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Techno-Economic Assessment of Renewable Energy Communities and Biomethane Valorization in a Medium-Sized Agricultural Enterprise

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Abstract

The promotion of energy from renewable sources is a key objective of the European Union's energy policy, as outlined in Directive (EU) 2018/2001, known as the Renewable Energy Directive II. This directive introduces the concept of Renewable Energy Communities (RECs), which are groups of citizens and/or small and medium-sized enterprises that produce and share electricity generated from renewable sources. Additionally, its amendment, Directive (EU) 2023/2413, sets a further goal of achieving an annual sustainable biomethane production of 35 billion cubic meters by 2030. Within this context, Northern Italy emerges as one of the European regions with the highest potential for biogas production. This thesis presents a techno-economic feasibility study for a medium-sized agricultural enterprise located in Piedmont, evaluating three possible configurations:

1. A Renewable Energy Community featuring a photovoltaic system installed on the farm’s rooftop.
2. A Renewable Energy Community incorporating both a photovoltaic system and an anaerobic digester, owned by the farm, to produce biogas from bovine manure and its subsequent combustion in a cogeneration plant.
3. Upgrading of biogas to biomethane through a pressure-swing adsorption (PSA) CO_2 capture process, followed by injection into the gas grid.

The analysis begins with the assessment of hourly electrical and thermal load profiles for the farm, along with the electrical load profiles of REC participants. A parametric analysis is then conducted to determine the optimal photovoltaic system size—identified as 150 kWp—based on the comparison of key energy and economic performance indicators (KPIs). The anaerobic digestion plant and hourly biogas production, along with associated energy consumption, are subsequently dimensioned. Starting from a minimum cogeneration plant size of 100 kW and an initial photovoltaic installation of 50 kWp, the combustion engine size is gradually increased while the photovoltaic capacity is reduced, maintaining a maximum total production limit of 150 kW. Finally, the CO_2 capture process based on hourly biogas production is designed and simulated using PSA technology, and the associated economic KPIs are evaluated. Incentives for shared electricity within RECs are considered according to the CACER Decree, while biomethane injection incentives are referenced through the Biomethane Decree. Among the REC configurations, the photovoltaic-only option proves most economically advantageous, as the high capital and maintenance costs of the anaerobic digester render the payback period and net present value less competitive. Conversely, configurations including cogeneration demonstrate superior performance in terms of self-consumption and energy self-sufficiency. Regarding biomethane production and sale, the analysis highlights that financial incentives are essential to ensure investment viability, as the market price of natural gas, as established by the Energy Market Operator (GME) on the Day-Ahead Market, is insufficient to guarantee economic return. In conclusion, under current incentive schemes, biomethane production and sale represent the most economically viable renewable energy strategy for a medium-sized agricultural enterprise.

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INTRODUCTION

Climate change represents one of the most pressing challenges facing human society today. The rising global temperature, driven by anthropogenic greenhouse gas (GHG) emissions, has intensified the urgency for a complete transformation of the global energy system. In response to this crisis, numerous countries are enacting ambitious decarbonisation policies aimed at reducing dependence on fossil fuels and transitioning towards sustainable energy systems.

This imperative was formally recognized in 2015, when nearly all countries adopted the Paris Agreement (PA) [1] under the COP21 held in Paris. The primary goal of the PA is to strengthen the global response to the threat of climate change acting on the concepts of mitigation and adaptation:

- mitigation: an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases [1].
- adaptation: adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities [1].

These concepts are underlined on the second article of the Paris Agreement with these sentences:

- Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.[2]
- Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production. [2]

- Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development. [2]

To meet both global and local climate objectives while ensuring energy security and system resilience, a redefinition of the current energy paradigm is essential. This new paradigm should be based on low-carbon solutions that ensure minimal environmental and social impact, using renewable and recyclable resources and applying high-efficiency technologies. Moreover, the transformation of the energy system must uphold principles of energy justice, energy democracy, and energy citizenship. These concepts call for an inclusive and equitable transition where all individuals have the right to participate in, benefit from, and shape the energy system. Hence, ensuring a right energy transition means not only achieving carbon neutrality through mitigation but also adapting energy infrastructures and institutions to protect the most vulnerable and reduce inequalities as outlined in the Paris Agreement. [3]

In response to these changes on the energy production and dispatch, the European Commission started a deep revision of the common legislative framework on energy called: Clean Energy Package (CEP)[4], introduced in 2019. This legislative framework is a set of eight legislative acting on the promotion of renewable energy, energy efficiency and the active participation of citizens in the energy transition. Inside the CEP there are two directives that provide, for the first time at the European scale, formal recognition of energy communities, which empower citizens to produce, consume and share renewable energy[5]. Indeed, Renewable Energy Communities can support the achievement of the Sustainable Development Goals presented in the 2030 Agenda, in particular:

- SDG7: Affordable and Green Energy[6].
- SDG11: Sustainable Cities and Communities[6].
- SDG13: Climate Action[6].

