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ENERGY COMMUNITIES: CURRENT TRENDS AND ISSUES ON SHARED RENEWABLE ENERGY TO ACCELERATE THE ENERGY TRANSITION

Supervisor:
Prof. Chiara D'Alpaos

Student:
Matteo Meneghetti

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Abstract

In the period of energy transition currently underway, distributed renewable energies (RES) such as solar photovoltaic are an increasingly widespread reality both in professional and residential use. They represent an essential tool in reducing the environmental impacts associated with energy production. Renewable energy sources such as solar and wind energy are however characterized by a high non-programmability, it is therefore necessary to undertake a path aimed at their optimization in terms of management efficiency. This objective can be achieved through the creation of energy communities (E.C.), in which different members can exchange energy produced from renewable sources with each other.

In this scenario, members with different consumption profiles interact to maximize the community's energy self-consumption, minimizing the purchase of energy from the grid and reducing the input of the renewable energy they produce. From an economic point of view this translates into a general reduction in the costs associated with the purchase of energy, directly reducing the costs in the bills of the members who compose them. This economic advantage allows their development also with a view to reducing the level of energy poverty or economic aid in critical contexts.

The multiple benefits brought by E.C. have been recognized by the European Community, which already in 2008 introduced the first standard that defines, protects and regulates E.C. in Europe. Subsequently, Italy also took steps to integrate E.C. into its regulatory framework, with the aim of encouraging their implementation and involvement of the population for a greater diffusion.

This paper provides a picture of the current situation relating to E.C. on the Italian territory, describing legislation, technical aspects and the different market schemes that can be implemented. Subsequently, the results of a survey aimed at investigating the technical and administrative characteristics of the E.C. present in the Italian territory are examined. Finally, the study of the relationships between the size of the community and the maximization of economic savings is dealt, with the aim of providing useful indications for the optimal sizing of the community.

The study is carried out starting by considering that the energy demand of the E.C. is partially satisfied through the consumption of renewable energy produced by the E.C. itself. This fraction of self-consumption[1] is assumed increasing with the number of members of the E.C., until

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[1] The self-consumption of renewable energy within an E.C. represents the fraction of the community's energy demand satisfied through the consumption of renewable energy produced by the community itself.

its stabilization when a certain number of members is exceeded. Starting from this concept, a mathematical model has been developed to observe the variation of the Net Present Value of the E.C. as the number of members varies.

The results of a questionnaire conducted by questioning the administrations of some Italian energy communities are also presented and discussed within the thesis. The questionnaire allows to observe both technical and managerial information. From a technical point of view, points such as the technologies and energy systems used, their size and the levels of self-consumption achieved are investigated. Instead, from a managerial point of view, aspects such as the size of the E.C., its legal form, the type of its members and any critical issues encountered during the implementation process are investigated. Some of the information extracted from the questionnaire concerning the behavior of the E.C. were used to define the model that describes the Net Present Value of the E.C.

Contents

Chapter 1

Introduction

In 2015, world leaders set new goals in the fight against climate change. The Paris Agreement presents a joint and shared action plan to limit global warming. The plan provides a long-term view; in this sense, governments have agreed to keep the global average temperature rise below 2°C above pre-industrial levels and to continue efforts to limit it to 1.5°C [1].
In 2019, the European Community presents the European Green Deal, which is a package of strategic initiatives that aims to start the EU in a considerable green transition, with the main objective of achieving climate neutrality by 2050. The package includes regulations concerning energy, transport, climate, environment, agriculture, industry, and sustainable finance. One of the key points of this initiative is the goal of reducing net greenhouse gas emissions in the EU by at least 55% by 2030, compared to 1990 levels [2].
The achievement of the objectives of the European Green Deal is again expressed and helped with the introduction of the "Fit to 55" legislation in 2021. This package provides for the revision of various environmental and energy regulations, with the adaptation of taxation and incentives that regulate it [3]. In the same year, world leaders gathered at COP 26 in Glasgow to confirm their commitment to the ecological and energy transition [4].

Achieving the ambitious environmental objectives requires the implementation of a range of actions that affect different sectors. In order to reduce carbon dioxide emissions, the main actions to be implement are the limitation of energy demand, the reduction of energy poverty and the decarbonisation of the energy sector. A further effect of this type of policy is the increase of energy security and the reduction of dependence on energy imports [5].
As reported in all the aforementioned regulations, European and worldwide regulators recognize renewable energy as one of the key points for achieving environmental objectives. Photovoltaics, together with wind and hydroelectric plants, are well suited to a substantial replacement in the production of conventional energy. One of the advantages of renewable plants is their predisposition to be installed in a distributed way on the territory. At a legal level, the promotion of distributed renewable energies (DRE) in Italy is guaranteed by the legislative decree 28/2011, which makes

the installation of renewable energy systems compulsory in new homes and after substantial renovations [6].

While DREs may seem like an excellent solution to environmental and energy problems, they encounter other problems. Their main criticality is represented by the intermittency of energy production and its stochastic nature. In other words, it is difficult to predict exactly whether a renewable system will be productive at any given time as the availability of the renewable source is not under the human control [7]. The intermittence of renewable energy sources makes it impossible to rely on a single renewable system such as photovoltaics. Furthermore, especially at the residential level, the energy produced by photovoltaic systems is typically obtained with a mismatch between production and consumption. In this case the production peak is obtained around noon or 2 pm, while the demand peaks are localized in the hours before and after working hours. An aid to bridge the gap between production and demand is given by storage systems, typically lithium batteries. The batteries allow electricity to be stored during the hours of maximum production and make it available with high efficiency at the moment of demand, even at night [8]. The main limiting factor to the diffusion of batteries is their cost, which is typically high. Therefore, the installation of batteries large enough to meet the energy demand in any condition is generally impractical.

To get around the batteries problem, the concept of an energy community is introduced. Several members with renewable energy sources and characterized by different demand profiles cooperate by exchanging the energy produced. In this way, when a member is not consuming the energy produced by himself he can exchange it with a member who needs it at that moment. This technique allows to maximize the consumption of energy produced from renewable sources avoiding its transport and dissipation in the national electricity grid. Considering the potential of energy communities (E.C.) for the efficiency of the energy sector and therefore the reduction of environmental impacts, this thesis intends to investigate this concept and provide useful information that can help the development of new E.C.

Chapter 2

Framework description

Contents

2.1 Regulatory framework

The field of energy communities since 2008 is under European regulation, which aims to guarantee a correct implementation of the E.C. and their incentive. These regulations were subsequently incorporated into Italian legislation and refined at regional level. In this chapter, the regulatory frameworks in the various levels of competence will be presented and discussed, starting from the European framework up to the local one, highlighting how the different laws and decrees influence the implementation of the E.C.

2.1.1 European regulation

Since the birth of the European Union, energy management and environmental protection have been key points of European policy, closely linked together. To improve the regulation related to these theme, in 2008 the EU introduced the first set of measures specially defined for energy and the environment. These measures were introduced with the aims of greenhouse gases reduction, renewable energy increase, and energy efficiency improvement. The European Commission defines as necessary the introduction of the above-mentioned objectives, both to contrast the already known global warming and to increase the energy security of member States. For the energetic aspects, it is important to highlight that the European Countries are dependent on energy imports from external countries to meet their needs. To give a scale of measurement of these approaches, in 2012 the cost of importing gas and oil for Member States amounted to 400 billion euros, equal to 3.1% of the European GDP of that year. Moreover, the continuous development of economic giants such as China and India unbalances the energy market, pushing the purchase prices of primary energy to the detriment of European buyers [9].

In this context, European policy is developed following some essential principles useful for achieving the objectives set. The main principles of the European regulatory framework are:

a) making an ambitious commitment to reduce greenhouse gas emissions in line with the 2050 roadmaps;

b) the simplification of the already present European political framework and simultaneous improvement of the complementarity and coherence of objectives and instruments;

c) ensuring the necessary flexibility for the Member States to define a transition to a low-carbon system which is suited to national circumstances, the chosen energy mix, and their energy security needs and which allows costs to be kept to a minimum;

d) strengthening the regional cooperation between Member States to help them to address common energy and climate challenges more cost-effectively;

e) exploiting the momentum from which the development of renewable energies has arisen by defining a policy based on a more efficient approach;

f) the improvement of energy security and simultaneous transition to a competitive and low-carbon energy system through joint actions, market integration, import diversification, sustainable development of indigenous energy sources, investments in the necessary infrastructures, energy savings in end-use, and support for research and innovation;

g) the fair distribution of efforts between the Member States reflecting the specific circumstances and capabilities of each.

Based on these principles European regulatory framework has been integrated over the years with various directives related to different energetic thematics linked together[10]:

- Renewable Energy Directive Directive 2009/28/EC
- Energy performance of buildings Directive 2010/31/EU
- Energy efficiency Directive 2012/27/EU
- Internal electricity market Directive 2009/72/EC
- Internal electricity gas market Directive 2009/73/EC

In addition to these directives, the work of the European bodies continued by introducing other packages of directives updated over time, in order to gradually improve economic and environmental policies by periodically increasing the ambition of the pre-fixed objectives. The most relevant package of directives relating to energy communities was introduced in 2019 under the name of "Clean Energy Package", these directives are detailed in the following chapter.

Clean Energy Package

In 2019, the European Commission introduced the "European plan on climate change", also called "Clean Energy Package" or CEP. It represents a set of four directives and four regulations that acknowledges and set out legal frameworks for certain categories of community energy [11]. The directives and regulations contained in the CEP are the following:

- Energy Performance of Buildings Directive (EU) 2018/844;
- Renewable Energy Directive (EU) 2018/2001;
- Energy Efficiency Directive (EU) 2018/2002;
- Governance of the Energy Union and Climate Action Regulation (EU) 2018/1999;
- Electricity Regulation (EU) 2019/943;
- Electricity Market Directive (EU) 2019/944;
- Regulation on Risk-Preparedness in the Electricity Sector (EU) 2019/941;

  - Regulation on the European Union Agency for the Cooperation of Energy Regulators (EU) 2019/942.

As we will see later, the energy communities field is touched from both the Renewable Energy Directive (EU) 2018/2001 and the Electricity Market Directive (EU) 2019/944.

The European climate change plan aims to help the European Community achieve the objectives set as regards the reduction of energy production impacts. These objectives should be reached by 2030 and they can be summarized as follows:

- 32% of Renewable Energy Sources consumption;
- 32.5% of energy efficiency.

The third goal, the 40% reduction in greenhouse gases emissions by 2010, was updated in June 2021 from the Regulation (EU) 2021/1119, called "European Climate Law" [12]. This new regulation increases the greenhouse gases reduction fixing two different points on the timeline:

- 40% reduction in greenhouse gases emissions by 2030;
- to achieve climate neutrality in 2050.

To achieve these extraordinary objectives, the European Commission defines as necessary the integration of a consumer-centric approach to the energy market to increase the citizens' responsibility regarding energy and emission.

Energy communities in EU regulation

With the Clean Energy Package, for the first time, the European legislation recognized citizens' rights to enter the energy market directly, building the legal framework needed for the diffusion of collective energy production.

The CEP defines two essential energy communities:

1. **Renewable Energy Communities**: They are defined in the Renewable Energy Directive (EU) 2018/2001, generally called "RED II". The REC is based on the member's autonomy and proximity of the energy sources. This type of community can manage different energy typologies (electricity, thermic energy, and gas), only if they are generated from renewable sources [13].
2. **Citizen Energy Communities**: They are defined in the Internal Electricity Market Directive (EU) 2019/994. The CEC can manage only electric energy produced both from renewable and nonrenewable sources. Moreover, this community is not based on the autonomy and proximity principles [14].

Both the Renewable Energy Directive and Electricity Market Directive identify energy communities as legal entities based on the public and voluntary participation of the members. They can merge in different organizational forms as cooperatives, associations, and others (see chapter 2.3.2 on page 26). These kinds of market actors are characterized by the fact that their main purpose is not to generate economic profits but to achieve economic, social, and environmental benefits for their members. The already-mentioned public participation principle ensures that the participation at these projects should be open to all potential members. From the opposite point of view, the participants must be able to leave the energy community without losing access to the energy network managed by the same community.

As they are described in two different regulations, renewable energy communities and citizen energy communities differ in some aspects [15]. The following list shows the main differences found between them, considering the Renewable Energy Directive for the renewable energy communities and the Electricity Market Directive for the citizen energy communities.

- **Participant**: In citizen energy communities, natural people, local authorities, and companies of all sizes can participate. For the renewable energy communities, the participation criteria are quite restrictive, they accept only natural people, local authorities, and small or medium companies, as long as the energy sector is not their main sector.

- **Activities**: Citizen energy communities can manage only electricity both from renewable and non-renewable sources. In contrast, renewable energy communities can manage several forms of energy such as electricity, thermal energy, and gas but only if they are obtained from renewable sources.

- **Geographical scope**: Renewable energy communities implement the local principle, these communities must be developed in proximity to the energy sources. In contrast, citizen energy communities do not have limitations from a geographical point of view.

- **Autonomy**: Renewable energy communities should be able to remain autonomous from other traditional market actors that participate in the community. Citizen energy communities do not require autonomy, but the decisions should be taken by the members that are not related to large-scale commercial activities or other activities focused on energy production.

- **Effective control**: Renewable energy communities can be controlled by their members such as natural people, local authorities, and small or medium companies. For the citizen energy communities, the control is more detailing defined from the Electricity Market Directive as « *the possibility of exercising decisive influence on an undertaking, in particular by: (a) the ownership or the right to use all or part of the assets of an undertaking; (b) the rights or contracts which confer decisive influence on the composition, voting or decisions of the organs of an undertaking.* [14]»

European Green Deal

An important set of regulations that will increase the interest in energy communities in the next future is the European Green Deal, or EGD. The EGD is a set of policy initiatives proposed in 2019 by the European Commission with the goal, among others, of achieving climate neutrality in Europe by 2050. Moreover, the EGD touches on other issues, laying the foundations for the economy of tomorrow with reference strategies on the circular economy, building renovation, biodiversity, agriculture, smart mobility, and innovation [16].

The process of drafting the EGD is not yet completed, but the main points that touch on the environmental and energy issues should be:

a) Increased European climate ambitions for 2030 and 2050 with a 55% reduction in greenhouse gas emissions by 2030 and climate neutrality in 2050;

b) Upgrading the European energetic regulamentation by introducing a full digitized and connected energy market;

c) Increasing of the offshore wind farms and the other renewable sources on which to base the European energy system;

d) Ensuring an affordable EU energy supply;

e) Innovating the construction sector to improve the energetic efficiency of the buildings.

2.1.2 Italian regulation

In Italy, the concept of energy community was introduced with the "National Electric Strategy" on 10th November 2017, written by the Economic Development Minister. This document contains the ten-years plan to manage the update of the national energetic system, increasing the renewable energy diffusion, improving energy efficiency, and increasing the security and diversity of energy sources [17].

Energy communities in Italian regulation

Today, the Italian regulation about the energy communities is based on Art. 42-bis of Decree n.162 of 30th December 2019, in Italy known as "*Decreto milleproroghe*". This decree defines the condition under which it is possible to activate the collective self-consumption of energy, so the condition for creating an energy community [18]. This document takes into account the European Directives 2018/2001 and 2019/944 but it does not represent their implementation; instead, it explicitly wants to monitor the creation of new communities to collect useful elements for the implementation of European Directives [19]. To fully implement the European Directive 2018/2001, the legislative decree n. 199 of 8th November 2021, entered into force on 15th December 2021. This decree aims to improve the previous regulatory requirements and expand the number of possible participants in the energy communities [20].

Both the decree Decree n.162 of 30th December 2019 and the Decree n. 199 of 8th November 2021 distinguish between two aggregation cases; the first one is represented by self-consumers of renewable energy are acting collectively, while the second one is the case of renewable energy community. By combining the information of the two decrees, the characteristics of the two aggregates can be described as:

1. **Self-consumers of renewable energy are acting collectively**: the collective consumption is made by some self-consumers located in the same house, building, or condominium, in which one or more renewable power plants are located. In this case, the power plants can be owned by members or by an external company that is not considered a member of the self-consumers.

2. **Renewable energy community**: several members can be present with their power connections under the same medium voltage electric grid, connected to the same primary cabin. In this case, according to the European directive, the members can be natural people, local authorities, and small or medium companies, as long as the participation in the energy community is not their main sector. In addition to these, the decree n. 199 of 8th November 2021 enables the participation in energy communities of additional members such as territorial bodies and local authorities, including municipal administrations, research bodies, religious bodies, those of the third sector and environmental protection as well as local administrations[21].

Thanks to the integration of the Decree n. 199 of 8th November 2021, after its application (15th December 2021) the new aggregates implement energy plant with an electric power until 1 MWp, significantly higher than the previous threshold of 200 kWp [21].According to the same law, to obtain the incentives from the energy exchange, the plants must have been started up after 16TH December 2021. By considering the energy sharing, the members share the energy produced using the existing distribution network. The shared energy is equal to the minimum between the electricity produced and fed into the grid by renewable source plants and the electricity taken from all the associated customers. The associated members can have some energy storage system like batteries, in this case also the consumed electricity used to recharge these systems is considered in the estimation of the energy taken from the associated customers [18].

As already seen in the European framework, these kinds of associations have the aim to give economical, environmental, and social benefits to the community, with a free and voluntary membership base. In addition, the Italian regulation introduces particular attention to the low-income and vulnerable families, which can receive appreciable help by reducing energy costs.

The European directives are not yet implemented in Italy, but with Law n.53 of 22nd April

2021 called "European Delegation Law 2019-2020", the government wants to verify the correspondence between the law and the European directives and prepare the legislative bodies to write the necessary rules. This law is composed of 29 articles for the implementation of 39 European directives [22]; the following are the two most relevant articles in the field of energy communities:

- Article n.5 contains the principles and the criteria for the recipient of the European directive (EU) 2018/2001 related to the renewable energy communities;
- Article n.12 contains the principles and the criteria for the recipient of the European directive (EU) 2019/944 related to the citizen energy communities.

Concerning communities, the law aims to encourage the creation of all self-consumption systems, including collective ones, from renewable sources, even on existing buildings. To reach this goal, it highlights the need to simplify the regulatory framework and harmonize the authorization procedures relating to self-consumption and storage. In addition to aspects closely linked to the communities, some important points related to the electric grid are proposed. First of all the need for a power grid upgrade, focused on the implementation of smart grid and the promotion of ancillary services based on standardized character. Moreover, a more active role on the part of network operators is required, with the introduction of economic sanctions towards electricity companies in the event of a violation of the obligations relating to energy communities [23].

2.1.3 Regional regulation

Usually, the energy community takes on a purely local dimension, creating a system with its autonomy that must coordinate in a very specific environment and be closely linked to local regulations. Therefore, each region must develop its regulatory framework in which to identify the peculiarities and specificities typical of the area. This authority is guaranteed by art. 117 of the Italian Constitution. This article provides that the Regions can legislate in this matter within the limits of the fundamental principles established by state law and on the condition that the detailed regional and state regulations do not conflict with the regulations and constraints deriving from the Community system and obligations. Some regions such as Piedmont, Puglia, Sardinia, and Liguria have already implemented laws in favor of energy communities.

Regulation of the Piemonte region

The Piemonte region was the first Italian region to draft a regional law specifically designed to encourage the creation of energy communities in its territory. This law is n. 12 of 03 August 2018, entitled "Promotion of the institution of energy communities" [24]. Later, this law became a reference for other regions such as Puglia, Sardinia, and Liguria, which have reinterpreted it to adapt it to their local characteristics.

Like the national regulation, this law identifies energy communities as non-profit entities and stimulates their development in order to overcome the use of oil and its derivatives and to facilitate the production and exchange of energy generated mainly from renewable sources. It also recognizes in the energy communities the objective of implementing forms of energy efficiency and reduction of consumption for its members. Taking up the national definitions, also according to the Lombardy region, both public and private entities can participate in energy communities. From the point of view of consumption, the members of an E.C. must self-consume at least 70% of the energy produced, against the 60% required by other regions such as Veneto, Puglia, and Sardinia [25].

