.

References

[1] Wikipedia. The kyoto protocol.
https://it.wikipedia.org/w/index.php?title=protocollodikyotooldid=138389114.

[2] UNFCC. Paris agreements.
https://it.wikipedia.org/wiki/accordodiparigi(2015).

[3] EEA. Emission trend from 1990 to 2050.
https://www.eea.europa.eu/en/analysis/indicators/total-greenhouse-gas-emission-trends.

[4] IEA. Energy supply in the european union.
https://www.iea.org/regions/europe/energy-mix.

[5] IEA. Energy source evolution in the european union.
https://www.iea.org/regions/europe/energy-mix.

[6] IEA. Italy general description.
https://www.iea.org/countries/italy.

[7] IEA. Italian electricity production.
https://www.iea.org/countries/italy/electricity.

[8] IEA. Italian electricity consumption.
https://www.iea.org/countries/italy/electricity.

[9] TERNA. Description document 2022.
https://download.terna.it/terna/documentodescrizionescenari20228da74044f6ee28d.pdf.

[10] European Union. Laws against climate change.
https://eur-lex.europa.eu.

[11] European Union. Directive ue 2018/2001.
https://https://eur-lex.europa.eu/it/legal-content/summary/renewable-energy.html1.

[12] Ministero dell'ambiente e sicurezza energetica. Le comunità energetiche rinnovabili faq.
https://www.mase.gov.it/sites/default/files/le%20comunita%cc%80%20
energetiche%20rinnovabili%20-%20faq.pdf.

[13] Daniela Patrucco. Cer e cacer: le conferme e le novità dalle regole operative del gse.
https://www.qualenergia.it/pro/articoli-pro/cacer-conferme-e-novita-regole-operative-gse-comunita-energetiche.

[14] Gestore Servizi Energetici. ”guida al simulatore per l'autoconsumo diffuso.
www.autoconsumo.gse.it.

[15] Biblus Acca. Ritiro dedicato 2024.
www.biblus.acca.it.

[16] Gestore Servizi Energetici. Cer, le novità introdotte dal decreto mase e approfondimenti sulle regole operative
https://www.gse.it/mediasite/media-gallerysite/documents/formazione%20webinar%20cacer.pdf.