The presence of Renewable Energy communities leads to the inclusion of the local people in the decision-making process and benefits-sharing, improving the social acceptance of the energy transition process. They are expected to switch from traditional passive consumers to active prosumers, directly involved in the field of energy[7].

In this context, solar energy represents the most prominent renewable energy source currently employed within Renewable Energy Communities (RECs). Photovoltaic (PV) systems dominate the renewable energy market in these communities due to their widespread availability and technological maturity. However, this study seeks to offer an alternative perspective by emphasizing the potential integration of diverse renewable energy sources within RECs, in particular biomass and biogas. While PV systems provide significant economic advantages, their energy production typically peaks during midday hours—coinciding with periods when community members are often away from their homes. This temporal mismatch between production and consumption reduces the immediate sharing potential of the energy generated and underscores the need for energy storage solutions to enhance both self-consumption and the overall self-sufficiency of the community. In regions where agricultural activity is prevalent, and thus organic waste is abundant, the deployment of anaerobic digestion systems presents a viable opportunity. The biogas produced through this process can be utilized in combined heat and power (CHP) systems, with the biogas storage tank effectively serving as an energy buffer. This approach introduces a degree of operational flexibility, enabling communities to determine the timing and quantity of energy production based on demand, thereby supporting a more balanced and resilient energy system.

In the light of the considerations outlined above, the primary objective of this work is to conduct a techno-economic analysis of a farm seeking to invest in energy production and efficiency improvements. The goal is to reduce reliance on grid-supplied electricity and natural gas, thereby decreasing energy expenditures, while simultaneously generating economic and social benefits for the surrounding community.

To this end, several energy system configurations will be assessed in order to identify the most advantageous solution for the farm. The configurations proposed include:

- Deployment of a Photovoltaic (PV) system.
- Implementation of a Combined Heat and Power (CHP) system fuelled by biogas.
- Biogas upgrading to produce biomethane.

The latter configuration incorporates carbon capture technologies, specifically Pressure Swing Adsorption (PSA), with the aim of upgrading biogas in biomethane. The techno-economic simulations have been developed and executed using MATLAB, enabling the quantitative comparison of each scenario thanks to specific KPIs.

The thesis is structured into four chapters:

Chapter 1 provides a comprehensive overview of Renewable Energy Communities (RECs) in the European context, with particular attention to the evolution of the legal framework—from the Renewable Energy Directive II (RED II), part of the Clean Energy for All Europeans Package, to its transposition into Italian law via the 'Decreto CACER' and the 'Testo Integrato Autoconsumo Diffuso (TIAD)'.

In Chapter Two, the characteristics of the area where the agricultural company will be located are analysed, along with the waste production from the livestock and the company's thermal and electrical load. Furthermore, the electrical loads of the Renewable Energy Community (REC) will be defined using an open-source Python-based tool called "RECopt", developed by Politecnico di Torino, by analysing the residential buildings that could potentially be part of the REC.

In Chapter Three, different configurations will be presented, with particular focus on the energy-related Key Performance Indicators (KPIs) of the Energy Community. Additionally, the Pressure Swing Adsorption (PSA) capture process will be introduced and simulated using the open-source tool "toPSAIl", developed in MATLAB.

In Chapter Four, the final economic results of the different configurations will be presented and compared to identify the most suitable solution. Furthermore, possible future developments will be discussed, providing insights that could support the creation of new Energy Communities.

Chapter 1- European and Italian Regulatory Framework

1.1 European Regulatory Framework

In 2019, the European Union established its energy policy to reduce dependence on fossil fuels in favour of cleaner energy sources and to achieve the goals set by the Paris Agreements[2] on greenhouse gas emission reductions. Within this energy policy framework, the agreements contained in the "Clean Energy for all Europeans package" (CEP) [4] are included. The CEP marked a significant step forward in the implementation of the European energy strategy, which can be summarized in four key points:

- Security in energy supply by diversifying sources and ensuring solidarity and cooperation among European countries.
- A fully integrated energy market that allows the flow of energy within the EU through appropriate infrastructure and without technical or regulatory barriers.
- Improving energy efficiency in crucial sectors by supporting research and innovation to develop low-emission technologies.

Action against climate change by reducing greenhouse gas emissions until reaching net zero emissions by 2050 as stipulated in the Paris Agreements[2].

The CEP[4] consists of four regulations and four directives that place consumers at the centre of energy policies, offering them the opportunity to choose their supply sources, and to produce and sell energy independently. For the first time, not only is the role of individual citizens recognized — as self-consumers or active customers — but also the aggregation of multiple users into self-consumption groups or renewable energy communities, to achieve environmental and social goals. In particolar:

- Directive 2018/2001/EU[4], known as the Renewable Energy Directive (RED II), promotes renewable energy and defines Renewable Energy Communities.

- Directive 944/2019/EU[8], known as the Internal Electricity Market Directive (IEM), sets common rules for the internal market of electricity and defines Citizen Energy Communities.