To ensure the effectiveness of the communities, with this law a control system is introduced. Therefore the C.E. draw up an energy balance within six months of their establishment. Subsequently, within twelve months of their establishment, they will have to draw up a strategic document that identifies the actions for the reduction of energy consumption from non-renewable sources and the efficiency of energy consumption.

This law not only updates aspects of the communities but also implements new commitments by the region itself. First of all, the region undertakes to financially support the construction phase of the E.C. acting economically on the preparation of projects and documentation. Secondly, a standing technical committee is established between the energy communities and the region. This committee will have various tasks including that of acquiring data on the reduction of energy consumption, the share of self-consumption and the share of renewable energy use, and that of identifying ways to manage energy networks more efficiently.

Regulation of the Veneto region

A law specifically developed for energy communities has not yet been implemented in the Veneto region, but a draft legislation to address this issue is under development. This draft legislation was presented on 20 July 2021 under the name of "Progetto di Legge N. 82; DGR 17/DLL 20/07/2021" and reports the commitment made by the Veneto region to encourage the creation of two figures: energy communities and groups of self-consumers of renewable energy that act collectively.

The text highlights that the central objective of energy communities is the value of the energy produced, and not the profit it makes: the objective is the self-consumption of renewable energy produced by the members of the community in order to increase energy efficiency and fight energy poverty by reducing consumption. Furthermore, it is specified that energy communities assume and maintain the status of energy producers if annually the share of energy produced destined for self-consumption by the members is not less than 60% of the total; this again points out that the fulcrum is self-consumption of energy and not its sale. With the proposed text, the Veneto region also pushes on the fact that the energy communities not only share the generation and consumption of energy among their members but can provide them with additional services such as energy storage, efficiency services, or other energy services with the primary objective of providing environmental, economic or social benefits [26].

The regional legislative framework was updated in July 2022 with the Regional Law n. 16 of 05th July 2022, entitled "*Promotion of the establishment of renewable energy communities and renewable energy self-consumers who act collectively on the regional territory*". This law aims to integrate the national Decree n. 199 of 8th November 2021 and to stimulate greater growth of energy communities in the regional territory. First, the definition of energy community is updated in accordance with the new national denomination (see chapter 2.1.2 on page 12). Secondly, the law includes in the program the promotion of collaboration with local electricity distributors and with the Energy Service Manager (GSE s.p.a.), aimed at ensuring the correct functioning and development of energy communities [27].

To better achieve its goals, the regional council will establish a technical table for the reduction of energy consumption. This team will monitor the activities and needs of the energy communities and will disseminate good practices to be implemented on the regional territory. To manage the local energy networks more efficiently, the technical table will also be able to consult the already mentioned Italian energy service manager (GSE), the Italian authority of regulation for energy and the environment ARERA, and the national agency for new technologies, energy, and sustainable economic development (ENEA).

2.1.4 Economic incentives and tax detraction

In September 2020, the Ministry for Economic Development has made operational the economic incentives required by the Decree-Law of 30 December 2019 n. 162, the so-called "*milleproroghe*" decree. With the aim of rewarding instant self-consumption, the coincidence between the place of production and consumption, and the use of storage systems. As regards incentives, the "*milleproroghe*" decree instructs the Minister of Economic Development to identify an incentive rate for the remuneration of renewable energy plants [18]. With the decree signed on September 15, 2020 by the Minister of Economic Development, a tariff of economic incentives is introduced on the Italian electricity market [28]. These incentives are supplied based on the amount of self-consumed or shared energy:

- Energy consumed within a collective self-consumption: 100 €/MWh;
- Shared energy into a renewable energy community: 110€/MWh.

These economic aids are designed only for new plants (installed after 1st March 2020) and they can be added to other incentives if present for those installations.

Moreover, considering the reduction in the distance of energy transport, a reduction on transport fee is added equal to:

- Shared energy for collective self-consumption: 10 €/MWh;

- Shared energy into a renewable energy community: 8 €/MWh.

We can also consider as an incentive the purchase, by the energy provider, of the energy not used and fed into the grid with an average value of 50 €/ MWh [29].

In addition to the incentives on the energy part, it is necessary to consider the tax concessions already present for the construction of renewable plants. With art. 16-bis of Decree n.917/1986 (T.U.I.R.) a tax detraction of 36% was envisaged. This value is updated from year to year and throughout 2021 the expenses related to energy plants have a tax deduction rate equal to 50% of the amount spent for each real estate unit, up to a maximum of 48,000 €. The tax deduction obtained is distributed over ten years, paying ten annual installments of the same amount [30].

Until the end of 2022, to relaunch the economy after the Covid-19 pandemic, in Italy, economic aid is issued in the form of tax detraction of 110%. The process to receive this bonus is not direct as for the 50% detraction. In this case, the tax detraction covers the building costs of some works related to the energetic efficiency of a building such as insulation improvement, boiler change, photovoltaic panels installation, energy storage installation, etc. To obtain the compensation, at least one of the three driving works must be completed (boiler change, external insulation, anti-seismic works), and considering all the works, the house must be improved by at least two energy classes [31].

2.2 Technical framework

The technical aspects of an energy community are part of the main points to be observed for the EC design, which allows or not to obtain success of the network. During the design phase, it is essential to define the correct technological choices, considering various aspects related to the specific case, such as available technologies, available energy sources, the presence of an already built infrastructure, social aspects of the area, and legal constraints.
From an economic point of view, each technology involves different initial and management costs. Therefore, the design choices of an EC must allow a return on investment in a short time, otherwise, no citizen will be interested in participating in the realization of the work. Fortunately, in the last years, technological progress is helping to make more affordable several technologies, that were previously more expensive or difficult to implement.

Taking into account these aspects, the ECs can be very different from each other, but all of them are characterized by three basic layers [32]:

1. Physical energy assets, with energy production and energy storage;
2. Information and communication technologies or ICT;
3. Grid connection of the physical energy assets.

2.2.1 Physical energy assets

The physical energy assets are represented by the energy resources, which include both energy production plants and energy storage plants that may be present. They are the starting point in the design of the energy community as they define the amount of energy that can be produced and stored.

Sometimes, the energy assets can be oversized to ensure energy availability even in the event of a shortage of the renewable energy resource or in the event of a malfunction.

Energy production technologies

According to the community type, that can be a renewable energy community or citizen energy community, the energy source can be respectively renewable or non-renewable. In the same community one or more production technologies can be used, in any case, they must be carefully chosen considering various factors such as:

- The legal framework;
- The geographical area and its characteristics;
- The resources present in that area;
- The presence of companies that can participate in the energy production;
- The presence of other stakeholders;
- The interaction between the plant and the surrounding environment.

In general, the most used renewable energy production technologies are [19]:

- Hydroelectric plants;
- Photovoltaic plants;
- Biogas or biofuel based cogenerations;
- Wood chip based cogenerations;
- Wind power plants;
- Geothermal plants.

In the case of non-renewable energy production technologies, other conventional techniques can be used, such as [33]:

- Gas turbines or micro gas turbines;

- Diesel or biofuel generators.

All these technologies have some particularities that make them the ideal solutions in certain situations and unsuitable in others. For example, in the case of a plant integration with a house or a residential building, the conventional choice is photovoltaic panels thanks to their simplicity and the absence of noise. Instead, in the case in which a facility wants to integrate its production line with energy production, it might prefer a cogeneration plant to use the heat produced within its production process.

Another important factor of choice is represented by the predictability of energy production, in particular, renewable energy as the photovoltaic ones are usually intermittent and unpredictable. Moreover, still photovoltaic energy is produced only during the day and this is not consistent with the needs of a domestic user, which has peak demand in the morning and the evening. From a technical point of view, this phenomenon is described by the fact that the load curve rarely follows the energy availability curve.

Energy storage technologies

To solve the above-mentioned problem of renewable energy and to reduce the peak energy demand on the electric grid, the installation of storage technologies can be a good choice. The elementary operation of storage systems can be described as follows: during the energy production phase, the surplus of energy (which would otherwise be fed into the grid or wasted) is used to charge the storage system. On the contrary, when the energy production is insufficient or absent, the required amount of energy is withdrawn by the storage discharging [34]. In other words, using this kind of system in energy management, the power consumption and production can be separated in time. Taking into account all the energy storage systems that can be used today and not just those currently used in energy communities, a great difference in usable technologies can be observed [35]. They can be divided into the following categories:

Technologies for the storage of electric energy:

- Electrochemical systems as lithium-ion batteries; thanks to their simplicity this is the most used technology for small-medium size electricity storage;
- Electric systems as supercapacitors: at the moment this technology is still under development but looks promising for the future thanks to its high energy density capacity;
- Systems based on electricity conversion in hydrogen: this system has been used in recent years instead of large battery systems, while hydrogen storage consumes a fair percentage of energy;
- Mechanical systems such as pumped hydroelectric storage: compressed air energy storage and

flywheel energy storage; the pumping of water in hydroelectric basins is a very widespread technology in the Italian territory to accumulate excess electricity during the night.

Considering the fast diffusion of electric vehicles, even they will become suitable instruments for electric energy storage. They can merge the storage capacity with the ability to move in space, this could allow them to expand the extension of energy communities to structures not directly connected to the community network. For example, an employee could charge the car battery from the charging station of a company connected to the EC and use the accumulated electricity in the evening in his home.

Technologies for the storage of thermal energy [36]:

- Sensible heat thermal storage systems: are based on the absorption and subsequent release of heat through a temperature variation of both a solid and liquid storage medium. At the moment it is the most used system for thermal energy storage;
- Latent heat thermal storage systems: are based on the absorption and subsequent release of heat during the phase transition undergone by the storage medium (usually a mixture of salts). This latest technology is evolving both from the point of view of materials and systems development;
- Thermochemical storage systems: are based on the energy absorbed and released during the breaking and formation of chemical or physical bonds during a completely reversible reaction. Nowadays there are small applications already commercialized for the energy optimization of processes.

Among all these technologies, the only ones actually used in existing energy communities are battery electricity storage systems and sensible heat storage systems. At the moment the other systems are too complex and expensive to be used by the members of the EC.

2.2.2 Information and communication technologies

The layer of information and communication technologies, also called ICT layer, includes all the physical and virtual tools necessary to allow and manage the exchange of energy and information. To maximize the network efficiency, the ICT layer must interact with all the components of the network, such as production plants, distribution system, storage systems, consumption points, and eventually with the connected electric vehicles.
A widespread and efficient ICT system is essential considering the typical aspects that characterize an EC: the aleatory nature of renewable energy sources, the high number of actors linked to the EC, the need to know the instantaneous exchange of energy between different producers and consumers, management of the storage system and so on.

To guarantee the efficient work of ICT, it is fundamental to maximize the transmission of this information and reduce the time required for their exchange. With this aim, the spread of smart meters has begun within the European Community.

Smart meter

A smart metering system is an electronic system capable of measuring electricity fed into the grid, or electricity consumed from the grid, providing more information than conventional meters.

To guarantee a large diffusion and their correct work, the European Commission with the 2012/148/EU Recommendation, fixed the list of the recommended common minimum functional requirements that every smart metering system for electricity should fulfill [37]:

- For the customer:
  - To provide readings directly to the customer and any third party designated by the consumer;
  - To update the readings frequently enough to use energy savings schemes;
- For the metering operator:
  - To allow remote reading of meters by the operator;
  - To provide two-way communication between the smart metering system and external networks for maintenance and control of the metering system;
  - To allow frequently enough readings for network planning;
- For commercial aspects of energy supply:
  - To support advanced tariff systems;
  - To allow remote on/off control of the supply and/or flow or power limitation;
- For security and data protection:
  - To provide secure data communication;
  - To fraud prevention and detection;
- For distributed generation:
  - To provide import/export and reactive metering.

The above-mentioned features should be able to guarantee advantages for all the EC components. From the consumer's point of view, good management can be helpful to control their energy consumption and also increase their energy efficiency. Moreover, they can implement more innovative services such as home automation systems and smart home solutions. On the other hand, the operator can achieve better management of the distribution and storage system, making them more efficient and cheaper.

2.2.3 Grid connection

The electrical (EG) grid is a fundamental part of each power system, both for a conventional one and an energy community. It is the interconnected network between all the members of the electricity market, from producers to consumers. A general EG is composed of several components linked together, they can be collected in three main sections [38]:

1. **Generation grid**: it includes generating stations and setting up transformers to provide the electricity to the transmission grid;
2. **Transmission grid**: in which the energy is delivered to distribution grids;
3. **Distribution grid**: it is composed of several substation transformers and finally electric power distributors to achieve the home voltage.

In addition, the so-called ancillary services are distributed along with the network. They represent the set of services necessary to ensure the proper work of the entire electrical system, including frequency regulators, voltage regulators, and grid restart systems.

Microgrid

Often the electric grid that allows the interaction between the energy community members is called a "microgrid" (MG) due to its system of close interactions. The principal aim of an MG is to allow the operation and correct management of the electricity network to connected users, but its presence can also bring advantages to the grid, such as increasing the efficiency of the network by reducing distances and therefore the loss of energy.
A microgrid combines, manages, and integrates various distributed energy resources composed of energy production systems, energy storage systems, consumers, and the infrastructures necessary for the working of the network. The definition of MG does not consider its size but its function and generally it is considered as MG a part of the total medium voltage or low voltage pre-existing electricity grid. More in general, the MG can work both connected to the utility power grid (also called public grid) or disconnected from that in islanded mode [39]. In the first case, if the MG can not operate in island mode, it should be defined as an electrical distribution network. The size of an MC is defined based on the number of actors and their distribution, the required peak power, the energy production capacity, and the storage capacity.

Considering the different situations in which an MG may be designed, there are four major types [39]:

- **Island microgrid**: a combination of distributed energy producers, and storage systems that can provide enough energy to the consumers. It is characterized by the ability to work separately from the public electricity grid;

- **Low voltage customer microgrid**: the system manages the production and energy demand of a single prosumer or a single building;
- **Low voltage microgrid**: the system manages a group of some energy producers, storage systems, and consumers connected under the same low voltage transformer;
- **Medium voltage microgrid**: the system manages a group of several energy producers, storage systems, and consumers connected under the same medium voltage transformer.

Looking at the Italian regulation, the low voltage customer microgrid can be considered the base for "self-consumers of renewable energy", while the low voltage microgrid can be represent of the "renewable energy community" [19].

Smart grid

Smart grids (SG) represent the evolution of microgrids, they are obtained thanks to the integration of the grid network with smart information and communication technologies.
The European Commission in 2014 defined SG as follows:

> *«Smart grids are energy networks that can automatically monitor energy flows and adjust to changes in energy supply and dem accordingly. When coupled with smart metering systems, smart grids reach consumers and suppliers by providing information on real-time consumption.»* [40]

To achieve these purposes, the SG is composed of both energy exchange lines and information exchange lines used to manage the numerous points of the network. The SG can, therefore, be divided into three main systems [38]:

- **Infrastructure system**: as for the conventional grid, it is the set of generation, transmission, and distribution grid. In addition, It includes hardware related to smart ICT that includes communication systems and measurement tools such as phasor measurement units, smart metering, and other sensors. Thanks to the developed management system, more grid components can be implemented into the same SG, allowing to increase the capacity and the users of the SG;
- **Metering and data management system**: it is the fundamental point of SG, it is the subsystem that processes the collected data from ICT and provides them with advanced management and control services. Data storage and processing tasks are carried out by ICT components distributed in the different nodes of the network that cooperate and communicate with each other both in wireline and wireless way;
- **Protection system**: it is carried out by components distributed in the different nodes of the network that cooperate and communicate with each other both in wireline and wireless

way. To achieve a high level of security, policies such as digital authentication of users and encryption of data transmissions are implemented.

The final objectives of the SG are the integration into the electricity system of diffuse energy resources (production and storage), the reduction of energy losses, and the efficient use of energy thanks to communication between producers, consumers, and storage systems. Furthermore, considering the management of the infrastructure, the SGs aim at improving the quality of the service, extending the useful life of the plants, reducing the costs of failure, and maintenance of local networks.

2.3 Social framework

Within an energy community, several players can participate, who can cooperate by forming E.C. with different legal forms. In the first part of this chapter the different players and their main characteristics are listed and discussed. In the second one, the main legal and governance forms that can be implemented in the administration of an E.C. are described.

2.3.1 Players

To achieve the set goals, energy community must include all the figures needed for its correct operation. Furthermore, to maximize efficiency and reduce costs, the EC must try to reach the highest possible number of participants. For this purpose, different components must become part of the community, each with its own characteristics necessary for the proper functioning of the EC.

The different members of the energy communities will be listed below and their main characteristics will be described.

Consumer

Every citizen has always consumed energy and resources to carry out his daily life. Within an EC, even ordinary citizens who do not have energy production systems can participate, these are defined as consumers and represent the simplest figure within the EC. From the consumer's point of view, he is a simple customer, who does not buy the energy produced and fed into the national grid but the energy produced by other members of the EC and fed into that grid. According to European regulations, in citizen energy communities, consumers can be individuals, local authorities, and companies of all sizes. For the renewable energy communities, the participation criteria are quite restrictive: as the REC, they accept only natural people and local authorities but companies must be small or medium companies, as long as the energy sector is not their main sector [15].

Producer

The producer is the one who owns an energy production plant and sells the energy produced,

in whole or in part, to the EC. According to European regulations, a distinction must be made between renewable energy communities and citizen energy communities:
A producer member of a renewable energy community can manage different energy typologies (electricity, thermic energy, and gas), only if they are generated from renewable sources. In contrast, a producer member of a citizen energy community can manage only electric energy produced both from renewable and nonrenewable sources. Moreover, as for consumers, producers of a REC can be only small or medium-sized enterprises, provided that the sale of the energy produced does not represent their main sector [15].

Prosumer

The prosumer represents a new figure widely diffused within the energy communities. He is a member of the EC who can sell the excess energy produced by his plant and therefore not consumed [10]. It is a member of the EC, it owns an energy production plant, and sells the surplus energy produced to the grid as a producer. Furthermore, when his energy production is not sufficient to meet his needs, the prosumer can purchase the necessary energy from the EC grid as a common consumer. This figure has spread thanks to the diffusion of renewable energy plants, which can be easily installed on the common houses, but it is based on aleatory energy resources. For example, a citizen member of a REC, who owns a roof-mounted photovoltaic plant, will sell his surplus energy during a sunny summer day and it may need to buy more power on a winter day. Moreover, without a private storage system, he could go from being a seller to being a buyer simply by going from day to night.

Aggregator

The aggregator is an electricity market operator who has the task of aggregating and merging different production and consumption units distributed in a single unit, which can be represented by an energy community. The aggregator can manage its customers by offering various services over the single energy supply, also allowing them access to the dispatching services market, to which individual users/producers would not have access [41]. In this way, these services can be offered to the TSO, supporting the operation of the network and the implementation of energy communities. The aggregator can therefore take on various essential tasks within the energy community, ranging from merging the different users, purchasing the necessary electricity from the national market, organizing the energy and infrastructure management of the community, and possibly managing the provision of ancillary services to the TSO.

Public authority

The authorities have the task of allowing and guaranteeing the diffusion of energy communities; to this end, the European Commission has drawn up specific directives that force Member States to implement laws that allow citizens to join and form EC. At the local level, local authorities can encourage the spread of EC by taking a direct part in them, both as consumers and as producers. In addition, they can act as facilitators by financing the development of the EC, thus owning a part of it and having decision-making capacity [42, 15].

In order to ensure the nonprofit nature of EC and objectives of benefit to citizens, it is not allowed the participation of energy services companies (ESCO) as active members of the energy communities. However, they can provide services related to the provision of energy infrastructure and plants to members.

Subject	**Action in EC**
Consumer	Buyer
Producer	Seller
Prosumer	Buyer and seller
Public authority	Promoter

Table 2.1: Summary of the different members and how they can participate in the EC.