Subsequently, on July 14, 2021, the EU adopted a new set of laws called the 'Fit for 55 package', which falls within the REPowerEU[9] policies, and modifies existing laws to achieve the emission reduction target of 55% by 2030 and climate neutrality by 2050. The key element of this provision is the amendment of RED II, which was modified at the end of 2023 when RED III [10]came into force. A fundamental role in this transition has been assigned to biomethane to quickly reduce dependence on fossil fuels. The goal is to increase biomethane production up to 35 billion cubic meters per year to replace imports of Russian gas.

1.1.1 The Renewable Energy Directive II and Its Revision

The RED II[4] was created to promote the increase in energy produced from renewable sources, placing the end user at the centre of the transition. The citizen, in a new perspective, is seen as an active element in the dynamics of electricity production and consumption. To promote this idea, the Directive introduces aggregation models of increasing complexity, defining and regulating individual self-consumption, collective self-consumption, and Renewable Energy Communities (RECs).

A renewable energy self-consumer is defined as a final customer who, operating in their own premises located within clearly defined boundaries or, if permitted by a Member State, in other sites, produces renewable electricity for their own consumption and may store or sell self-produced renewable electricity, provided that, for a renewable energy self-consumer other than households, such activities do not constitute their primary commercial or professional activity[4]. Consequently, jointly acting renewable energy self-consumers are defined as a group of at least two renewable energy self-consumers who act collectively and are in the same building or apartment block.

RED II then introduces RECs, defining them as a legal entity that:

- Based on open and voluntary participation, is autonomous and effectively controlled by shareholders or members who are in the vicinity of the renewable energy production installations owned and developed by the legal entity in question, in accordance with applicable national law.

- Whose shareholders or members are natural persons, SMEs, or local authorities, including municipalities.
- Whose primary purpose is to provide environmental, economic, or social community benefits to its shareholders or members or to the local areas in which it operates, rather than financial profits.

Article 22 states that Member States shall ensure that renewable energy communities have the right to:

- Produce, consume, store, and sell renewable energy.
- Share, within the same community, the renewable energy produced by the production units owned by that community of renewable energy producers/consumers.
- Access all suitable electricity markets, either directly or through aggregation, in a non-discriminatory manner.

It is therefore clear that RECs can provide ancillary services to the distribution/transmission network, in addition to the simple production of electricity. For this reason, RED II highlights the possibility of interaction between citizens and actors in the energy sector, to provide the skills needed to achieve common goals. Along these lines, Revison of RED II [10] does not substantially modify the legal structure of renewable energy communities but emphasizes that, in addition to producing and sharing electricity, they could also do the same with waste heat and cooling. This would be made possible through the promotion of district heating networks based on renewable energy, such as cogeneration plants powered by biogas, through economic support measures also targeted at renewable energy communities.

As regards biofuels and biogas, RED II states that their integration into the European energy mix can reduce carbon emissions, promote decarbonization in the transport sector, and reduce dependence on imported energy from other countries. To ensure the success of this process, the EU imposes a minimum share of biogas and biofuels to be used in the transport sector, which must reach at least 3.5% by 2030. Moreover, the directive establishes limits on the reduction of greenhouse gas emissions resulting from the use of biofuels and biogas in the transport, electricity, and heat and cooling production sectors, calculated using the algorithm provided in Annex V of the Directive.

In the Revision, biomethane plays an even more prominent role, especially considering the events between Russia and Ukraine. To reduce natural gas imports from Russia, Europe has implemented an investment plan of €37 billion aimed at increasing biogas production and promoting its conversion into biomethane. The European Commission proposes to overcome current barriers in biomethane production through the following measures:

- Establishing an industrial partnership for biogas and biomethane to boost the renewable gas value chain.
- Taking additional measures to encourage biogas producers to create energy communities.
- Providing incentives to shift from biogas to biomethane.
- Promoting the adaptation and upgrading of existing infrastructure and the construction of new infrastructure to enable the transport of more biomethane through the EU gas network.
- Closing gaps in research, development, and innovation.
- Facilitating access to financing and mobilizing EU funds under the Connecting Europe Facility, the cohesion policy, the Recovery and Resilience Facility, and the Common Agricultural Policy.

1.1.2 The Internal Electricity Market (IEM) Directive

The main purpose of the IEM Directive [8] is to adapt the European Union's electricity market to the technological and structural changes taking place in recent years. As stated in Article 1, the directive establishes common rules for the generation, transmission, distribution, storage, and supply of electricity, to create electricity markets within the European Union that are effectively integrated, competitive, consumer-cantered, flexible, fair, and transparent.

The first figure on which the IEM focuses is the active customer, who is a final customer or a group of associated final customers who consumes or stores the electricity produced in their own premises located within a defined area, or sells the self-produced electricity or participates in flexibility or energy efficiency mechanisms, provided that such activities do not constitute their primary commercial or professional activity.