2.3.2 Legal forms and governance

Considering the different technologies, components, and personal interests of citizens, some different legal forms can be assumed for energy community management. The main adaptable legal forms are now shown, they present different approaches to the ownership, to the members' control power, and different sizes [42].

- **Co-operatives**: their primary objective is to provide benefits to their members by energy providing and selling. Joining the community is voluntary and open to anyone willing to accept risks and responsibilities. All members have authority in governance and the allocation of profits, applying the principle of "one vote per member" to give equal power to every member.

- **Partnership**: also in this case, the members agree to work together to establish a legal partnership to provide energy services to the community. Unlike a cooperative, where every member has the same power, the voting power in the partnership is determined by the degree of participation that each individual puts in the EC. Another difference from the cooperative is that, in addition to providing a benefit to the community, partnerships can generate a profit.

- **Trusts and foundations**: these types of establishments are charitable organizations that have the purpose of providing a social benefit rather than a profit. These types of organizations allow entire communities to take advantage of the benefits, even when individuals cannot afford to participate due to their low economic standards.

- **Public utility companies**: they are managed by local administrations, which invest and

Figure 2.3.1: Energy communities legal forms. [42]

manage the utility on behalf of taxpayers and citizens. These forms are not very common but can be suitable to push the development of rural or isolated areas, where, without the presence of the administrations, there would not be sufficient economic funds and skills.

- **Public-private partnership**: If in the previous case the local authorities carry out actions for all the citizens of the area, in this case, the local authorities decide to make agreements with small groups of citizens and/or businesses in order to guarantee the supply of energy for the community.

Energy communities can arise from the desire of citizens (and other members) to achieve certain benefits, or they can be proposed both from authorities and companies. As shown in the Figure 2.3.1, in the first case, we talk about a bottom-up process and in the second case we talk about a top-down process.

2.4 Energy market

This chapter explains the different components of the Italian electricity market and how energy communities can operate in it.
In more detail, the components of the energy market are first described, then the energy trade market and the retail market are described; finally, the various interactions that an E.C. can have with the electricity market to achieve maximum benefits are discussed.

2.4.1 Members of the Italian energy sector

The Italian electricity market is managed directly by the Energy Market Manager (GME), under the control of the Energy Services Manager (GSE). Management is carried out in compliance with the regulations and updates prepared by GME and approved by the Ministry of Economic Development, after having consulted the Regulatory Authority for Energy, Networks and the Environment (ARERA).

ARERA

The so called "*Autorità di Regolazione per Energia Reti e Ambiente*" or Regulatory Authority for Energy, Networks and the Environment, founded in 1995 [43], it is an independent Italian administrative authority, which has the function of promoting the development of competitive markets in the electricity, natural gas, drinking water, district heating, district cooling, and urban and similar waste sectors. It performs these tasks through the tariff regulation of access to the networks, acting the control of service quality standards, the control of the functioning of the markets, and the protection of customers and end-users. ARERA's financing system does not take money from the state budget but directly from the revenues of regulated operators [44].

Transmission System Operator (TSO)

TERNA is the TSO in the Italian electric network, it is the society that manages and controls the national energy transmission structures, including high and very high voltage lines. It was founded in 1999 as property of the energy company ENEL [45], in 2004 it was placed on the stock market and now the majority shareholder is Cassa Depositi e Prestiti [46].

Distribution System Operator (DSO)

The DSOs represent the set of companies operating in the distribution of electricity, linking each user to the transmission line, working on the medium and low voltage line. In Italy, until the nineties, the electricity distribution system was managed under a monopoly regime by the company "ENEL" [47]. Subsequently, with a liberalization and privatization policy, several DSOs manage the distribution services, buying the energy on the national electricity market and reselling it to their customers/users in real-time [45].

Energy Services Manager (GSE)

The so called "*Gestore dei Servizi Energetici*", or GSE, is a society controlled by the Italian Ministry of Economy and Finance, which carries out its work following the indications of the Ministry of Ecological Transition. The GSE society was founded in 1999, as an effect of the liberalization of energy markets [48]. Nowadays the GSE plays a central role in encouraging and developing renewable energy sources in Italy. The company is also responsible for implementing the mechanisms for promoting energy efficiency. In addition to the direct management of technical and energy aspects, GSE supports institutions for the implementation of energy policies and public administrations through the provision of specialist services in the energy field [49].

Energy Markets Manager (GME)

The italian Energy Markets Manager is called "*Gestore dei Mercati Energetici*"; It is a company controlled by the GSE, founded in its current form in 2004. GME is the company responsible for the organization and management of the electricity market, as well as for ensuring the economic management of adequate availability of the power reserve [50].

Borsa elettrica

It is an organized system of offers, sales, and purchases of electricity introduced in 2004 to achieve market liberalization. This system is managed by the Energy Markets Manager and collects the operations necessary to carry out the Spot electricity market [50].

2.4.2 Energy trading market

The Italian energy market, as we know it, was born in 1999 with the introduction of the legislative decree of 16 March 1999, n. 79, also known as the Bersani decree, as part of the process of receiving the EU directive on the creation of an internal energy market (96/92 / EC). The new approach to the market was implemented to promote competition in energy production and energy selling sectors, with the creation of a trading area. In 2003, the "*Testo integrato della disciplina del mercato elettrico*" was approved and published with the decree of 19 December 2003 [51]. This text updates and collects the legislation necessary for the management of the electricity market.

The Energy trading market allows wholesalers, producers, and consumers to enter into hourly contracts for the purchase and sale of electricity. The entire market is divided into two types known as Spot electricity market and Forward electricity market [52].

Spot electricity market

This type of market, in Italian called “Mercato elettrico a pronti” or MPE, is closely linked to the "Borsa elettrica". Here each operator is confronted with the market itself and not with another natural person. In this way, the purchase and sale of energy are carried out using bargaining on an hourly basis where the meeting between supply and demand is carried out through the system of the marginal price.

Article 21 of the decree of 19 December 2003 divide MPE in four submarkets [53]:

- Day Ahead Market, in Italian *Mercato del giorno prima* or MGP;
- Intraday market, in Italian *Mercato infragiornaliero* or MI;
- Daily Products Market, in Italian *Mercato dei prodotti giornalieri* or MPEG;
- Dispatching service market, in Italian *Mercato del servizio di dispacciamento* or MSD

The **Day-Aheadend-users Market** (MGP) allows producers, wholesalers, and end customers to sell or buy blocks of electricity for the next day. The operators participate by submitting offers in which they indicate the quantity and the maximum or minimum price at which they are willing to buy or sell. The negotiations on the MGP take place before 12:00 on the day before the energy is delivered and the results are reported before 12:58.

The **Intraday Market** (MI) aims to make changes to the programs defined in the MGP through additional purchase or sale offers. The negotiations on the MI take place through several sessions between 12:55 on the day before the energy delivery and one hour before the start of each relevant period.

The **Daily Products Market** object is the continuous negotiation of energy. The negotiations can take place through sales and purchase offers based either on the "full unit price" or on the "unit price differential", that is the difference between the unit price and the average value recorded over a given period. The exchange can take place in several sessions relating to each delivery day, between 8:00 two days before the energy delivery, and 17:00 two days before the energy delivery.

The **Dispatching Service Market** (MSD) has as its object the procurement of the resources necessary for the management and control of the system, such as the resolution of intrazonal congestion, creation of the energy reserve, balancing in real-time. In this market, Terna acts as a central counterparty.

Forward electricity market

This market is also called MTE, from the Italian "*Mercato elettrico a termine*". In MTE operators buy and sell forward electricity contracts with delivery obligations. In this market, trading operations are aimed at reaching a bilateral agreement between two operators and take place under the control of GME. In this type of market, energy supply contracts for relatively long periods are negotiable, with a delivery period equal to the calendar month, quarter, and year [54].

Ancillary services

Ancillary services are the services necessary to ensure the safety and proper functioning of the entire electricity system. The method mainly used to obtain and manage ancillary services is represented by bargaining in the aforementioned dispatching service market (MSD), which allows them to be purchased in real-time.

These services can be divided into global ancillary services if necessary for the operation of the electricity transmission system, and into local ancillary services if necessary for the operation of the distribution networks only [55].

Providing ancillary services means changing your inputs or withdrawals in real-time, to meet the needs of the TSO who must ensure, for every moment, the balance between supply and demand of electricity on the grid. For this purpose, this type of service can be provided by both production and consumption of energy, therefore two figures can be distinguished [56]:

a) **Consumption unit**: a set of installations for the consumption of electricity connected to an electricity network, so that the withdrawal of electricity is used for a single-use or production purpose;

b) **Production unit**: a set of one or more generation groups powered by the same source, connected to an electricity network, and managed by a single entity.

The main ancillary services that can be provided are listed below:

- Reserve

  - Primary reserve
  - Secondary reserve
  - Tertiary reserve
- Balancing
- Resolution of electrical congestion
- Voltage regulation
- Emergency services
- Interruptibility of the load

2.4.3 Retail energy market

As for the Energy trading market, 1999 was a year marked by a great change, with the introduction of the already mentioned legislative decree of 16 March 1999, n. 79 or "*Decreto Bersani*" [45]. The objective of this retail market decree is to implement the free market, as from the European directive 96/92/CE. The liberalization of the market should have eliminated the state monopoly on the control of energy dispatching, known as the "enhanced protection market", but today these two forms of the market still coexist together.

Enhanced protection market

This type of market, in Italian called "*Mercato a maggior tutela*", represents the old concept of the energy market. In this market the Regulatory Authority for Energy, Networks and the Environment (ARERA) defines both energy price and the contractual conditions, updating the price every three months. For each geographical area, the enhanced protection service is committed to an operator, generally of the same corporate group as the local distributor. This service was supposed to end with the arrival of the free market, but its closure has been postponed several times. The decree n. 108 of 21 September 2018 [57]moved its closure to 2020, a date that was further moved to 2022 for individuals and 2021 for companies.

The enhanced protection market was maintained for micro-enterprises with power below 15 kW and for private citizens. The overcoming of the price protection is set on 1 January 2023 for companies, while for families it is expected by 10 January 2024. The "gradual protection service" will then be assigned to domestic customers who at that time have not yet chosen a free market supplier, ensuring the continuity of the electricity supply [58]. Small and micro-enterprises for which price protection is to be removed are automatically transferred to the so-called "gradual protection market". To ensure their electrical continuity, this market entered into service on 1st January 2021 and automatically assimilated two categories of companies. The first one is represented by small businesses with a number of employees between 10 and 50, and annual revenue between 2 million and 10 million euros, which own only low voltage connection points. The second includes micro-enterprises with fewer than 10 employees and an annual revenue of no more than 2 million euros, owners of a connection with a contractual power greater than 15 kW. On the other hand, micro-enterprises with a power lower than 15kW can remain in the market for greater protection until its complete closure. The Gradual Protection Service is provided by sellers selected by through specific bankruptcy procedures in order to obtain favorable agreements for consumers [59].

Free market

The free market, in Italian known as “Mercato libero”, was introduced in 1999 [45] to stimulate competitiveness in energy trading. This market is composed of several private energy companies, free to choose their energy price and contractual conditions [60].

These companies are competing with each other to get a greater number of users; to increase their customer portfolio, all the companies are pushed to decrease their energy prices or offer additional services. To date, some companies aim to attract young customers and therefore provide services completely provided online with the possibility of controlling their consumption and managing the contract simply from the smartphone. To exploit the thrust of the ecological transition and sustainable mobility, other companies can create favorable contracts for owners of electric cars, perhaps with the supply of charging systems to be installed at home.

To ensure compliance with the rules and consumer protection, even in this market ARERA and the antitrust act as controllers with a supervisory system.

2.4.4 Energy communities and self-consumer as market players

As already stated in previous chapters, the main purpose of energy communities and self-consumers is to increase the energy welfare of players and reduce energy procurement costs. However, these subjects can try to earn money from the sale of unused electricity. The following are the main mechanisms that make possible a market system that sees the prosumer or the energy community act as a peer. The term peer indicates that these players are generally private or small-sized companies that are not professionals in the field of energy production.

Peer to X

The peer to x category, also called P2X, is the most conventional and already widely used exchange systems category. It includes all the situations in which the peer acts as a seller while the buyer is a different figure. Depending on the type of service offered and its management system, the P2X market can be divided into different categories described as follows [41].

Peer to System

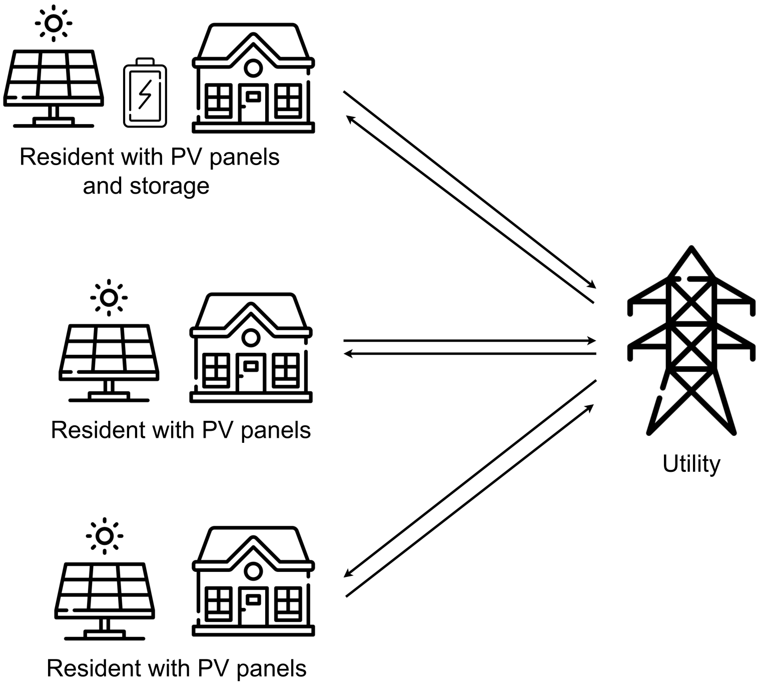

Figure 2.4.1: Representation of the peer to system electricity exchange.

This first exchange system represents the most classic and used energy sales system by a peer. In a very simple way, the owner of an energy production system that does not consume the entire produced energy injects in the electricity grid the fraction of energy not instantly consumed. The energy sold to the system will be paid at a price already agreed upon previously and that generally does not undergo variation for several years. The advantage of this system is its simplicity and the complete absence of constraints for the seller, it is therefore usable both by energy communities and simple self-consumers. Against this, working with a fixed energy price will be relatively low. On the other hand, working with a fixed price, the gain of the seller is usually low. Figure 2.4.1 provides a graphic representation of the energy exchange system between the various private individuals and the public electricity system. As shown with the arrows, each subject interacts only with the electricity grid, receiving and supplying energy to it.

Peer to System with Integrator

When several small prosumers want to act in the energy market, it may be convenient for them to work together to increase the electricity input capacity. In this case, the figure of the aggregator (see chapter 2.3.1 on page 25) who coordinates the various prosumers by grouping them may be necessary. Figure 2.4.2 provides a graphical representation of the interaction between individuals and the system when an aggregator is located between them. The aggregator collects the energy flows of private individuals and injects them into the electricity grid as a single flow. Considering the heterogeneity of the energy production systems and the possibility of the presence of storage systems, it may be necessary to implement integrated management of the system. In this case, the aggregator, in addition to the energy sale to the system, also takes care of the energy management

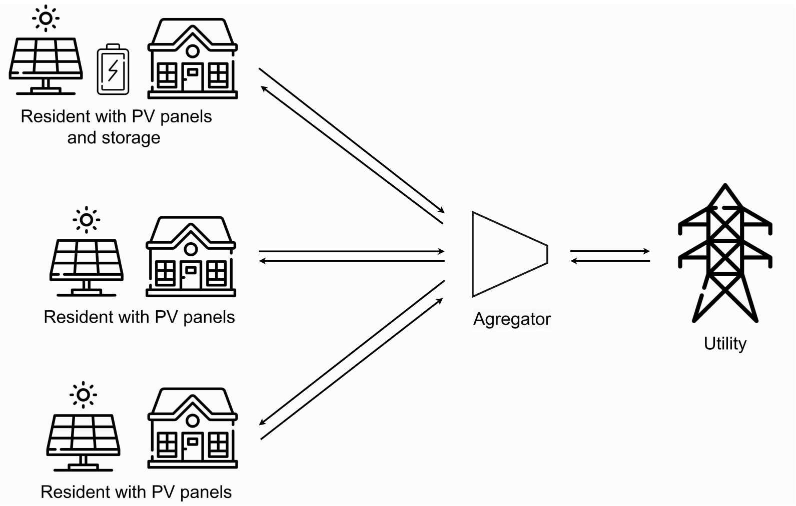

Figure 2.4.2: Representation of the peer to system electricity exchange with integrator.

of the members. This more advanced and complex figure can be defined as an integrator. The integrator's goal will be to maximize the energy efficiency of the prosumers under his control and increase their ability to feed energy into the grid to increase economic revenues.

Peer to Grid

Unlike the peer to system market, in the peer to grid market, the exchanged utility is no longer a simple energy injection but a specific energy injection able to provide a necessary grid service. These types of services are called ancillary services and are needed to make periodic corrections to the network for its correct operation (see chapter 2.4.2 on page 30). The request for the provision of ancillary services is the responsibility of the DSO which, when necessary, requests players to provide a certain service. Given the aleatoric nature of these services and the variation in their price about the market price of energy, their sale takes place on special informatic platforms at variable prices.

Peer to EV

This point is added to the list to provide the reader with information on a possible future trend.

Electric vehicles have become the target for the future of the private and public transport sector. These vehicles, to date, are equipped with large batteries that allow them to accumulate the considerable capacity of electricity necessary to have autonomy for many kilometers. Therefore, considering an electric vehicle that moves from point A to point B throughout the day, it can be seen as a storage system that allows you to sell, store and consume an energy reserve over time and space. A practical example could be a company equipped with a PV system and charging stations which acts as sellers during the day, recharging the cars of its employees. At the end of the day, employees could go home and use the energy stored in the car to meet the needs of their home. In this way, a new energy exchange paradigm could take hold, which no longer uses the electricity grid as an energy vector.

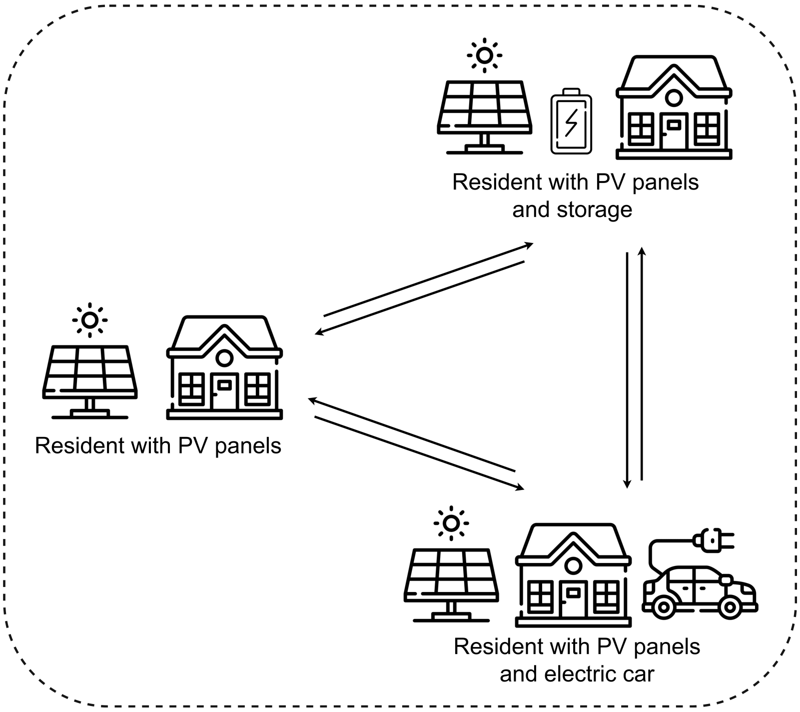

Figure 2.4.3: Representation of the peer to peer in a sandbox.