The Directive also defines Citizen Energy Communities, which are defined as a legal entity that:

- is based on voluntary and open participation and is effectively controlled by members or shareholders who are natural persons, local authorities including municipalities, or small enterprises.
- has the primary purpose of providing environmental, economic, or social community benefits to its members or shareholders or to the area in which it operates, rather than generating financial profits.
- may participate in generation, including from renewable sources, in distribution, supply, consumption, aggregation, energy storage, energy efficiency services, or charging services for electric vehicles, or provide other energy services to its members or shareholders.

1.1.3 Concluding Remarks

Renewable energy communities and citizen energy communities were created with the common goal of overcoming certain limitations imposed by national legislation regarding the role of final energy users, but they also present substantial differences dictated by the context, including the regulatory one, from which they developed. Both legal entities are characterized by open and voluntary participation, leaving the final user free to choose how and whether to join the communities; both Directives emphasize the participation of citizens, local authorities, and SMEs whose primary activity is not in the energy sector; the final goal is to generate social and environmental benefits rather than economic ones; finally, in both cases the configurations can carry out similar activities such as generation, distribution, storage, and consumption of electricity[11].

On the other hand, RED II emphasizes the concept of proximity of renewable energy production systems, while the IEM gives more freedom from a geographical point of view. CECs are not necessarily required to link their energy production to renewable sources. It is worth highlighting how this regulatory framework contributes to placing the consumer and their protection at the centre of the electricity market, in a context where renewable energies and the decentralization of energy production are putting the overall security of the electricity system under strain. For this reason, the Member States of the European Union were required to transpose the two directives by deadlines set for June 2021 for RED II and December 2020 for the IEM. Finally, as underlined in RED III, the Commission could consider the option of developing an EU strategy for the energy transition in rural areas as a support tool for the implementation of integrated energy solutions in such contexts, taking advantage of the numerous decentralized and small-scale biogas plants operating in the EU and integrating them into the broader renewable energy mix, while also addressing related environmental and social aspects by involving renewable energy communities[9].

1.2 Italian Regulatory Framework

Starting from the European Directives mentioned above, the Member States, over the years, have had to implement these guidelines by promoting laws to achieve the established objectives. As far as Italy is concerned, the pilot phase for the establishment of renewable energy communities began with the "Decreto Milleproroghe"[12] of 2020. Thanks to this decree, it was possible to experiment and collect information for the drafting of subsequent regulations, up to the CACER[13], [14], decree issued by MASE in 2023. From 2020 to 2023, during the experimental phase, according to GSE, 109 collective self-consumption configurations were implemented: 74 collective self-consumption groups and 35 energy communities. In terms of total power, 2.7 MW were installed, all related to photovoltaic systems [11]. From 2023 to 2025, however, growth in both number and installed capacity has been exponential. According to GSE's statistical report, renewable energy communities amount to 212 with a total installed capacity of 22.4 MW [15], ten times more than in the previous two years and not including collective self-consumption configurations. This demonstrates that the progressive relaxation of regulations regarding both the geographical limit and the installed power has had a positive impact on the national territory

1.2.1 Milleproroghe Decree

In Italy, the transposition of the RED II Directive began experimentally in 2020 with the implementation of Article 42-bis of Decree-Law no. 162/2019 (Decreto Milleproroghe) [16], and its amendment in Law no. 8/2020 [12]. Thanks to these laws, it was possible to launch a process aimed at testing the effects and potential of introducing widespread self-consumption schemes and renewable energy communities. Therefore, the users who can be part of these configurations are initially defined, directly citing RED II:

- In the case of renewable energy self-consumers acting collectively, subjects other than households may associate only if the activities related to self-consumption do not constitute their main commercial or professional activity.
- In the case of energy communities, shareholders or members are natural persons, small and medium-sized enterprises, territorial entities or local authorities, including

municipal administrations, and participation in the renewable energy community cannot constitute their main commercial and industrial activity.

The Decree introduces certain restrictions compared to the European Directive for the implementation of the two configurations, based on the characteristics of the Italian electricity distribution system:

- The participating subjects produce energy using plants powered by renewable sources with a total capacity not exceeding 200 kW.
- The participating subjects share the energy produced using the existing distribution network. The shared energy corresponds to the minimum, in each hourly period, between the electricity produced and fed into the grid by the renewable energy plants and the electricity withdrawn by the group of associated final customers. This corresponds to a virtual sharing energy approach.

The concept of proximity to the place of electricity production takes on a primary role within the Decree, as highlighted in Article 4, where:

- In the case of renewable energy self-consumers acting collectively, they are in the same building or apartment block.
- In the case of renewable energy communities, the consumption points of the users and the injection points of the plants are located on low-voltage electricity networks underlying the same medium/low-voltage (MV/LV) transformation substation.

These are the only limitations stated in the Decree, in which it is emphasised that participation in such configurations is also possible for low-income or vulnerable households. This is important to underline because the main objective of these associations is to provide environmental, social and economic benefits rather than financial profits.