Peer to Peer and virtual communities

A different format of energy trading is the direct exchange between private individuals, the so-called Peer to Peer or P2P. This exchange model was born following the increase in the sharing of distributed electricity production systems connected to distribution networks. At the European level, the exchange of energy based on a Peer to Peer model has not yet become a concrete reality [41].

P2P in sandboxes

The basic form of energy trading between individuals is P2P in sandboxes. A sandbox is defined as a space of limited size such as an apartment building or neighborhood in which some of the rules that usually apply to the production, transmission, distribution, and supply of electricity are temporarily suspended. In this basic form, one prosumer acts as a seller and another prosumer or consumer acts as a buyer. As shown in the figure 2.4.3, the fundamental point of this system is the direct exchange of electricity between the parties, which implies proximity between producer and consumer.

P2P with platform

The P2P exchange model involves the use of a telematics platform that takes the shape of an online market, in which private individuals can carry out the purchase and sale of energy. In this way, after registering on the platform, a single buyer can purchase the energy sold by a private seller, without the presence of an intermediary or an aggregator. Even in this case the buyer will

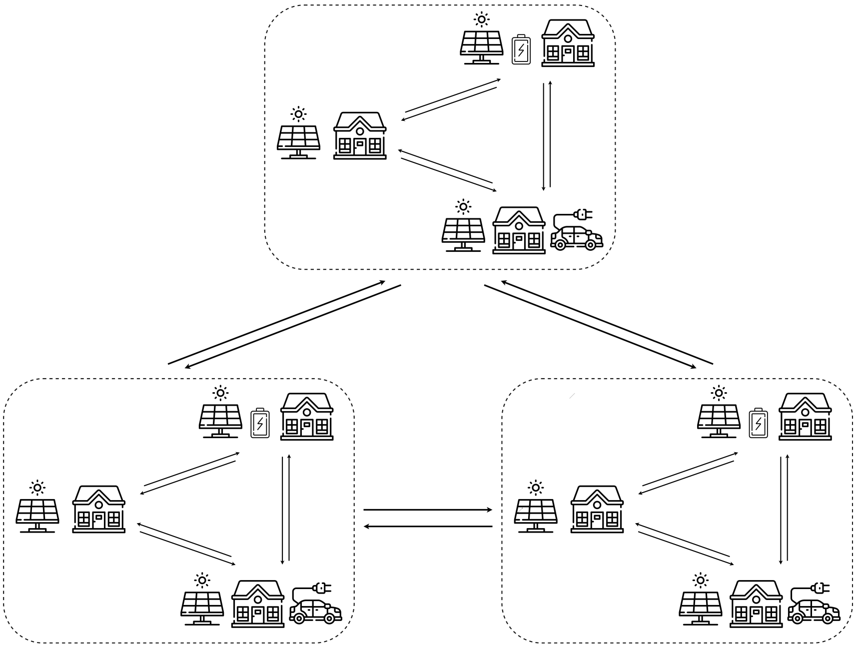

Figure 2.4.4: Representation of the exchanges of electricity between communities.

be represented by a consumer while the seller will be an energy producer. Only in recent years some pilot projects started, with the creation of platforms for the exchange of energy at the local level in Germany and the Netherland [41]. However, the European community is working on a platform called SHAR-Q [61], which allows the exchange of energy in a virtual way between private individuals in different European countries. Further, the use of these platforms could include the exchange of ancillary services such as the balancing system. The use of virtual exchange platforms allows the P2P system not to suffer from geographical constraints and not to require the necessary proximity between the producer and the consumer, which is the base principle of conventional energy communities. This is made possible by the use of the public transmission system, which allows creating a sort of virtual energy community between the various individuals who are carrying out an energy exchange. In this way, the exchange between private individuals is facilitated, but the concept of proximity and its benefits are lost.

P2P in communities

The P2P exchange model can be implemented between individuals, as defined above, but it could also be implemented between different communities. In the latter case, the energy sold would be the excess energy production of an energy community and the buyer would be another community that at that moment is unable to meet its energy needs, as shown in figure 2.4.4.

Chapter 3

Survey on energy communities: The Italian case

Contents

To deepen the knowledge of the energy communities in the Italian territory, a survey was carried out in this regard. The subjects to whom the survey was sent are the series of energy communities and self-consumption groups reported in the Legambiente report on “Comunità Rinnovabili” of 2021 [62]. A description of the data obtained from the interviews will be provided on the following pages. These data will also be discussed to provide useful information for future work on these issues. Since the regulatory framework is not yet complete and in force, the analyzed energy communities do not receive incentives and are not required to comply with regulatory constraints on energy communities.

3.1 Method

Starting from the aforementioned Legambiente document, the e-mail addresses of the various communities were searched. The initial number of communities taken into consideration is 47, all located in the Italian territory. Most of these communities have been built with the participation of the municipality concerned; therefore, most of the forms were sent to the technical offices of the various municipalities. Even considering municipalities or other interested entities, for 8 communities it was not possible to find a contact, or the contacts found were not working. The questionnaires were developed using the Google Forms platform, integrating multiple choice and open questions. The forms were sent using personalized e-mails to the individual addresses. Each e-mail contained the link to the questionnaire, a brief description of the questionnaire and why it was sent, and finally an attached PDF containing a copy of the questions. Even after three submissions of requests for compilation, the compilations obtained were 16, these replies are at the origin of the information shown below.

3.2 Locations

To begin the description of the situation, the geographical position of the sixteen communities for which the questionnaire was completed is provided. All energy communities are developed in a specific area, except the community called "Agricultural Energy at km 0" which extends into the agricultural areas of Veneto and Puglia. This is possible as the latter is made up of numerous agricultural realities coordinated by "Coldiretti", the association of Italian farmers. In the table 3.1 is the list of communities and their position in the table and even on the map to provide an easier visual explanation.

City	Province	City	Province
Rovigo	(RO)	Dobbiaco	(BZ)
San Martino di Lupari	(PD)	Bologna	(BO)
Pinerolo	(TO)	Perugia	(PG)
Chamois	(AO)	Serrenti	(SU)
Villar Pellice	(TO)	Prato	(PO)
Napoli	(NA)	Mafalda	(CB)
Ferla	(SR)	Paluzza	(UD)
Villanovaforru	(SU)	Veneto - Puglia	—

Table 3.1: Location of the interviewed.

3.3 Technical aspects

In this descriptive part, the data relating to the technical and numerical aspects of the communities, such as their size and the renewable sources used, are explained and discussed.

3.3.1 Technologies

Analyzing the technologies used for energy production within the communities, it is noted the presence of photovoltaic systems in fifteen of the sixteen communities analyzed. From the figure 3.3.1 we can also see the second most used renewable energy production method is solar thermal, which is used within four communities.
Subsequently, among the communities that do not apply solar thermal, three employ cogeneration systems for the simultaneous production of electricity and thermal energy. More in detail, two of them are powered by biogas while the third is powered by biomass. Finally, only one energy community uses wind turbines to produce electricity while another uses hydroelectric systems to extract energy from rivers.

As regards the production of thermal energy, four communities employ heat pumps powered, at least partially, by photovoltaic systems. It is interesting to note that three of these four communities also produce thermal energy through solar thermal systems. Considering the distribution of the thermal energy produced, four communities use district heating networks to distribute the heat to the various members. Moving the focus to electricity management, it emerged that four communities have implemented their own energy management by installing battery storage systems. Three of these systems are present in communities that produce electricity solely from photovoltaics, while the fourth is installed in the presence of photovoltaic, wind, and hydroelectric. To conclude, it is important to note how three communities have installed charging stations for electric cars, but only one of these has storage systems for the energy produced.

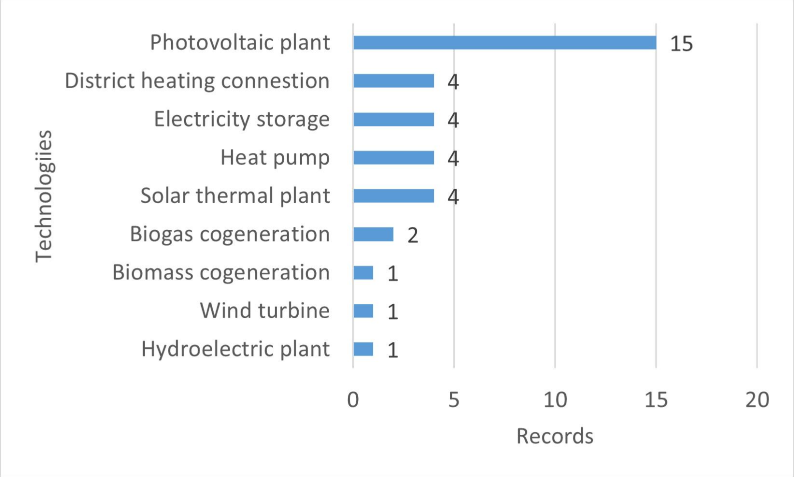

Figure 3.3.1: Number of energy communities applying each technology.

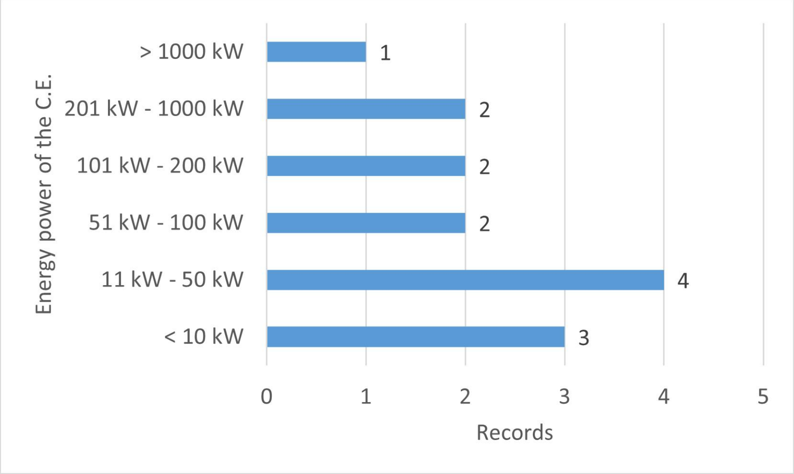

Figure 3.3.2: Number of communities for different electric power ranges.

3.3.2 Sizes

Analyzing the size of the communities, a certain heterogeneity can be seen. As can be seen from the figure 3.3.2, there are both small communities with power below 10 kW, and a community larger than 1000 kW. The power range that has the greatest presence is that of 11-50 kW, which records four communities out of a total of fourteen data collected.

As for the ability to meet their energy needs through the renewable energy produced, the energy communities interviewed declared different values between 20% and 90%. This demonstrates how the choice of the type of members, their number, and the technologies used can vary the level of self-consumption and independence of the community.

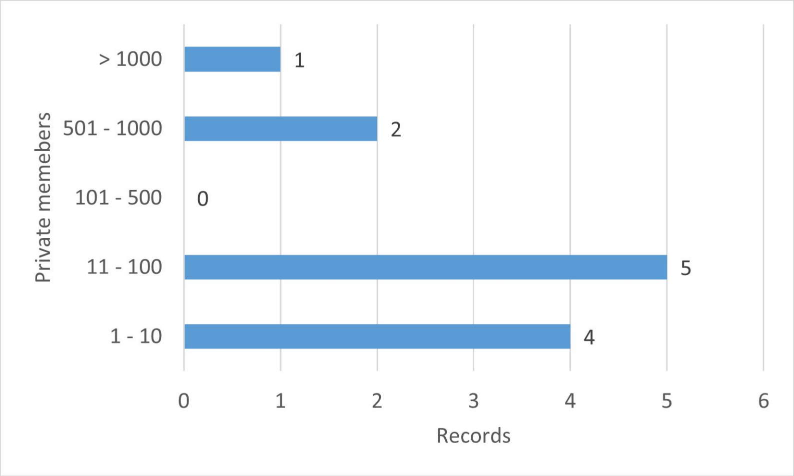

Figure 3.3.3: Number of communities for different private members ranges.

3.3.3 Members

For better use of the data provided in relation to the number of members of the energy communities, the members of the communities have been classified into two distinct categories. The first category is represented by private members, which include households or individual private users. The second instead is composed of the so-called other users, which include: private companies, companies, public offices, farms, etc. From the figure 3.3.3 relating to private members, most of the communities interviewed have less than one hundred private users. Only three communities have more than five hundred private members, with one over a thousand. The high value of the latter can be justified as it is represented as a single energy community, but it would be more correctly defined as an energy cooperative that distributes to the members the energy produced by some hydroelectric plants.

As can be seen from the figure 3.3.4 also observing the non-domestic members, most of the energy communities have a small number of users, which is typically less than ten. In this category, there is only one community with more than one hundred non-domestic members and two that exceed five hundred. These last two communities are particular cases: one is the cooperative, while the other is a set of different communities that group farms in two distinct Italian regions through the collaboration of local associations. Therefore, these two are not to be understood as energy communities by regulatory definition.

3.4 Administrative aspects

To provide useful insights, this second part analyzes the results relating to the administrative and financing aspects of the energy communities interviewed. Below are the different members, funders, and governance models employed.

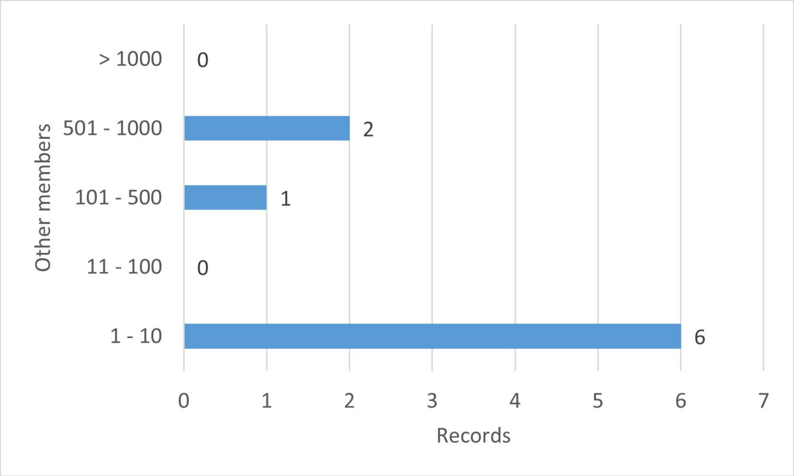

Figure 3.3.4: Number of communities for different non-domesti members ranges.

3.4.1 Components

The promoters, those who promote and implement the energy community (See chapter 2.3.1), have been identified in various categories. Each community has made explicit one or more promoters who have proved relevant in the realization of the community. The category that has proved most active in promoting energy communities is that of private companies (Figure 3.4.1). With seven records, it includes both companies that will participate as a member or prosumer, and energy distribution operators who will participate as managers of the energy aspects of the community. Subsequently, with six records, the participation of the individual municipalities affected by the community is sown as relevant. In general, two different cases can be distinguished: in the first case the municipality, together with others, is a normal promoter, while in the second case the municipality is the only promoter of the community. Generally, the municipality is the only promoter when it encourages the creation of an energy community to improve the economic situation of a specific residential building context, typically in a situation of energy poverty. Furthermore, the participation of citizens is not negligible. This category has collected four records proving itself as the third category for relevance. Finally, is interesting to highlight that once a university is indicated as a promoter, confirming the interest of research in this field.

The figure 3.4.2 shows who are the financiers who have repeatedly participated economically in the creation of energy communities. As seen for the promoters, even in the case of the financiers in the first place are the private companies with six records. This category again includes private entities and DSOs; if the former is motivated by economic savings, the latter will have an advantage in the management of the community. Subsequently, both with five records, there are municipalities and other public bodies (excluding regions and provinces); These two categories, together with the regions and provinces, demonstrate how important it is for public bodies to participate also financially in the formation of energy communities. In particular, the use of public funds reduces the cost of building the community, which can be a significant obstacle in their realization.

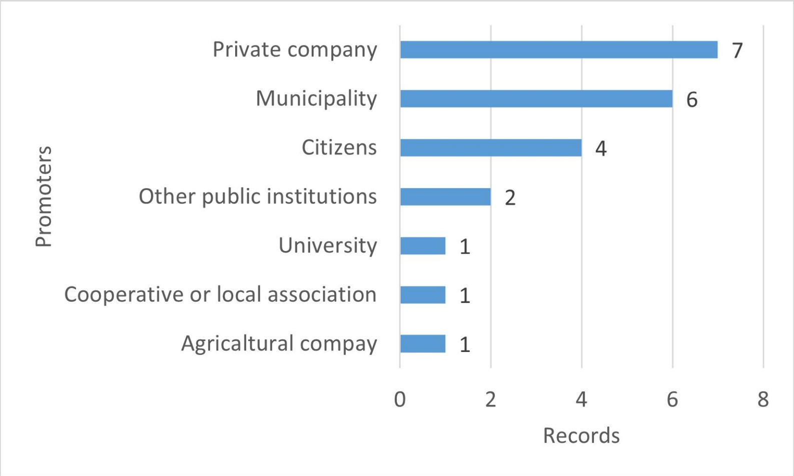

Figure 3.4.1: Number of communities for each type of promoter.

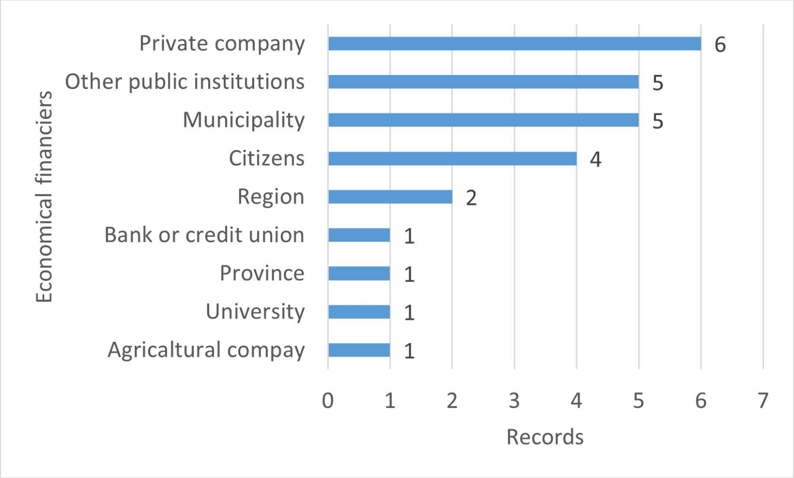

Figure 3.4.2: Number of communities for each type of economical financiers.

3.5 Strengths and weaknesses

The questionnaire submitted ends with questions relating to the weaknesses and strengths of the creation of the energy community. By analyzing the answers to the questions relating to the critical issues encountered in the community's implementation process, the long bureaucratic times of the processes necessary for the realization of the E.C. are repeatedly reported. In addition, the limited knowledge about energy communities, which keeps citizens away from this sector, has been limiting for the realization of some E.C.
From a technical point of view the biggest restriction was found in the limitation to the secondary booth, which significantly limits the number of members who can participate in the community. It is important to note that this limitation has been removed with the decree [21], which moves the limit from the secondary substation to the primary substation.

On the other hand, as regards the strengths and positive aspects found in the creation of communities, the presence of the municipality among the promoters has often explicitly facilitated the creation of various communities. In other cases, the presence of local associations that know future members and their needs has proved to be a key factor in their involvement. Finally, the case that saw a university participate in the study and creation of the community, found a contribution of knowledge fundamental to the success of the C.E.

Chapter 4

Energy community size optimization

Contents

This chapter studies the trend of the economic savings generated by the energy community as the number of members that make it up varies. This study is carried out with the final aim of determining if there is an optimal number of members for which it is no longer convenient to increase the dimension of the energy community.