Furthermore, an incentive scheme for these configurations is defined, along with methods to facilitate direct access for public entities, such as municipalities or public administrations. As for the incentives, these are provided by the GSE and are aimed at rewarding instantaneous self-consumption and storage systems. Although incentives are provided by the GSE, ARERA, with Resolution 318/2020 [17], defines the tax relief applicable to shared and self-consumed energy in the two configurations, while the Implementing Decree of the MISE dated 16 September 2020 identifies the incentive tariff applied to the share of shared energy.

1.2.2 ARERA Resolution

ARERA Resolution 318/2020 [17]regulates the methods and economic arrangements related to the electricity subject to collective self-consumption or sharing within renewable energy communities, pursuant to Article 42-bis of Decree-Law 162/19 [16]. Within the Resolution, the remuneration due to the two configurations is defined, which is not technically applicable to the shared energy quota and is subsequently provided by the GSE. The tariffs differ for the two configurations. In the case of a group of renewable energy self-consumers acting collectively, the following are provided:

- a contribution for the valorisation of shared electricity (C_{AC}), equal to the product of the shared electricity E_{AC} and the unitary flat-rate monthly self-consumption fee $CU_{Af,m}$. This parameter is defined as the algebraic sum of the transmission tariff for low-voltage users ($TRAS_E$) and the highest value of the variable component of low-voltage distribution (BTAU).
- a contribution that considers the network losses avoided thanks to local production.

Regarding renewable energy communities:

- a contribution for the valorisation of electricity depending on $TRAS_E$ and BTAU.

The economic relief resulting from the reimbursement by the GSE of the described tariffs amounts to:

- €10/MWh for shared energy in collective self-consumption configurations.
- €8/MWh for shared energy in renewable energy communities.

1.2.3 Legislative Decree Implementing the RED II Directive

On 22 December 2020, the technical rules for accrediting RECs were published, and in the first months of 2021 the first configurations were activated. It has been shown that:

- The 200 kW capacity limit is suitable for residential and public buildings but represents a barrier to the installation of plants on large industrial surfaces, reducing attractiveness for the third sector [18].
- There is no incentive to install renewable energy sources (RES) other than photovoltaics, due to the small size of the plants and the non-differentiated incentive according to the type of plant [18]
- There are difficulties in creating residential user communities due to the secondary substation constraint. Geographically close users may be connected to different secondary substations, making the creation of RECs impossible even for interested users [18]

To overcome these critical issues and with the objective of promoting the formation of new energy communities, on 8 November 2021, the Italian government issued Legislative Decree 199/21 [19], the Decree that definitively transposes RED II. This was also necessary to accelerate the path towards the country’s sustainable growth, in line with the European decarbonisation targets.

As a first step, the concept of shared energy is modified, and defined as the minimum, in each hourly period, between the electricity produced and fed into the grid by renewable energy plants and the electricity withdrawn by the group of associated final customers located in the same market zone. Energy may also be shared through storage systems, and the generation and storage plants subject to sharing must be under the availability and control of the community.

Article 5 defines the general characteristics of the incentive mechanisms that reward RECs and collective self-consumption configurations in a scalable way, also based on plant capacity. Article 8 modifies the constraints of previously issued laws as follows:

- Renewable energy plants with an individual capacity not exceeding 1 MW may access the incentive.

- The incentive is granted only with reference to the share of energy shared by plants and consumption users connected under the same primary substation (MV/HV).
- The incentive is granted in the form of an incentive tariff applied only to the share of energy produced by the plant and shared within the configuration.

The main innovations are therefore represented by the possibility to expand the geographical area that may host production plants, and consequently the possibility to carry out larger-scale projects that can effectively meet the needs of an entire community.

For RECs, the Decree states that:

- The community is a legal entity and may include natural persons, SMEs, territorial bodies and local authorities, including municipal administrations, research and training institutions, religious bodies, third sector and environmental protection organisations, as well as local authorities listed in the register of public administrations published by the National Institute of Statistics (ISTAT), which are located within the municipalities where the sharing plants are situated.
- Regarding companies, participation in the renewable energy community may not constitute their main commercial and industrial activity.
- The members of the community use the distribution network to share the energy produced, also using storage systems, in accordance with the same rules established for citizen energy communities. Energy may be shared within the same market zone, provided that the requirement of connection to the same primary substation is met.
- Renewable energy plants for electricity generation developed by the community must have entered into operation after the entry into force of the Legislative Decree, without prejudice to the possibility of including existing renewable electricity generation plants, up to a maximum of 30 per cent of the total capacity attributable to the community.
- The community may generate energy from other renewable sources for use by its members, promote integrated home automation interventions, energy efficiency measures, as well as ancillary and flexibility services.

1.2.4 Testo Integrato Autoconsumo Diffuso

In 2022, ARERA issued the ‘Testo Integrato Autoconsumo Diffuso’ (TIAD) [20], which regulates the methods for calculating the amounts of energy that can be incentivised and for the valorisation of widespread self-consumption configurations provided for in Legislative Decree 199/21 [19]. Among the configurations taken into consideration, the following stand out:

- groups of renewable energy self-consumers acting collectively.
- groups of active customers acting collectively.
- renewable energy communities.