The problem is addressed in several steps listed below. The initial part describes the member's energy consumption and their ability to produce and share renewable energy. Afterwards, the cost items in the cases with and without energy community are mathematically defined and processed. Finally. Graphs and numerical outcomes are then used for discussion of the results.

4.1 Model setup

The model describing the energy and economic aspects of an energy community is presented in this section. Starting from the energy demand, the equations and assumptions underlying the model that will be analyzed later are explained.

4.1.1 Household's energy demand

The annual energy demand of the entire community (d) at year t is considered constant for each $t \in (0, T)$ and normalized to 1 [63]. As shown in the equation 4.1.1, it is provided by the sum of each member's annual energy demand (d_i).

$$d = \sum_{i=1}^{n} d_i = 1 \tag{4.1.1}$$

The annual energy demand of the single member (d_i) is the sum of the different daily integrals of the hourly load curve $l_i(s)$ [63]. This sum is calculated in one year as explained in the equation 4.1.2.

$$d_i = \sum_{i=1}^{365} \int_0^{24} l_i(h)\, dh \tag{4.1.2}$$

From the point of view of the contributions satisfying the individual energy demand, equation 4.1.3 shows that it is filled by different factors.

$$d_i = \xi_i + b_i + \tilde{s}_{-i} + \gamma_i \tag{4.1.3}$$

The first contribution is represented by the total individual instant self-consumption (ξ_i), originating from the renewable energy produced by the member i and directly consumed by himself. The second factor is b_i, which represent the fraction of energy provided by the battery of the storage system. The third factor is $\tilde{s}_{-i}$, which represent the amount of renewable energy received

from the other members. The final fraction of energy demand is satisfied by energy purchasing from the grid, this energy fraction is represented with the factor γ_i.
Together, the instantaneous individual self-consumption of member i (ξ_i), the consumption of energy stored in the battery of member i (b_i) and the consumption of shared energy received by member i ($\tilde{s}_{-i}$) provide the total individual self-consumption (σ_i). In other words, σ_i represents the amount of energy consumed by member i that is obtained from the production of renewable energy. The σ_i concept is shown by the equation 4.1.4.

$$\begin{aligned} \sigma_i &= \xi_i + b_i + \tilde{s}_{-i} \\ d_i &= \sigma_i + \gamma_i \end{aligned} \tag{4.1.4}$$

According to this equation and the stochastic nature of photovoltaic energy, instantaneous individual self-consumption is less then total individual self-consumption ($\xi_i < \sigma_i$).

By assumption, the shared energy received by $i-th$ member from the other members ($\tilde{s}_{-i}$) is the same amount. Considering a number n of members taking part to the energy community, equation 4.1.5 expresses this concept providing the total shared energy (s).

$$s = \sum_{i=1}^{n} \tilde{s}_{-i} = n \cdot \tilde{s}_{-i} \tag{4.1.5}$$

Adding the total individual self-consumption (σ_i) of all members of the energy community the total self-consumption of the community (σ) can be determined. Equation 4.1.6 explains how, similarly to the individual case 4.1.4, even the total self-consumption of n individuals can be broken down into the overall instantaneously self-consumed energy (ξ), overall consumption of stored energy (b) and overall consumption of shared energy (s). By expanding the concept expressed above in the individual case, even observing at the community level the overall self-consumed energy instantaneously is lower than the total self-consumed energy ($\xi < \sigma$).

$$\sigma = \sum_{i=1}^{n} \sigma_i = \xi + b + s \tag{4.1.6}$$

It is important to highlight that the total self-consumption of n individuals (σ) is different from the total amount of renewable energy produced within the energy community, which i define as a. In other words a represents the annual PV-capacity normalized to fit the assumption $d = 1$, while σ represents the amount of renewable energy truly self-consumed by the members. It is therefore considered that the total individual self-consumption of n members is lower than the renewable energy produced internally at the energy community ($\sigma < a$). This is due to several inefficiencies present in the energy community overall system; these inefficiencies may be due to the charging efficiency of the storage system and its saturation.

Now, back to the total energy demand of n individuals, equation 4.1.4 can be substituted into equation 4.1.1. In this way, the equation 4.1.7 is obtained, explaining that the energy demand of

n individuals (d) is satisfied through the sum of the total self-consumption of n members (σ) and the purchase of energy from the grid of n members (γ).

$$d = \sum_{i=1}^{n} [\sigma_i + \gamma_i] = \sigma + \gamma \tag{4.1.7}$$

As explained above[1], also in this case the self-consumption of n members is lower then the energy demand of n members ($\sigma < d$)[2].

Upgrading equation 4.1.7 with the definition of sigma represented by equation 4.1.6, I obtain the equation 4.1.8. Total demand consumed by n individuals (d) is composed of the energy instantaneously consumed by n individuals (ξ), the energy stored into the battery system and consumed from n individuals (b), the energy shared by n individuals (s) and the energy purchase from the grid by n individuals (γ).

$$d = \xi + b + s + \gamma = 1 \tag{4.1.8}$$

The equations found above and their elements are the basis for the formulation of the models and their study.

4.1.2 Battery energy storage

By assumption, the storage is considered as a single shared battery system, collecting the energy not instantly consumed by the members who produce it. After storing it in a shared battery, it makes the energy available to other members. As described in the section 4.1.1 the storage of energy through batteries does not allow to reach a full efficiency due to two factors: because the battery has a specific charge and discharge efficiency; moreover, once the full capacity of the battery has been filled, it is no longer possible to accumulate energy inside of it. Therefore, the coefficient of performance $\eta < 1$ is introduced to fill these inefficiencies.

4.1.3 Sale of photovoltaic energy

In some moments of the day, typically during the summer period, it may happen that the amount of energy produced by the photovoltaic systems is greater than the energy consumed by the energy community at that time. The excess energy is shared or stored in the batteries, but once batteries reach their saturation and members are not consuming enough energy, if the overproduction persists, the excess energy is sold to the electricity grid. The amount of sold energy is calculated as the photovoltaic production (a) minus the instantaneous self-consumption

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[1] In the individual case ($d_i = \sigma_i + \gamma_i$) is explained that $\sigma_i < d_i$ due to the unpredictability of the production of renewable energy

[2] The equation $\sigma < d$ can also be read as $\sigma < 1$

(ξ), minus the energy sharing (s) and minus the amount of energy stored in the battery (b) divided by the storage efficiency (η). Equation 4.1.9 shows how the revenue obtained from the sale of the excess energy per year t ($R^{sale,t}$) is obtained by multiplying a sale price (p^s) by the amount of renewable energy produced but not used just explained.

$$R^{sale,t} = p^s \cdot (a - \xi - \frac{b}{\eta} - s) \tag{4.1.9}$$

Starting from the previous equation, the revenue obtained from the sale of excess energy in T-years can be obtained by adding the revenue faced in T years as shown by equation 4.1.10.

$$R^{sale} = \sum_{i=1}^{T} [p^s \cdot (a - \xi - \frac{b}{\eta} - s)] \tag{4.1.10}$$

4.1.4 Economic incentives

Economic incentives are a sum of money released to the energy community in relation to the amount of overall shared energy. As discussed in the section 2.1.4, in the case of renewable energy communities, the incentives are calculated as an economic compensation for each kWh of renewable energy exchanged between the various members [28]. Equation 4.1.12 shows how the annual amount of the incentives received by the energy community (in^t) can be obtained by multiplying the unitary self-consumption incentive (ι) by the sum of the shared energy within the E.C (s).

$$in^t = \iota \cdot s \tag{4.1.11}$$

By adding the equation 4.1.11 in the considered years (T), the equation 4.1.12 is easily obtained. This equation represents the economic incentives obtained over the years T.

$$in = \sum_{i=1}^{T} [\iota \cdot s] \tag{4.1.12}$$

4.1.5 Investment cost functions

As the complete system is made up of a photovoltaic plant and a storage facility, the investment costs can also be divided into two items.
According to the most recent literature, the investment costs related to the photovoltaic system are considered as a positive linear function with respect to the PV-capacity (a)[63].

$$I^{PV} = k_1 \cdot (\frac{a}{\alpha})^q \tag{4.1.13}$$

Equation 4.1.13 is composed of the term $k_1 > 0$, which is a dimensional parameter related to the production cost of renewable energy over the unit of time. This term is multiplied by the photovoltaic annual average production (a). The term a is divided by $\alpha > 1$ and then the ratio is raised through the factors $q > 1$, which give a concave trend to the energy demand.
The investment cost related to the storage system are described by the equation 4.1.14.

$$I^S = k_2 \cdot (\frac{b}{\eta \cdot \alpha})^q \tag{4.1.14}$$

This equation multiplies the energy storage cost dimensional coefficient $k_2 > 0$ by the amount of energy stored into the battery (b) corrected with the factors $\eta < 1$ and $\alpha > 1$. Also in the case the factor $q > 1$ is present.

Both the obtainment of k_1 and k_2 are discussed in the chapter 4.3.1

4.1.6 Price of grid-purchased energy

The price of the grid-purchased energy in year t (p^t) is obtained starting from the initial price (p_0), applying the rate of change in the price of energy represented by the constant $\mu > 0$. Through the function 4.1.15 a linear increasing of energy price is obtained.

$$p^t = p_0 \cdot (1 + \mu)^t \tag{4.1.15}$$

4.1.7 Discount rate

The members of the energy community are recognized as residential users, therefore they can be considered price-takers and subject to the discount rate r. To ensure the convergence of the discounting functions (which see both the presence of r and μ) it is also necessary that the relation $r > \mu$ be satisfied. Only in this case the ratio $\frac{(1+\mu)^t}{(1+r)^t}$ can decrease as t increase.

4.2 Investment value and optimal EC size

Starting from the framework in the previous sections, this section models the value of the investment of the E.C. in order to define and maximize the economic savings generated.

4.2.1 Operative costs

The operating costs faced by the energy community are made up of the management costs of the shared energy. Energy management costs consider the payment to the energy manager of an economic amount related to the fraction of shared energy (s). The management cost is calculated considering an hypothetical management price k_0[3] paid for each unit of managed energy. From this points the equation 4.2.1 is obtained as the multiplication of shared energy (s) and management price (k_0), which represents the annual operating costs related to the energy management defined as C_t^{MA}.

$$C_t^{MA} = k_0 \cdot s \tag{4.2.1}$$

Starting from the previous equation, the equation 4.2.2 can be obtained by discounting the costs faced in T years.

$$C^{MA} = \sum_{i=1}^{T}[\frac{1}{(1+r)^t} \cdot k_0 \cdot s] \tag{4.2.2}$$

4.2.2 Investment value

As already widely discussed, the main advantage provided to the energy community is economic saving. This saving is calculated as the difference between the costs faced over a time span T [4] between a model before E.C. and a situation where the E.C. is present.

Situation without E.C.

With the absence of the energy community, the costs are only linked to the purchase of energy. According to the hypothesis of equal annual energy demand among the different members, the annual energy demand of n members is represented by d. This value must then be multiplied by the price of the year t (p^t) obtained through the equation 4.1.15 and discounted through the discount rate (r). Finally, the annual costs are added together in a summation from year 1 to T. In this way the equation 4.2.3 is obtained, which allows to calculate the cost in the case of absence of E.C.

$$C^{NC} = \sum_{t=1}^{T}[\frac{(1+\mu)^t}{(1+r)^t} \cdot p_o \cdot d] \tag{4.2.3}$$

Situation with E.C.

Moving on to analyze the costs in the case of energy community, they are given by the sum of investment costs 4.1.5, discounted operating costs 4.2.1 and energy purchase[5]. These costs must be reduced considering the revenue generated by the sale of the energy surplus 4.1.10 and the

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[3] To give an idea of the dimension k_0, it is initially assumed to be equal to $p_0 \cdot 0.1$

[4] Time horizon T generally set 25 years to consider the useful life of the systems.

[5] In functions 4.2.4 e 4.2.6 the cost of purchasing energy is indicated as E^P.

incentives received 4.1.12. The discounted costs incurred over time from 1 to T by the E.C. are therefore defined by equation 4.2.4.

$$C^{EC} = I^{PV} + I^{S} + C^{MA} + E^{P} - R^{sale} - in$$

$$\begin{aligned} C^{CE} = {} & k_1 \cdot (\frac{a}{\alpha})^q + k_2 \cdot (\frac{b}{\eta \cdot \alpha})^q + \sum_{i=1}^{T} [\frac{1}{(1+r)^t} \cdot k_0 \cdot s] \\ & + \sum_{t=1}^{T} [\frac{(1+\mu)^t}{(1+r)^t} \cdot p_o \cdot \gamma] - \sum_{i=1}^{T} [p^s \cdot (a - \xi - b/\eta - s)] \\ & - \sum_{i=1}^{T} [\iota \cdot s] \end{aligned}$$

$$\begin{aligned} C^{CE} = {} & k_1 \cdot (\frac{a}{\alpha})^q + k_2 \cdot (\frac{b}{\eta \cdot \alpha})^q + \sum_{i=1}^{T} [\frac{1}{(1+r)^t} \cdot ((k_0 \cdot s) + \\ & + ((1+\mu)^t \cdot p_o \cdot \gamma) - p^s \cdot (a - \xi - b/\eta - s) - \iota \cdot s] \end{aligned} \tag{4.2.4}$$

Costs saving

The net present value of the investment of the E.C. it is represented by the cost saving generated in the T period. This value is obtained from the difference between the cost function in case of absence of energy community (shown in equation 4.2.3) and the cost function with the presence of energy community (shown in equation 4.2.4). The resulting formula is reported in equation 4.2.5 and more detailed in equation 4.2.6:

$$NPV = C^{NC} - \{\, I^{PV} + I^{S} + C^{MA} + E^{P} - R^{sale} - in \,\} \tag{4.2.5}$$

$$\begin{aligned} NPV = {} & \sum_{t=1}^{T} [\frac{(1+\mu)^t}{(1+r)^t} \cdot p_o \cdot d] + \\ & - \Bigg[k_1 \cdot (\frac{a}{\alpha})^q + k_2 \cdot (\frac{b}{\eta \cdot \alpha})^q + \\ & + \sum_{i=1}^{T} [\frac{1}{(1+r)^t} \cdot ((k_0 \cdot s) + ((1+\mu)^t \cdot p_o \cdot \gamma) - p^s \cdot (a - \xi - b/\eta - s)] + \\ & - \iota \cdot s \Bigg] \end{aligned} \tag{4.2.6}$$

As can be seen, equation 4.2.6 is made up of two terms. The term in the first line represents the expenditure for the purchase of energy in the case of energy community absence. The other lines compose the second term, which represents the energy community case, characterized by investment costs, operating costs, energy purchase and energy selling.

4.3 Calibration

As discussed in the introduction to this section, the model expressed by this paper represents a residential energy community. Therefore, values in line with this assumption were searched. This chapter explains how the values used in the processing were obtained and the study relating to their refinement.

4.3.1 Investment cost

As already mentioned in chapter 4.1.5, the investment costs are composed by two different part: the costs related to the storage system and the costs related to the photovoltaic plants. Both of them are calculated through some dimensional parameters, these parameters are discussed below.

Photovoltaic plants cost parameters

The calculation of LCOE is given by the literature as expressed in the function 4.3.1 [64]. The term $C(t)$ represents the net costs, which include the initial investment, operating and maintenance costs and insurance costs. $LCOE(t)$ represents the costs expressed in $€/MWh$ while $E(t)$ is the annual production of electricity. $E(t)$ is the energy produced at year zero, called S, multiplied by a degradation factor e^{dt} which decreases the energy produced over time.

$$\begin{gathered}\int_0^T C(t)e^{-rt}\,dt = \int_0^T LCOE(t)\cdot E(t)\cdot e^{-rt}\,dt \\ E(t) = S\cdot e^{-g\cdot t}\end{gathered} \tag{4.3.1}$$

Considering that the LCOE found in literature already assume an internal degradation factor, a coefficient $g = 0$ is assumed. The coefficient k_1 will be unitary (considered in in terms of € per kWh) to be multiplied by a in the equation 4.1.13. Therefore, S can be set equal to $1kWh$.
The right part of the equation 4.3.1 can be integrated (assuming $g = 0$, $S = 1kWh$) to obtain the equation 4.3.2, which represents the investment cost per single kWh of renewable energy produced per year through k_1.

$$k_1 = \frac{LCOE}{r}\cdot(1 - e^{-d\cdot T}) \tag{4.3.2}$$

Parameter k_1 is elaborated by evaluating two different $LCOE$ and two different discount rates (r). From these elaborations the data reported in the table 4.1 are obtained [63].

In the same way as explained for $LCOE$ and K_1, $LCOS$ and k_2 can be processed trough the equation 4.3.3. Parameter k_2 is elaborated by evaluating two different $LCOS$ and two different discount rates (r). From these elaborations the data reported in the table 4.2 are obtained[63].

LCOE [€/kWh]	**T [years]**	**k_1**	
		r 4%	r 6%
0,090	25	1422	1165
0,110	25	1738	1424

Table 4.1: Table of vaules for k_1.

LCOS [€/kWh]	**T [years]**	**k_2**	
		r 4%	r 6%
0,290	25	4582	3756
0,315	25	4978	4078

Table 4.2: Table of vaules for k_2.

$$k_2 = \frac{LCOS}{r} \cdot (1 - e^{-r \cdot T}) \tag{4.3.3}$$

4.3.2 Energy price

The reference price of energy was obtained starting from the historical prices of the period 2011 - 2020 provided by ARERA [65]. This time frame was chosen to have relevant data but not influenced by the period 2021 - 2022 characterized by a high price alteration[6]. The average energy price observed is 18.85 c€/kWh, while the minimum price is 16.62 c€/kWh and the maximum price is 21.23 c€/kWh. Using a least squares regression of energy prices, a μ value of 0.0275 is obtained. This value represent an annual price increase of 2.751% during th period 2011 - 2020.

4.3.3 Self-consumption function

As already discussed in chapter 3, the percentage self-consumption function (σ) represents the fraction of energy consumed by the C.E. coming from renewable sources within the C.E. in relation to the total energy consumed in a year. The function σ representing self-consumption is imagined as a positive function of n, that is, it grows as the number of members n increases and the matching between energy supply and demand of the members increases. However, this increase is assumed to be of low significance after reaching a certain number of members; therefore, it is assumed that the curve representing the function σ tends to flatten after a certain number of members.
The data obtained from the survey shows that in the presence of energy communities with more than 20 - 30 members a level of self-consumption between 85% and 90% can be achieved. This

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[6] The same source shows an electricity price in the fourth quarter of 2022 equal to 66.01 c€/kWh

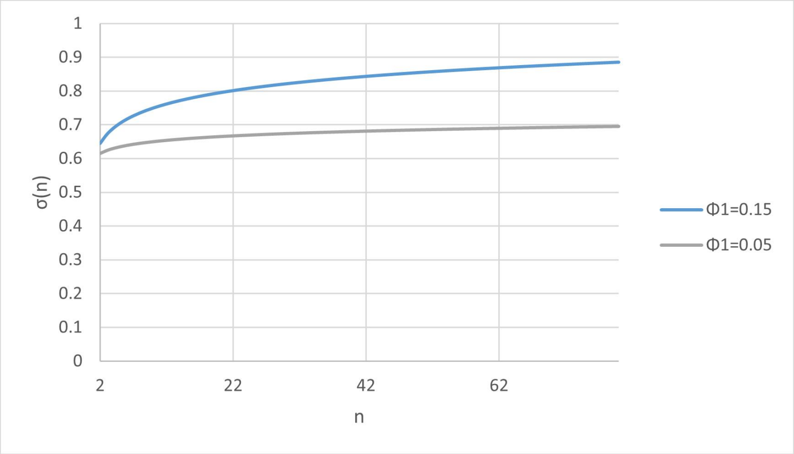

Figure 4.3.1: σ variation according to different ϕ_1 ($\phi_2 = 0.6$).

threshold therefore represents the maximum extreme of the σ function.

Starting from the above hypotheses, an increasing logarithmic function was assumed with the number of members n. To adhere to the levels of self-consumption reported above, two parameters called ϕ_1 and ϕ_2 have been included, which allow me to optimize the σ function in order to make it in line with the real trend. The equation thus obtained is the one shown by equation 4.3.4:

$$\sigma = \phi_1 \cdot \log_{10}(n) + \phi_2 \tag{4.3.4}$$

The parameters ϕ_1 and ϕ_2 represent the key part in the study of this function; therefore, the trend of σ with different values ϕ_1 and ϕ_2 has been examined. The variation of the σ function as these parameters change is presented below.

The first graph shows the variation of the function σ as ϕ_1 varies. Both plotted functions are obtained with ϕ_2 equal to 0.6 but, in the first case ϕ_1 is set equal to 0.15, while in the second case ϕ_1 is set equal to 0.05. From figure 4.3.2, it can be seen how a smaller ϕ_1 flattens the curve by reducing the increase in self-consumption obtained as the number of members (n) increases.

The second graph shows the variation of the function σ as ϕ_2 varies. Both plotted functions are obtained with ϕ_1 equal to 0.15 but, in the first case ϕ_2 is set equal to 0.60, while in the second case ϕ_2 is set equal to 0.50. From figure 4.3.2, it can be seen how the variation of ϕ_2 translates the curve vertically, reducing or increasing the percentage of self-consumption in a constant manner for each value of n.

The set of parameters that bring the function closest to the real situation is: ϕ_1=0.15 and ϕ_2=0.60. Therefore, the function σ used to carry out the simulations in the MATLAB environment is shown by the equation 4.3.5, producing a series of self-consumption values between 0.645 and 0.885.

$$\sigma = 0.15 \cdot \log_{10}(n) + 0.6 \tag{4.3.5}$$

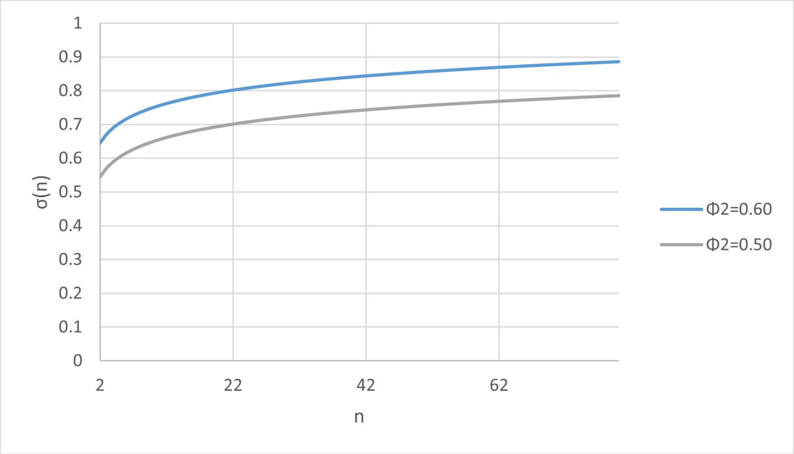

Figure 4.3.2: σ variation according to different ϕ_2 ($\phi_1 = 0.15$).

n	σ	**n**	σ
2	0.645	45	0.848
5	0.705	50	0.855
10	0.750	55	0.861
15	0.776	60	0.867
20	0.795	65	0.872
25	0.810	70	0.877
30	0.822	75	0.881
35	0.832	80	0.885
40	0.840		

Table 4.3: Values of σ obtained with$\phi_1 = 0.15$ and $\phi_2 = 0.60$

The complete series of self-consumption value is given in table 4.3 and graphically shown in figure 4.4.1.

4.4 Main results and comparative statics

Starting from the mathematical model discussed above, a study was conducted on the trend of costs and economic savings generated by an E.C. as the number of members varies. The values entered in the model, developed in the Matlab environment, are those obtained in the "Calibration" chapter, extended in some relevant ranges to study their influence.
In this section the data obtained from the processing are shown and discussed. All the simulations are developed with a time scale (T) equal to 25 years and maximum number of members (n^{max}) equal to 80 members. During the simulations parameters as $LCOE$ and $LCOS$ are changed, as a consequence the parameters k_1 and k_2 change. Then simulations are carried out with different

Symbol	Dimension	Value	Meaning	Source
$LCOE$	€/kWh	0.09	Levelized cost of energy	(Andreolli et al. 2022 [63])
$LCOS$	€/kWh	0.29	Levelized cost of storage	(Andreolli et al. 2022 [63]))
k_0	-	0.05	Management cost parameter	Our computation
k_1	-	1.165	PV production cost paramater	Our computation
k_2	-	3.756	Storage cost parameter	Our computation
P^0	€/kWh	0.1885	Energy purchase price	(ARERA 2022 [65])
P^s	€/kWh	0.1	Energy selling price	(ARERA 2022 [65])
r	-	0.06	Discount rate	(Andreolli et al. 2022 [63]))
μ	-	0.02	Annual anergy price increasing	Our computation
η	-	0.9	Battery efficiency	(Andreolli et al. 2022 [63]))
α	-	1.75	Initial cost correcting parameter	Our computation
q	-	1.05	Initial cost correcting esponent	Our computation
d_i	kWh/year	2700	Individual energy demand	(ARERA 2022 [65])
a_i	kWh/year	2916	Individual renewable production	(European commission 2022)
ξ	-	0.3	Percentual instant self-consumption	Our computation
b	-	0.3	Percentual battery storage	Our computation
T	years	25	Considered time	Our computation
n^{max}	-	80	Maximum number of members	Our computation
ι^c	€/kWh	0.1	Incentive per self-consumed energy	(Economic Dev. M. 2020) [28])
ι^s	€/kWh	0.11	Incentive per shared energy	(Economic Dev. M. 2020) [28])

Table 4.4: Input data used for the reference elaboration.

values of instantaneous self-consumption and accumulation in the batteries.

Reference simulation results

The reference simulation is obtained by using the parameters shown in the table 4.4. Figure 4.4.1 shows the percentage of self-consumption trend (σ normalized to 1) obtained by application of the function 4.3.5; this trend is used in all simulations, including the reference one. The self-consumption values start from $\sigma = 0.65$ for $n = 2$ up to $\sigma = 0.89$ for $n = 80$. From the figure it is easy to observe the logarithmic trend attenuated by the presence of ϕ_1=0.15 and ϕ_2=0.60 previously discussed.

By entering the data from the table 4.4 into the equation 4.2.4 and processing them for each n from 2 to 80, the figure 4.4.2 is obtained. This figure shows the trend of costs of the E.C. (C^{CE}) as the variation of n. These costs are calculated over a total of 25 years and consider initial costs(I^{PV}, I^S), management costs (C^{MA}), energy purchase (E^P), energy sale (R^{sale}) and the received incen-

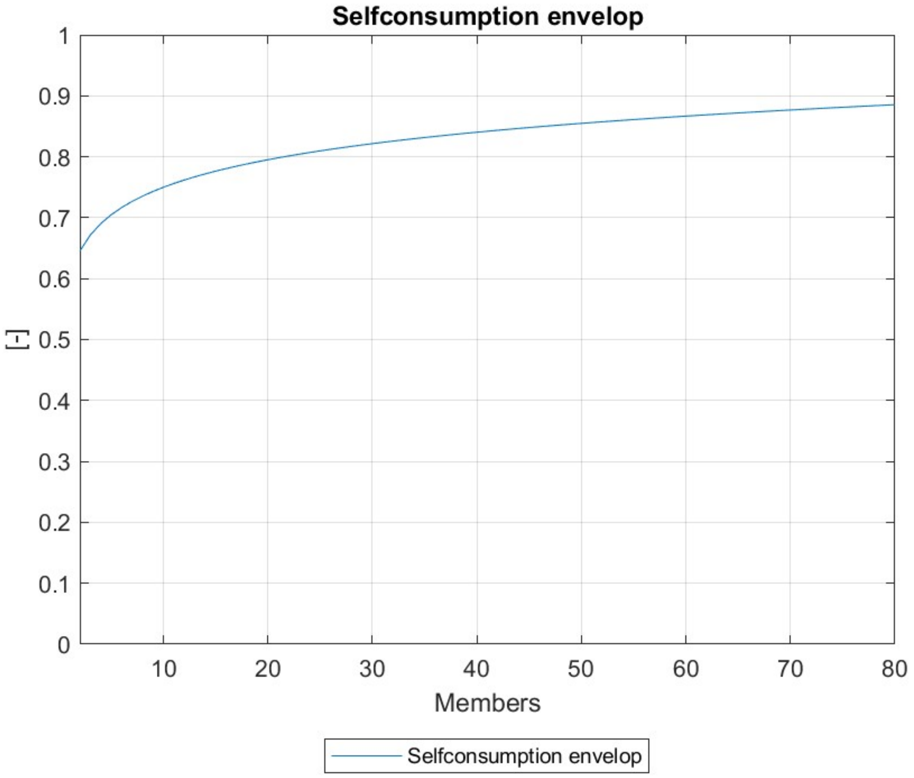

Figure 4.4.1: Trend of the percentage self-consumption function in relation to the number of members.

tives (in^c, in^s). From this figure it is difficult to observe the actual cost trend, as at the level of E.C. all cost items seem to grow almost linearly.

The aim of this thesis is to study the costs and savings trend at the individual member level; for this reason, and to better notice the cost variations, the aforementioned economic items, but on an individual level, are shown in the graph 4.4.3. This figure shows, as n varies, the initial costs, operating costs, revenues and incentives for individual member i. Thanks to this graph, the variations of the different items can be seen more easily. First of all, following the blue line, it can be seen that thanks to the presence of economic incentives and revenues from the sale of energy not consumed, individual costs are considerably reduced. In other words, the total costs are less than the sum of investment costs, management costs and energy purchase costs. As discussed in chapter 2.1.4, economic incentives are linked to energy sharing; for this reason the curve representing them grows with an increase of n as the percentage of energy exchanged increases. Increasing the exchange reduces the fraction of energy sold outside the community; therefore, the curve describing the revenue from the sale of energy has a decreasing trend. As a result of the assumptions made in this elaboration, the initial costs (or investment costs) show an increasing trend with n. These assumptions are mainly two: the fact that each new member is associated with an increase in the size of the photovoltaic system and the storage system and the non-linear

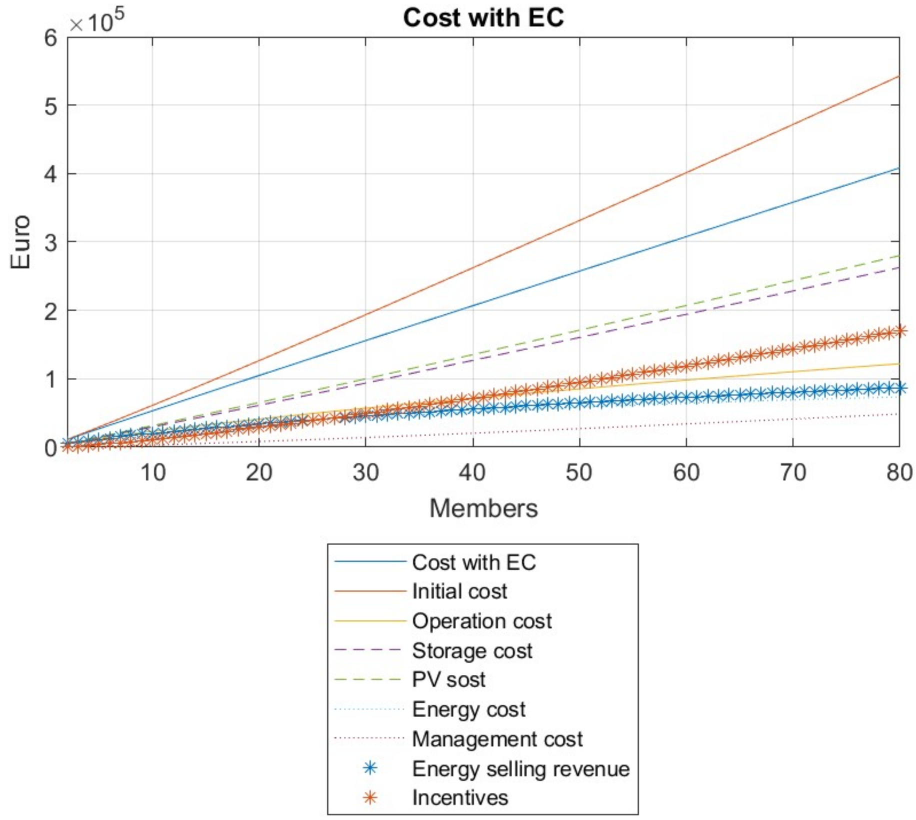

Figure 4.4.2: Costs trend of an EC related to the variation in the number of members.

model used to determine the investment costs. Finally, operating costs are shown decreasing since, as n increases, the decrease in energy purchase costs exceeds the increase in operating costs.

From the difference between the cost function in case of absence of E.C. (C^{NC}) and the cost function with the presence of E.C. (C^{CE}) the cost saving of the E.C. is obtained. As reported in chapter 4.2.2, the cost saving of the E.C. correspond to the net present value of the E.C. ($NPV(n)$). The mentioned cost saving and the costs in both the case with and without E.C. are shown in the figure 4.4.4. Moreover, for the same reason of the previous figures, the individual cost saving ($NPV(n)/n$) is printed in the figure 4.4.5. This figure highlights the flattening of the economic saving curve after a certain value of n.

In addition to individual cost savings, the concept of marginal individual cost savings is introduced. It represents increase in cost savings generated by the entry into the EC of $n-th$ member compared to the savings generated upon entry of the previous member[7]. In other terms the marginal individual saving for n is equal to $NPV(n)/n - NPV(n_{-1})/(n-1)$. The results of the mentioned elaboration are sown in figure 4.4.6. The trend in marginal savings shows how for the single member the entry of a new member into the E.C. always leads to an increase in savings, but this increase is reduced more and more until it becomes negligible (compared to initial increases) when the curve reaches an asymptotic behavior.

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[7] The marginal individual saving represent the derivative of the function $NPV(n)/n$

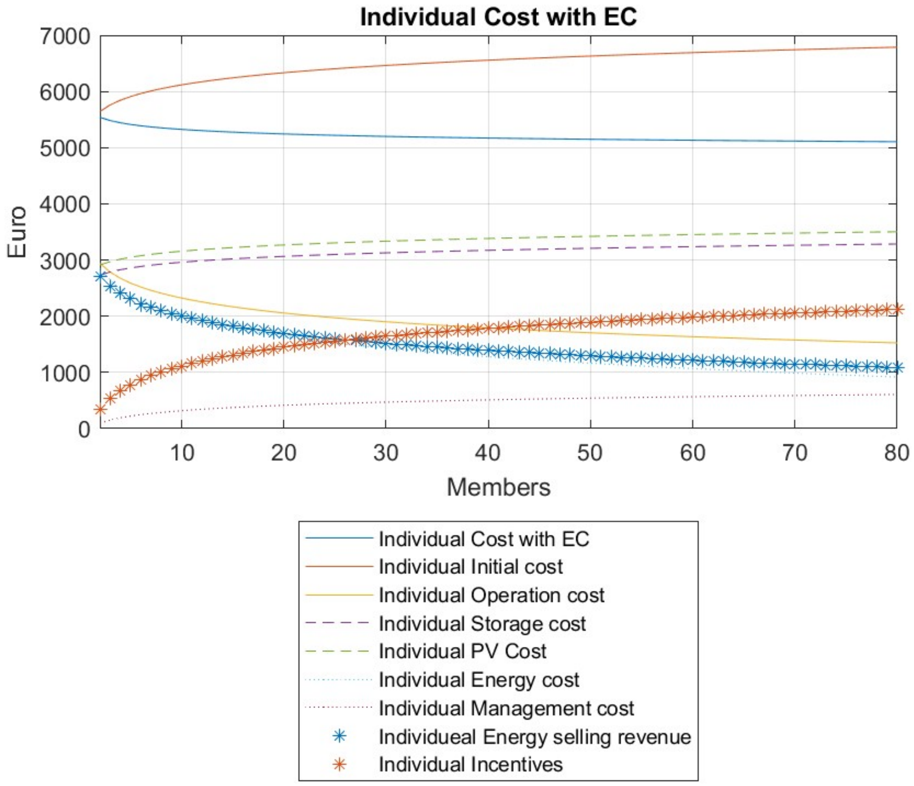

Figure 4.4.3: Individual costs trend of an EC member related to the variation in the number of members.

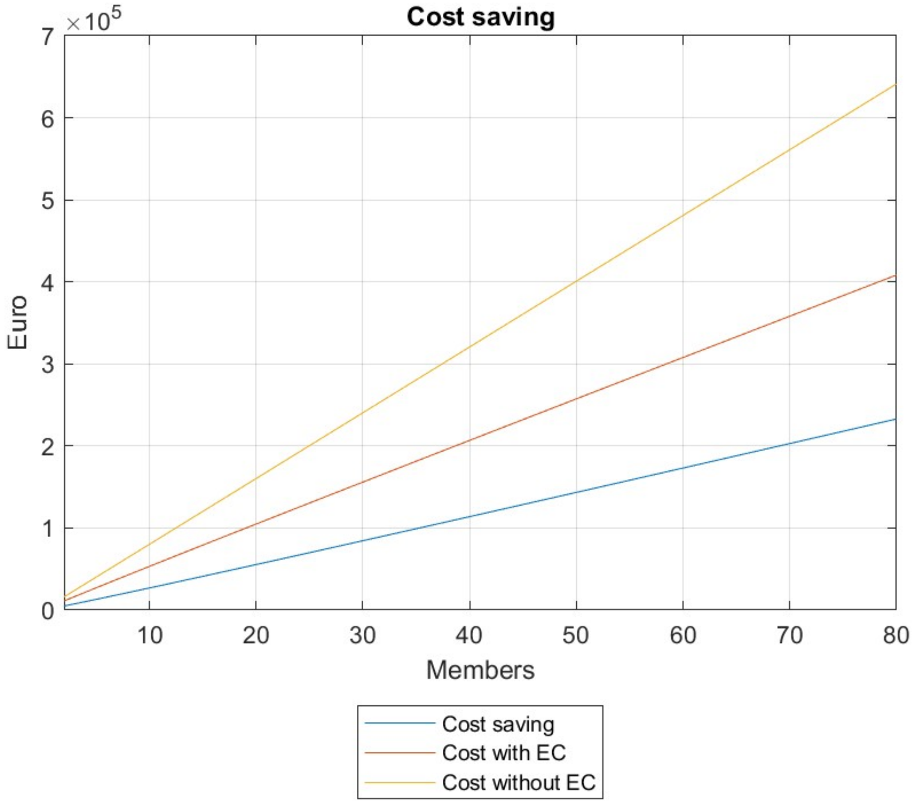

Figure 4.4.4: Cost saving of an EC related to the variation in the number of members.