The TIAD reiterates the duties and limits within which a REC can be established and, with respect to previous decrees, adds that the electricity fed into the grid for sharing purposes must be produced by generation plants managed by a producer who is a member of the citizen energy community, or by third-party producers, including those other than the representative of the configuration, provided that, in relation to the electricity fed into the grid, said generation plants are under the availability and control of the community itself. This allows external companies to be part of RECs and to act as aggregators or managers of energy and economic flows, supporting users especially in technical aspects.

Furthermore, the methods by which the GSE:

- quantifies the self-consumed electricity on an hourly basis.
- allocates the self-consumed electricity to each production plant within the configuration.
- determines the valorisation of the self-consumed electricity.
- lays the foundations for the application of the incentive.
- defines the areas underlying the same primary substation and makes them available on an online map.

are also defined. In the case of RECs and individual remote self-consumers, the GSE calculates monthly the contribution for the valorisation of self-consumed electricity (E_{ACV}), equal to the product of the self-consumed electricity (E_{ACV}) and the unitary flat-rate monthly self-consumption fee ($CU_{Afa),m}$). Compared to the previous Decrees, the valorisation of self-consumption is reduced by the variable part of the distribution tariff, since the distribution network is used. Finally, since the self-consumption valorisation zone is now extended to the primary transformation substation, distinguishing between electricity shared within the same market zone and self-consumed electricity, in addition to the previously described changes for calculating the share of self-consumed energy, the TIAD extends the new rules to already existing configurations.

1.2.5 PNRR

The 'Piano Nazionale Ripresa e Resilienza' (PNRR) [21]represents a national investment plan covering sectors such as agriculture, industry, and digitalisation. In Mission 2 "Green revolution and ecological transition", it is emphasised that the ecological transition is fundamental, also to comply with the decarbonisation targets imposed by the European Union.
In Component 2 of Mission 2 (M2C2), defined as "Renewable energy, hydrogen, grid and mobility", five guidelines for reforms and investments are issued to:

- increase the share of energy produced from renewable sources.
- enhance and digitalise network infrastructures.
- produce hydrogen, promoting its distribution and end uses.
- develop sustainable local transport.
- develop competitive supply chains in Italy.

About renewable energy communities and the production of biomethane, reference is made to the first point mentioned above. In the PNRR, in fact, it is highlighted that the Government aims to provide support to energy communities, particularly in municipalities with a population of less than 5,000 inhabitants, to allow the installation of at least 1,730 MW of additional capacity from renewable sources with an expected expenditure of €2.2 billion. Similarly, €1.9 billion has also been allocated to the biomethane supply chain. In this case too, the aim is to support the construction of new plants for the production of biomethane in order to inject it into the grid or use it as fuel for agricultural machinery, with the goal of promoting a form of circular economy within primary sector companies, where waste products can be used to produce fuel, but also digestate that can be used for crops.

1.2.6 MASE Ministerial Decree

The last step for the current regulation of Renewable Energy Communities was the decree of 12/7/2023 called Decreto CACER [13], [16]. In this Decree, the methods of incentivization to support the RECs and the self-consumption configurations are defined. Furthermore, a scheme is defined for the provision of capital contributions of up to 40% of eligible costs for the configurations in municipalities with a population of less than 5,000 inhabitants as provided within the PNRR.

The beneficiary subjects to access the incentives must meet certain requirements such as the nominal power of the individual plant, which cannot exceed 1 MW, and that such plants and the points of production and withdrawal must fall under the same primary substation, as also specified in the TIAD.

To the share of energy shared through the portion of the distribution network under the same primary substation, an incentivizing tariff in the form of a premium tariff is attributed. This tariff takes effect from the date the plant enters into operation and lasts 20 years. The economic contribution is equal to the sum of the products on an hourly basis between the premium tariff and the incentivizes shared electricity.

$$C_{ACI} = \sum TIP_h * E_{ACI,h} \quad (1.1)$$

Where the incentivize shared electricity determined on an hourly basis is defined as:

$$E_{ACI,h} = \text{MIN}\left(E_{immessa,h}; E_{prelevata,h}\right) \quad (1.2)$$

And consequently, the injected and withdrawn energy:

$$E_{injected,h} = \sum_{y=1}^{n} E_{injected\,POD\,y} \quad (1.3)$$

$$E_{prelevata,h} = \sum_{y=1}^{n} E_{whitdrawn\,POD\,y} \quad (1.4)$$

In these equations, the injected and withdrawn energy corresponds to the incentivize energy expressed in kWh. The premium tariff TIP is variable on an hourly basis as it depends on the zonal price of the energy market and is defined as:

$$TIP_h = \{\text{MIN}[CAP; TP_{base} + \text{MAX}\,(0; 180 - Pz)] + FC_{zonale}\} * (1 - F) \quad (1.1)$$

TP_{base} is the base value of the tariff and is defined according to the power of the production plant:

60 €/MWh	With Pi > 600k W
70 €/MWh	With 200 kW < Pi <= 600 kW
80 €/MWh	With Pi <= 200k W

TABLE 1: BASE VALUE OF THE PREMIUM TARIFF

CAP is the threshold value of the applicable tariff:

100 €/MWh	With Pi > 600k W
110 €/MWh	With 200 kW < Pi <= 600 kW
120 €/MWh	With Pi <= 200k W

TABLE 2: CAP, MAXIMUM APPLICABLE PREMIUM TARIFF

FC_{zonale} is the tariff correction factor that considers the different levels of insolation of photovoltaic plants and is defined based on the location of the plant:

4 €/MWh	Centre
10 €/MWh	North

TABLE 3: TARIFF CORRECTION FACTOR FOR CENTRE AND NORTH REGIONS

The parameter F is related to the possible provision of a capital contribution. This varies linearly between 0, in the case the capital contribution is not used, and 0.5, in the case where the capital contribution equals 40% of the initial investment. This non-repayable funding falls within the guidelines expressed within the PNRR and concerns Renewable Energy Communities established in municipalities with a population of less than 5,000 inhabitants. In the capital contribution defined by the PNRR, the following expenses are eligible:

- Realization of renewable energy plants (for example: components, inverters, mounting structures, electrical components, etc.).
- Supply and installation of storage systems.
- Purchase and installation of machinery, plants, and hardware and software equipment, including expenses for their installation and commissioning.
- Construction works strictly necessary for the implementation of the intervention.
- connection to the national electricity grid.

- prefeasibility studies and expenses necessary for preliminary activities, including expenses necessary for the establishment of the configurations.
- design, geological and geotechnical surveys, the cost of which is borne by the designer for the project definition.
- work supervision, safety.
- technical and/or administrative testing, consulting and/or technical-administrative support essential to the implementation of the project.

Furthermore, the maximum reference investment cost is also defined as:

1050 €/MWh	With 600 kW < Pi <= 1.000 kW
1100 €/MWh	With 200 kW < Pi <= 600 kW
1200 €/MWh	With 20 kW < Pi <= 200 kW
1500 €/MWh	With Pi <= 20k W

TABLE 4: MAXIMUM CAPITAL CONTRIBUTION RELIEF ACCORDING TO THE PNRR BASED ON THE SIZE OF THE PLANT

1.3 Evolution of Italian Regulation for Biomethane Production

The reduction of greenhouse gas emissions and the growth of renewable energy production are two pillars of European socioeconomic policies. Through the stipulation of the 'Energy Roadmap 2050', the objective of the European Union is to achieve a reduction of 85%-90% in greenhouse gas emissions compared to 1990 levels by 2050[22]. In this context, bioenergy plays a fundamental role, as they can ensure their use in three crucial sectors such as the energy, thermal, and transport sectors. Specifically, starting from the second half of the 2000s, the production of biogas from anaerobic digestion experienced rapid development. The use and increase in the number of anaerobic digesters for biogas production was also made possible thanks to the versatility of the biomass that can be used, such as: organic waste, wastewater, livestock effluents, and residues from the agricultural and food supply chains.
To date, biogas is mainly used for the combined production of electricity and heat (CHP). Referring to 2019, in Europe there were 18,943 biogas CHP plants and 725 for upgrading biogas into biomethane. To underline the rapid growth of the sector, in 2024 there were more than 20,000 plants to produce biogas and more than 1,500 plants to produce biomethane [23], [24], which represent a growth of more than 50% in just 5 years. Furthermore, for the next 5 years, 27 billion euros have been allocated for the construction of new plants for the production of biomethane, with Denmark, Poland, and Italy as the driving forces of the sector.
The upgrading of biogas into biomethane in recent years has been favoured by several limitations in its use as a vector for heat production, since large amounts of the latter cannot be used on-site and the lack of infrastructure such as district heating leads to the loss of large amounts of energy. On the contrary, biomethane can be used in combined cycles with gas turbines, which achieve higher efficiencies compared to internal combustion engines used for biogas, it can be injected directly into the grid and thus used in places other than the production site, and finally, it can also be used as a fuel in the transport sector[22]. In addition to the technical evidence, this change in production has also been driven by the policies of individual states, which have incentivized the production of biomethane to the detriment of electricity production through biogas.