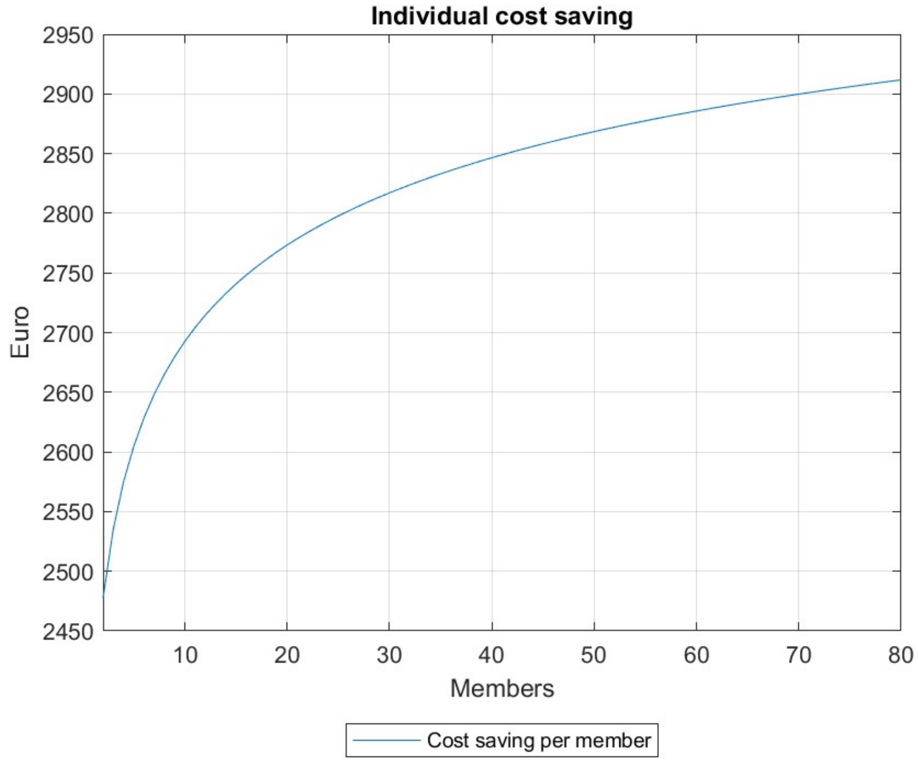

Figure 4.4.5: Individual cost saving of an EC member related to the variation in the number of members.

To provide more usable and scalable information, the figure 4.4.7 is obtained. This figure shows the trend of the marginal cost savings calculated annually for each installed kWp of installed photovoltaic system. In this way the information obtained can be adapted to any size of photovoltaic system and with different duration of years.

Comparison results

To provide an analysis on the relevance of the parameters used, a comparative analysis is carried out. The analysis is performed by creating different scenarios in which each one is modified by changing one parameter at a time.

- **Scenario A**: This scenario represent the reference case developed using the data from the table 4.4;
- **Scenario B**: In this scenario the investment costs are increased setting $LCOE = 0,11$ €$/kWh$ and $LCOS = 0,315$ €$/kWh$;
- **Scenario C**: This scenario consider a situation where investment costs are set as linear with $\alpha = 1$ and $q = 1$;
- **Scenario D**: This scenario is designed to observe the influence of management cost by setting $k_0 = 0,075$;

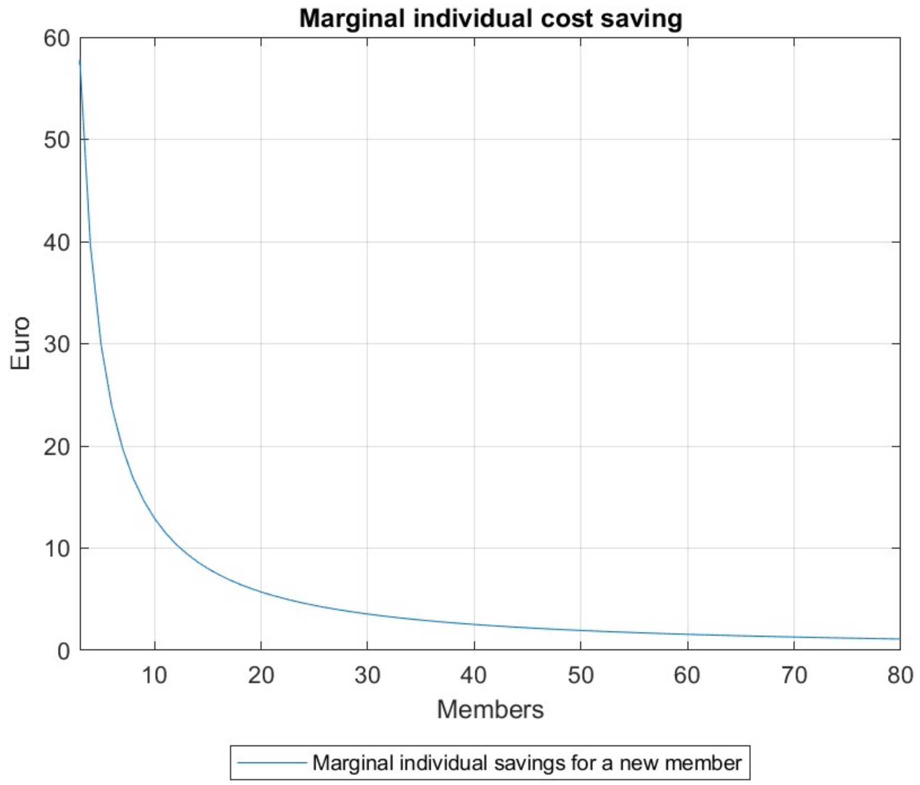

Figure 4.4.6: Marginal individual cost saving of an EC member related to the variation in the number of members.

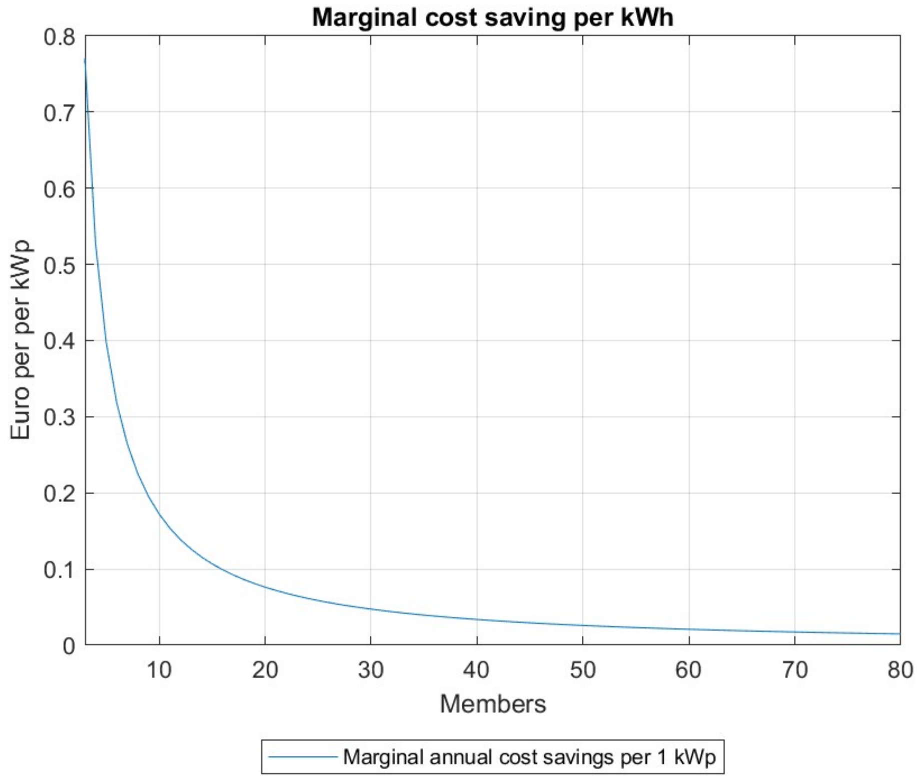

Figure 4.4.7: Marginal annual individual cost saving of an EC member per installed kWp related to the variation in the number of members.

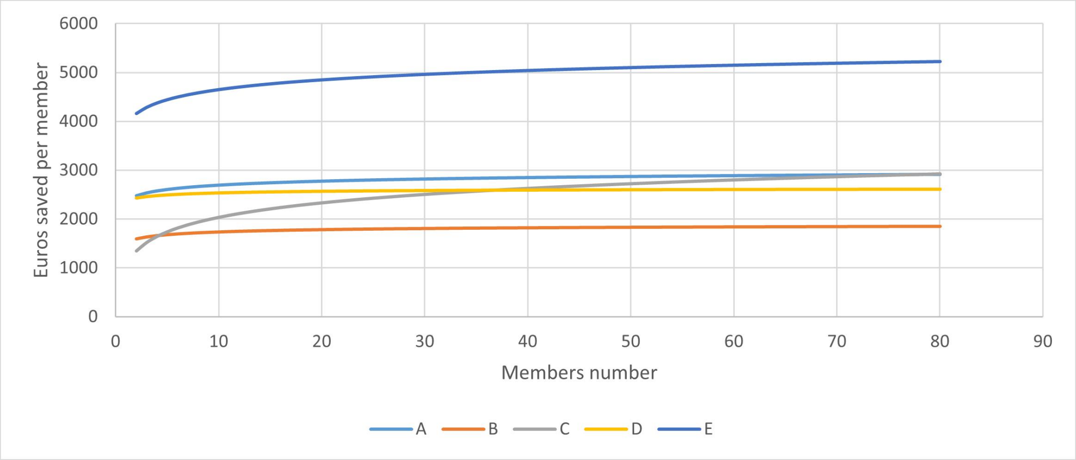

Figure 4.4.8: Comparison of different individual costs saving of an EC member related to the variation in the number of members in different model configurations.

- **Scenario E**: This scenario shown the effect of the energy price by setting $P^0 = 0,25$ €$/kWh$.

The mentioned scenarios are analyzed in Matlab simulations to observe the effects the modified parameters and their relation to the NPV of the energy community.
The different individual cost savings are obtained and shown in figure 4.4.8; from the figure, the different behavior of the scenarios are highlighted. Scenario **E**, the one with increased energy price, is the only one with a relevant growth in individual cost saving. Obviously, by increasing the energy price, the consumption of self-produced, stored, and shared renewable energy improves the economic saving in every point of the simulation. Scenario **B**, representative of a higher investment costs, shows a curve with a similar shape to the reference one, but a translation that decreases the economic saving for every member number. Instead, scenario **D**, shows that in the case of an increase in management costs, the behavior of the individual savings curve varies. In this case, the curve flattens out as members number increases and energy exchange increases, but the starting point for two members is almost unchanged. The case with the most particular behavior is the scenario **C**, with the linear progression of the investment costs. This setting produces an individual cost curve that starts from a value significantly lower than the reference case and grows rapidly as the number of members increases.

The comparison between the scenarios has been extended to the variation of the marginal individual economic savings, which are calculated in the single year for a photovoltaic system with a size of $1kWp$. Figure 4.4.9 shows what is obtained from the comparison processing. The aim of this figure is to compare the variation in cost savings upon the entry of a new member in the different scenarios. Reference case **A** reports the trend shown in figure 4.4.7. It can be seen that both scenario **B** with increased initial costs and scenario **D** with increased energy prices show a reduction in the variation of marginality, synonymous with a flattening of the individual economic savings curve. On the other hand, scenario **C** with linear investment prices and scenario **E** with an

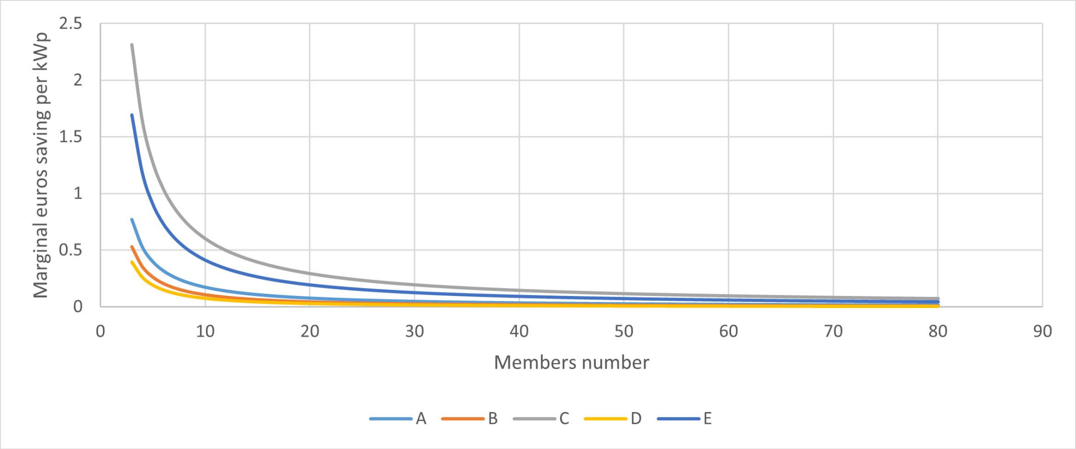

Figure 4.4.9: Comparison of different marginal annual individual costs saving of an EC member per installed kWp related to the variation in the number of members in different model configuration.

	Delta A	**Delta B**	**Delta C**	**Delta D**	**Delta E**
3-10	0,3590	0,2357	1,1473	0,1732	0,8160
11-20	0,1076	0,0627	0,3953	0,0436	0,2651
21-30	0,0583	0,0312	0,2312	0,0208	0,1504
31-40	0,0392	0,0197	0,1641	0,0126	0,1046
41-50	0,0292	0,0138	0,1273	0,0086	0,0799
51-60	0,0230	0,0104	0,1040	0,0062	0,0644
61-70	0,0189	0,0081	0,0879	0,0046	0,0539
71-80	0,0159	0,0065	0,0762	0,0036	0,0463

Table 4.5: Average marginal annual individual cost saving per installed kWp related to different ranges of members number.

increased energy price show a significant increase in the variation in marginality. It is important to highlight that in each case the marginality curve tends to decrease rapidly until it stabilizes when a large number of members is reached.

To investigate the trend of marginal savings in the various scenarios, table 4.5 has been produced. This table report the average marginal values in 8 ranges of members number. For instance, the first row shows the average variation in cost saving for an increase of member in the range $n \in 3 - 10$[8] (E.i.: moving from 4 members to 5 members). The columns allow to compare the variations in the different scenarios. To make the comparison easier, the cells are colored with a color scale from green to red, representing respectively the maximum and minimum variation.

The same data of the previous table are shown graphically in figure 4.4.10. This figure represents

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[8] Due to the necessity of one more data to have a variation, the first range start at $n = 3$ instead of $n = 2$ like the other figures; all the other ranges consider a range of 10 members

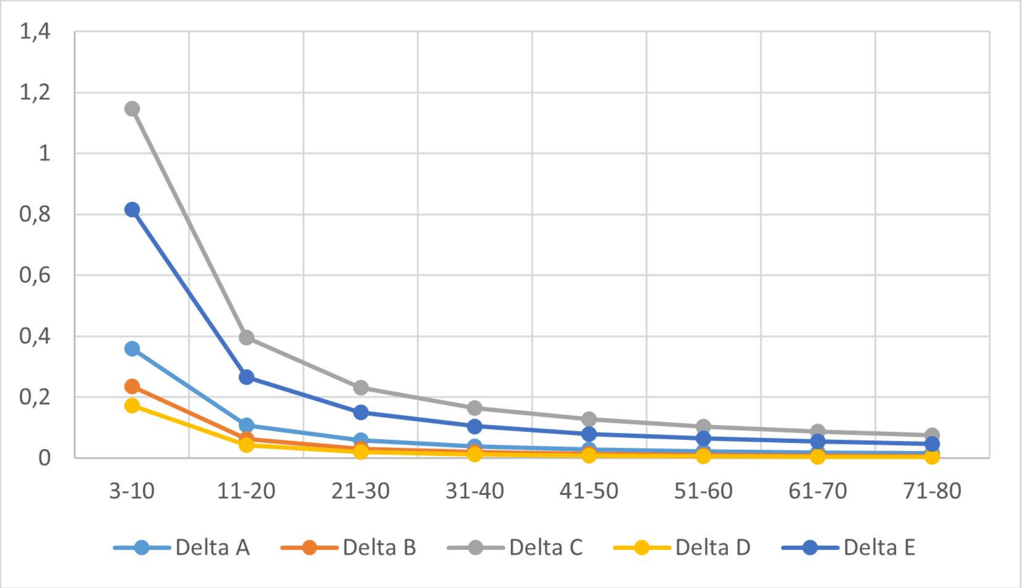

Figure 4.4.10: Average marginal annual individual costs saving per installed kWp related to different ranges of members number, graphical representation

a behavior similar to figure 4.4.9, where scenarios **B** and **D** show a minor variation if compared to the reference scenarios **A**. On the other hand, scenarios **C** and **E** show a significantly greater initial variation than the reference case. This visualization shows that from the $21 - 30$ members range the variation in marginality is drastically reduced. To increase the degree of detail in the small variations, the semi-log graph 4.4.11 is created. The semi-logarithmic representation expands the measurement scale of values below unity, representing a variation of one order of magnitude for each horizontal axis. In this way it can be seen that in the 21-30 members range, the average marginal variations are within the value of 0.02 and 0.23 (From table 4.5 the highest variation value is 0.2312 for scenario C, while the lower value is 0,0208 for scenario D). These values are already significantly lower than the value related to the entry of the third member into the reference energy community **A**, which introduces a variation equal to 0.77 (The highest variation value for $n = 3$ is 2.3122 for scenario C, while the lower value is 0.3964 for scenario D). For the final 71-80 members range, the average marginal variations are within the value of 0.003 and the value of 0.076 (From table 4.5 the highest variation value is 0.0762 for scenario C, while the lower value is 0.0036 for scenario D).

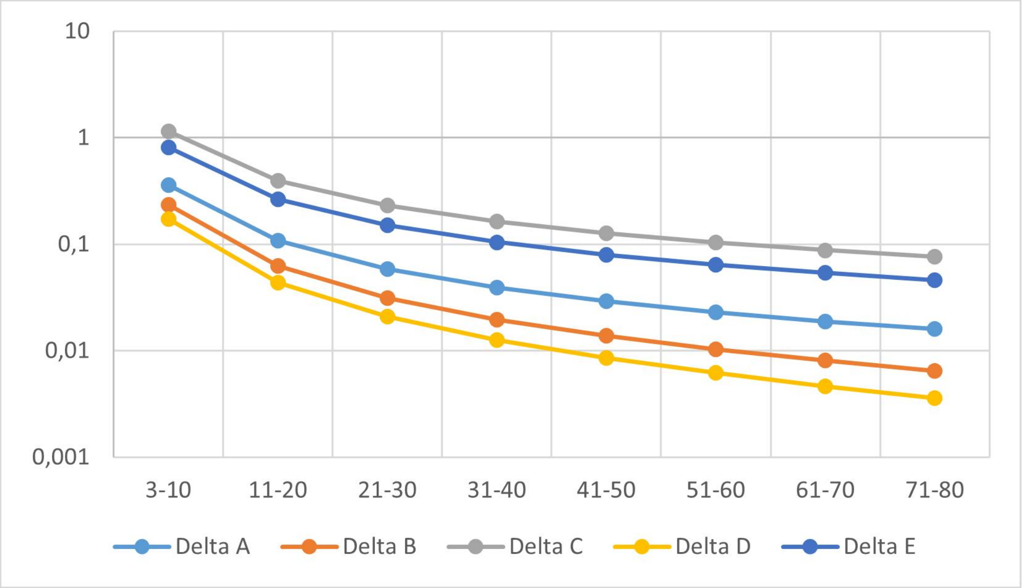

Figure 4.4.11: Average marginal annual individual costs saving per installed kWp related to different ranges of members number, semi-logarithmic representation.

Chapter 5

Conclusion

The main objective of this thesis was to create a model that describes in detail the net present value of a renewable energy community and its behavior as the number of members varies. The study of the model is preceded by an initial analysis of the current situation and a survey to better understand the real condition on the Italian territory. These were two fundamental layers of research to have in-depth knowledge on the subject in the absence of public data on energy communities.

As anticipated, the first in-depth layer is about the general description of energy communities. The concept of renewable energy community was introduced by European legislation through the Renewable Energy Directive 2018/2001 [13]. Subsequently, each European Member State transposed the directive through a process of internal legislation. In Italy this process was activated in 2019 through the "Decreto Milleproroghe" [18], which prepares the field for future legislation. To date (December 2022), this legislative process is still incomplete and being integrated by the competent bodies. The Decree of the Ministry of Economic Development of 8 November 2021 [21] anticipated some aspects such as the maximum power of individual plants set at 1 MWp, the incentives for sharing energy and the same primary substation as geographical limit. To complete the regulatory process, the Ministry of the Environment and Energy Security must publish a specific Ministerial Decree on shared energy, expected for the end of 2022 or the beginning of 2023. Until this decree is published, it is not possible to start energy communities and take advantage of obtaining incentives. Moreover, those who today build an energy community risk being exempt from recognition when the ministerial decree comes into force if some key points of the previous regulatory framework change.

Even if energy communities are also designed to reduce the power peaks in the electric grid by increasing the local consumption under the primary substation, they are not suitable for providing ancillary services such as regulation or balancing. This is due to the unpredictable nature of renewable energy forms, the only ones that can be generated in an energy community. In the extreme

case a community with an oversized storage system could provide a primary reserve system, but this would reduce the efficiency of the energy community.
Looking at the incentives, these are paid annually in proportion to the amount of shared energy. This "pay by results" approach stimulates the correct design of the systems and the maximum sensitivity in the community members. On the other hand, in this way the members do not have an initial facilitation in the purchase and installation of energy systems, which represent the bigger cost. Energy communities often have members who live in energy-poverty, and it is usually impossible for them to buy an energy plant at full price. In these cases the presence of public entities or third sector entities that actively deal with the installation of the systems becomes important, while energy-poor members will participate as consumers, obtaining part of the incentives without having purchased the system.

The second research layer was aimed at understanding the functioning of the energy communities already present on the Italian territory. Since the regulatory framework is not yet complete and in force, these energy communities do not receive incentives and are not required to comply with regulatory constraints on energy communities. Since there is no database relating to energy communities, a survey was designed and sent to 47 communities traced through the 2021 Legambiente Report [62]. Due to various limiting factors, only 16 compilations were obtained. A study was carried out from these answers which highlighted various factors. At the social level, the importance of the presence of companies or municipalities in the implementation of the energy community was highlighted, which were identified as the main promoters of the initiatives.
Observing the technical aspects, the clear superiority of photovoltaic systems compared to all other technologies stands out. Thanks to their simplicity and relative low cost, photovoltaic systems are absent in only one of the communities analysed.
Looking at the power, most of the conventional communities have electrical production capacities below 100 kWp. These communities are generally characterized by fewer than one hundred members. From the analysis there are also some large communities that could be considered as a union of several small communities, typically in the agricultural sector.

Taking everything into consideration, an economic model was developed that describes the net present value - cost saving - of an energy community and evaluates its behavior as the number of members increases. The information underlying the model is obtained from the two previous layers, integrating the information from the descriptive framework with the information obtained from the survey. A limiting factor that limited the accuracy of the model is given by the impossibility of finding certain and validated information relating to the self-consumption and the cost items. This is due to the absence of a database or mapping related to energy communities as they are a new segment of the energy market. In addition, there has been low participation by the engaged companies, which have shown to be without data to and adverse to share their information. Therefore, the data set used in the calculation model is obtained by combining literature and computation data.

The first step in the elaboration of the economic model was the definition of the energy demand satisfaction, first for the $i-th$ member and then for the whole community, composed of n members. According to the obtained model, total demand consumed by n individuals (d) is composed of the energy instantaneously consumed by n individuals (ξ), the energy stored into the battery system and consumed from n individuals (b), the energy shared by n individuals (s) and the energy purchase from the grid by n individuals (γ). The sum of overall instantaneously self-consumed energy (ξ), overall consumption of stored energy (b) and overall consumption of shared energy (s) is defined as the total self-consumption of n individuals (σ). The function σ representing self-consumption according the number of members n is imagined as a positive function of n; σ grows as the number of members n increases and the matching between energy supply and demand of the members increases. However, this increase is assumed to be of low significance after reaching a certain number of members; therefore, it is assumed that the curve representing the function σ tends to flatten after a certain number of members. The data obtained from the survey shows that in the presence of energy communities with more than 20 - 30 members a level of self-consumption between 85% and 90% can be achieved. This threshold therefore represents the maximum extreme of the σ function. Starting from the above hypotheses, an increasing logarithmic function was assumed, with a range of values moving from the lower value of $\sigma = 0,65$ when $n = 2$ to the higher value of $\sigma = 0,89$ when $n = 80$.

After the elaboration of the energy demand satisfaction, the complete economic model was developed. The proposed model considers an energy community of residential users only, equipped with photovoltaic systems and battery system as electricity storage. The dimensions, and the related costs, of the photovoltaic system have been calibrated assuming that the installed systems correspond to a peak power of 3 kWp for each member of the community. The battery storage system has been assumed to be large enough to allow the accumulation of the amount of energy b, processed from the input values.

The model calculates the total cost (C^{EC}) in the 25 years of operation of the energy community as the sum of initial costs for the purchase and installation of the photovoltaic system (I^{PV}) and the storage system (I^{S}), management costs (C^{MA}), energy purchase costs (E^{P}) and deducts the revenue from the sale of the energy surplus (R^{sale}) and the incentives obtained (in). The net present value of the energy community is obtained from the difference between the cost in case of absence of energy community and the above mentioned cost with the presence of energy community. For this reason, the net present value is also called cost savings. The results show that investment costs are the main cost factor in the implementation and management of the energy community analyzed. Economic inventions prove to be important in making the energy community profitable, significantly reducing costs in the long run. Incentives are linked to instantaneous energy sharing,

for this reason they grow with an increase of n as the percentage of energy exchanged increases. Increasing the energy exchange the fraction of energy sold outside the community decreases, this causes a decrease in revenue from the sale of energy as n increase.
To better describe the cost saving for a member of the energy community, the concept of marginal individual cost savings was introduced and discussed. It represents increase in cost savings generated by the entry into the EC of $n - th$ member compared to the savings generated upon entry of the previous member. The elaborated marginal savings shows how for a single member the entry of a new member into the E.C. always leads to an increase in savings, but this increase is reduced more and more until it becomes negligible (compared to initial increases) when the simulated energy community reaches a number of members greater than 40.
A comparative analysis was carried out to provide a feedback on the relevance of the parameters used. The analysis was performed by creating different scenarios in which investment costs value, investment costs models, management cost and energy price are changed to study their effect on the model. Both the scenario with an increase in initial costs and the scenario with an increase in energy prices show a reduction in the variation in marginal cost savings. In contrast, the scenario with linear investment prices and the scenario with increased energy price show a significant increase in the variation in margins. It is important to highlight that in any case the margin curve tends to decrease rapidly until it stabilizes when a large number of members is reached. From the comparison it was obtained that in the 21-30 members range, the average marginal variations are within the value of 0.02 and 0.23. Similarly, for the final 71-80 members range, the average marginal variations are within the value of 0.002 and the value of 0.076. These values are significantly lower than the value related to the entry of the third member into the reference energy community, which introduces a variation equal to 0.77. With these results, it can be said that even changing set of parameters, the economic advantages introduced by the growth in the number of members n decreases as n increases until it becomes negligible compared to the initial cost reductions. In other words, the NPV - or individual cost savings - is not growing linearly with the number of members in the energy community; therefore, an excessive number of members taking part to the energy community does not bring a significant economic benefit to the members already present within it.

This thesis provides a useful mathematical model that describes the economic behavior of a residential multi-member energy community, a model not yet present in the literature. The use of this model in order to obtain precise numerical results has crashed with the absence of exact input data for the calibration of the model, which are obtainable only after years of operation of the energy communities. Because of this, the results obtained only provide an indication of the ideal behavior of an energy community and are not able to provide exact results to be applied in real life. Natural development of this elaborate is to settle waiting for a safe and complete regulatory framework, necessary to perfect the mathematical model. To calibrate the exact parameters, however, it will be necessary to obtain the relative data of self-consumption of different real energy communities, possibly obtained in a full calendar year. I hope in the future this thesis can be a starting point for the development of a more accurate model useful to the world of science and business to spread a technology capable of improving our society.

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Appendix A

Appendix

A.1 MATLAB script

A.1.1 Comparison and plotting script

```
clear
close all
clc

%% Input data 1
p=0.1885;           %Energy starting price Euro/kwh
ps=0.1;             %Energy selling price Euro/kwh
mu=0.02;            %Energy inflation
r=0.06;             %Discount rate
k0=0.05;            %Management cost Euro/kwh
%LCOE=0.11;         %PV cost Euro/kwh
LCOE=0.09;
%LCOS=0.315;        %Storage cost Euro/kwh
LCOS=0.29;
eta=0.9;
q=1.05;             %Initial cost esponent
alpha=1.75;         %Initial cost coeffecient
T=25;               %Duration years
nmax=80;            %Maximum number of members

%%-----------------

xi_p =0.3;          %Instant self consumption (%)
b_p=0.6-xi_p;       %Battery storage (%)
d_i=2700;           %Individual energy deman kwh/anno
a_i=2916;           %Individual PV energy production kwh/anno

%Data elaboration fo case 1
```

```
[RR,RR_i,RR_im,CE,CE_i,XX,k1,k2,nopt,Rmax]=EC(LCOE,LCOS,k0,p,ps,r,mu,eta,alpha,q,T,d_i,a_i,xi_p,b_p,nmax);
Aoutput=[LCOE,LCOS,k0,k1,k2,p,ps,r,mu,eta,alpha,q,T,d_i,a_i,xi_p,b_p,nopt,Rmax];

%% Input data 2
p=0.1885;           %Energy starting price Euro/kwh
ps=0.1;             %Energy selling price Euro/kwh
mu=0.02;            %Energy inflation
r=0.06;             %Discount rate
k0=0.05;            %Management cost Euro/kwh
%LCOE=0.11;         %PV cost Euro/kwh
LCOE=0.09;
%LCOS=0.315;        %Storage cost Euro/kwh
LCOS=0.29;
eta=0.9;
q=1;                %Initial cost esponent
alpha=1;            %Initial cost coeffecient
T=25;               %Duration years
nmax=80;            %Maximum number of members

%%-----------------

xi_p =0.3;          %Instant self consumption (%)
b_p=0.6-xi_p;       %Battery storage (%)
d_i=2700;           %Individual energy deman kwh/anno
a_i=2916;           %Individual PV energy production kwh/anno

%Data elaboration fo case 2
[mRR,mRR_i,mRR_im,mCE,mCE_i,mXX,k1,k2,nopt,Rmax]=EC(LCOE,LCOS,k0,p,ps,r,mu,eta,alpha,q,T,d_i,a_i,xi_p,b_p,nmax);
Boutput=[LCOE,LCOS,k0,k1,k2,p,ps,r,mu,eta,alpha,q,T,d_i,a_i,xi_p,b_p,nopt,Rmax];


%% Figures
x=RR(1,:);
yR=RR(2,:);
yf=XX(2,:);
yce=RR(3,:);
ync=RR(4,:);
yR_i=RR_i(2,:);
%--------------------------------------------------
figure(1)
plot(x,yR,x,yce,x,ync)
R=RR(2,nmax-1);
ce=RR(3,nmax-1);
nc=RR(4,nmax-1);
maxy1=1.2*max([R ce nc]);
legend('Location','southoutside')
```

```
legend('Cost saving','Cost with EC','Cost without EC')
title('Cost saving')
axis auto
xlim([2 nmax])
xlabel('Members')
grid on
figure1=figure(1);
set(gcf,'Position',[100 100 600 500])
fig1=gcf;
%-------------------------------------------------
figure(2)
plot(x,yR_i)
legend('Location','southoutside')
legend('Cost saving per member')
title('Individual cost saving')
xlim([2 nmax])
xlabel('Members')
ylabel('Euro')
grid on
set(gcf,'Position',[100 100 600 500])
fig2=gcf;
%-------------------------------------------------
figure(3)
yR_im=RR_im(2,:);
plot(x,yR_im)
legend('Location','southoutside')
legend('Individual marginal savings for a new member')
title('Individual marginal cost saving')
xlim([3 nmax])
xlabel('Members')
ylabel('Euro')
grid on
set(gcf,'Position',[100 100 600 500])
fig3=gcf;
%-------------------------------------------------
figure(4)
plot(x,yf)
legend('Location','southoutside')
legend('Selfconsumption envelop')
title('Selfconsumption envelop')
axis([2 nmax 0 1])
xlabel('Members')
ylabel('[-]')
set(gcf,'Position',[100 100 600 500])
grid on
fig4=gcf;
%-------------------------------------------------
figure(5)
```

```
yci=CE(3,:);
yco=CE(4,:);
ycs=CE(5,:);
ycpv=CE(6,:);
ycen=CE(7,:);
ycma=CE(8,:);
yrev=CE(9,:);
yinc=CE(10,:);
plot(x,yce,x,yci,x,yco,x,ycs,'--',x,ycpv,'--',x,ycen,':',x,ycma,':',x,yrev,'*',x,yinc,'*')
legend('Location','southoutside')
legend('Cost with EC','Initial cost','Operation cost', 'Storage cost', 'PV sost','Energy cost', 'Management cost','Energy selling revenue','Incentives')
title('Cost with EC')
xlim([2 nmax])
xlabel('Members')
ylabel('Euro')
grid on
set(gcf,'Position',[100 100 600 500])
fig5=gcf;
%-------------------------------------------------
figure(6)
yce_i=CE_i(2,:);
yci_i=CE_i(3,:);
yco_i=CE_i(4,:);
ycs_i=CE_i(5,:);
ycpv_i=CE_i(6,:);
ycen_i=CE_i(7,:);
ycma_i=CE_i(8,:);
yrev_i=CE_i(9,:);
yinc_i=CE_i(10,:);
plot(x,yce_i,x,yci_i,x,yco_i,x,ycs_i,'--',x,ycpv_i,'--',x,ycen_i,':',x,ycma_i,':',x,yrev_i,'*',x,yinc_i,'*')
legend('Location','southoutside')
legend('Individual Cost with EC','Individual Initial cost','Individual Operation cost', 'Individual Storage cost', 'Individual PV Cost','Individual Energy cost', 'Individual Management cost','Individueal Energy selling revenue','Individual Incentives')
title('Individual Cost with EC')
xlim([2 nmax])
xlabel('Members')
ylabel('Euro')
grid on
set(gcf,'Position',[100 100 600 500])
fig6=gcf;

%% Figures Comparison
mx=mRR(1,:);
```

```
myR=mRR(2,:);
myf=mXX(2,:);
myce=mRR(3,:);
mync=mRR(4,:);
myR_i=mRR_i(2,:);

figure(7)
plot(x,yR,x,yce,x,ync,x,myR,'--',x,myce,'--',x,mync,'--')
R=RR(2,nmax-1);
ce=RR(3,nmax-1);
nc=RR(4,nmax-1);
maxy1=1.2*max([R ce nc]);
legend('Location','southoutside')
legend('Cost saving case A','Cost with EC case A','Cost without EC case A','Cost
    saving case B','Cost with EC case B','Cost without EC case B')
title('Cost saving')
axis auto
xlim([2 nmax])
xlabel('Members')
ylabel('Euro')
grid on
figure7=figure(7);
set(gcf,'Position',[100 100 600 500])
fig7=gcf;

figure(8)
plot(x,yR_i,x,myR_i,'--')
legend('Location','southoutside')
legend('Cost saving per member case A','Cost saving per member case B')
title('Individual cost saving')
xlim([2 nmax])
xlabel('Members')
ylabel('Euro')
grid on
set(gcf,'Position',[100 100 600 500])
fig8=gcf;

%% Figures exporting
exportgraphics(fig1,'Cost_saving.jpg')
exportgraphics(fig2,'Individual_cost_saving.jpg')
exportgraphics(fig3,'Individual_marginal_savings.jpg')
%exportgraphics(fig4,'Selfconsumption_envelop.jpg')
exportgraphics(fig5,'Cost_EC.jpg')
exportgraphics(fig6,'Individual_Cost_EC.jpg')
exportgraphics(fig7,'Comparison_cost_saving.jpg')
exportgraphics(fig8,'Comparison_individual_cost_saving.jpg')
disp('fine')
```

A.1.2 Net Present Value calculation function

```
function [RR,RR_i,RR_im,CE,CE_i,XX,k1,k2,nopt,Rmax]=EC(LCOE,LCOS,k0,p,ps,r,mu,eta,alpha,q,T,d_i,a_i,xi_p,b_p,nmax)
k1=LCOE/r*(1-exp(-r*T));    %PV cost coeff
k2=LCOS/r*(1-exp(-r*T));    %Storage cost coeff

RR=zeros(4,nmax-1);      %Output data matrix
RR_i=zeros(2,nmax-1);    %Individual output data matrix
RR_im=zeros(2,nmax-1);   %Individual marginal output data matrix
CE=zeros(10,nmax-1);      %Output data matrix for EC case
CE_i=zeros(10,nmax-1);    %Indivual output data matrix for EC case
XX=zeros(2,nmax-1);      %Output data matrix for f

%% Iteration
for n=2:nmax
    sigma_p=0.15*log10(n)+0.6;                  %Self-consumption percentage
    XX(1,n-1)=n;
    XX(2,n-1)=sigma_p;                          %Self-consumption envelop output data

    s_p=sigma_p-b_p-xi_p;                       %Shared fraction (%)

    gamma_p=1-sigma_p;                          %Purchased fraction (%)

    d=d_i*n;                                    %Total energy demand (kWh/year)

    sigma=sigma_p*d;                            %Total self consumption  (kWh/year)
    xi=xi_p*d;                                  %Collective instant self-consumption  (kWh/year)
    s=s_p*d;                                    %Total shared energy  (kWh/year)
    b=b_p*d;                                    %Total stored energy  (kWh/year)
    gamma=gamma_p*d;                            %Total purchased energy  (kWh/year)
    a=a_i*n;                                    %Total renewable energy production  (kWh/year)



    nc=0;
    co=0;
    cen=0;
    cma=0;
    Rev=0;
    Inc=0;

    for t=1:T
        nc=nc+(((1+mu)^t)/((1+r)^t))*p*d; %sum - Cost without EC
    end

    cpv= k1*(a/alpha)^q;                    %Initial cost of PV
```

```
    cs=k2*(b/eta/alpha)^q ;             %Initial cost of storage
    ci=cs+cpv;                          %Initial cost with EC

    for t=1:T
        cen=cen+(((1+mu)^t)/((1+r)^t))*p*gamma;      %sum - energy purchase
    end

    for t=1:T
        cma=cma+(((1+mu)^t)/((1+r)^t))*k0*s;         %sum - management costs
    end

    for t=1:T
        Rev=Rev+ps*(a-xi-b/eta-s);                 %sum - energy selling
    end

    for t=1:T
        Inc=Inc+0.11*s;                      %sum - incentives
    end



    co=cen+cma;                     %Operative costs with EC
    ce=ci+co-Rev-Inc;               %Cost with EC
    R=nc-ce;                        %Cost saving
    R_i=R/n;                        %Cost saving per member

    RR_im(1,n-1)=n;
    if n>2
        RR_im(2,n-1)=R_i-RR_i(2,n-2);   %Marginal cost saving per member
    end


    CE(1,n-1)=n;
    CE(2,n-1)=ce;
    CE(3,n-1)=ci;
    CE(4,n-1)=co;
    CE(5,n-1)=cs;
    CE(6,n-1)=cpv;
    CE(7,n-1)=cen;
    CE(8,n-1)=cma;
    CE(9,n-1)=Rev;
    CE(10,n-1)=Inc;

    CE_i=CE./CE(1,:);
    CE_i(1,:)=CE(1,:);

    RR(1,n-1)=n;
    RR(2,n-1)=R;
```

```
    RR(3,n-1)=ce;
    RR(4,n-1)=nc;
    RR_i(2,n-1)=R_i;

    Rmax=max(RR_i(2,:));
    nopt=find(RR_i(2,:)==Rmax)+1;
end
```

A.2 Tables

Year	Avarage Price	Year	Avarage Price
	c€/kWh		c€/kWh
2011	16.18	2016	18.46
2012	18.72	2017	19.28
2013	19.08	2018	20.39
2014	19.10	2019	20.67
2015	18.68	2020	17.89

Table A.1: Energy price and price variation for domestic use with 3 kW of power and 2,700 kWh of annual consumption.