1.3.1 Laws for the Promotion of Biogas

Agricultural biogas is a renewable source closely linked to rural areas. In Italy, its development dates to the second half of the 2000s and has allowed the primary sector to achieve important objectives in terms of income diversification and improvement of the environmental performance of the livestock sector. All this was necessary because the Italian agricultural system suffers from certain structural weaknesses, such as the average size of farms, the low level of innovation, and the poor propensity for aggregation[25], [26]. It is therefore established that remuneration from agricultural products alone would have led Italian farms to fall victim to strong international competition. In this context, the Italian government implemented various forms of incentives for biogas production starting in 2008:

- DM 18 July 2008: the production of electricity from agricultural biogas effectively began following the introduction of the All-Inclusive Tariffs, which set the incentivizing tariff for the sale of electricity at €280/MWh. This incentive mechanism was reserved for plants with a nominal power not exceeding 1MW and remained in force until the end of 2012. This tariff was granted for 15 years and included an incentive component and a component for the valorisation of the electricity fed into the grid[26].
- DM 6 July 2012: sets reduced tariffs compared to the all-inclusive one, but valid for a duration of 20 years. The incentive system was modified in order to segment incentives based on the size of the plant and type of feedstock. This was done to promote plants up to 300kWe mainly powered by livestock effluents[26].
- DM 6 November 2014: offered plant owners the possibility of reducing the incentive received in exchange for extending the all-inclusive tariff incentive period by 7 years. However, the cut was such that it made the investment made a few years earlier economically unfeasible; therefore, the proposal was essentially not accepted by any agricultural plant. However, the clause of this decree provided, as a penalty, the prohibition of access to any type of electricity incentive at the end of the current one. This directive therefore represents an obstacle to electricity production by the plants once the incentives ended [26].
- DM 23 June 2016 represents a modification to the 2012 DM. One of the new features introduced by the new decree is the exclusion of the use of maize as feedstock for the

plants, as also provided by RED II. The tariffs provided by the new decree did not substantially change the incentive framework[26].

Most Italian biogas plants went into operation between 2009 and 2012, so those that benefit from the all-inclusive tariff will reach the end of the incentive period at the latest by 2027. In the five-year period between 2009 and 2014, from the GSE report on electricity production from renewable sources, one can observe an exponential trend of plants coming into operation with the electrical power produced doubling in the same period. Since the end of the all-inclusive tariff incentives, however, there has been a substantial standstill in the construction of new plants. This is highlighted by the fact that between 2022 and 2023 gross electricity production from biogas experienced a decline of -4.6%. Nonetheless, it remains a significant RES within the Italian energy portfolio—in fact, in 2023, 14% of the electricity produced from renewable sources was due to its combustion[27]. To date, no state incentives are planned for the commissioning of new biogas plants, and current bioenergy regulations aim to promote the development of biomethane for grid injection, transport use, or cogeneration. Starting in 2013, there have been three fundamental regulations for the development of the biomethane supply chain in Italy.

1.3.2 Laws for the Promotion of Biomethane

DM 5 December 2013: in the decree, the term *biomethane* is specified for the first time and is defined as biogas which, following appropriate chemical-physical treatments, meets the quality characteristics set by ARERA for injection into the natural gas grid. The decree incentivizes and allows the use of biomethane for grid injection, cogeneration, and as fuel for transport. It was applied to new plants that entered into operation from 18 December 2013 to 18 December 2018 or existing biogas plants converted, even partially, to biomethane production after 18 December 2013. The incentive guaranteed for the injection of biomethane into the grid corresponded to double the price of natural gas in 2012 minus the monthly average price of gas, and the incentive could also be increased by +50% if the plant was powered exclusively by waste and by-products of the agricultural supply chain. Furthermore, agricultural enterprises were entitled to a capital grant incentive of up to 40% of the investment [28].

DM 2 March 2018: promotes the use of biomethane and other advanced biofuels in the transport sector and represents a strategic measure aimed at promoting the use of renewable sources in transport, also through the development of circular economy initiatives and virtuous management of urban waste and agricultural residues. The plants that could access these incentives entered into operation after the entry into force of the decree, 20 March 2018, and no later than 31 December 2022. Plants producing advanced biofuels other than biomethane could also access the incentives. Biogas production plants converted to biomethane, which had already been incentivized for electricity production, could maintain the incentive for the remaining period on a share not exceeding 70% of the average annual incentivized production calculated from the date of commercial operation. The incentives provided for producers of biomethane released for consumption in transport were granted through the issuance of Certificates of Release for Consumption (CIC) plus a premium foreseen for certain raw materials, mainly by-products of the agricultural supply chain. Furthermore, the technical limits for the injection of biomethane into the grid were established, which are still in use today[29].

Carbon Dioxide	<= 2,5% [mol]
Oxygen (O_2)	<=0,6% [mol]
Higher Heating Value	34,95<HHV<45,28 [MJ/Sm3]
Wobbe Index	47,31<WI<52,33 [MJ/Sm3]
Relative density	0,555<rho<0,7 [-]

TABLE 5: CHARACTERISTICS OF THE BIOMETHANE INJECTED IN TO THE GRID

1.3.3 Ministerial Decree 15 september 2022 (Biomethane Decree)

The Decree originates in continuity with DM 2 March 2018 [29] and in coherence with the investment support measures provided by the transposition of the RED II Directive[4] with Decree 199/21[19] and by the PNRR[21], which, in mission 2, specifies the measure “Development of biomethane according to criteria for the promotion of circular energy” in order to support investments for the construction of new biomethane production plants and for the total or partial conversion of existing biogas plants. To promote the injection of biomethane into the grid, two types of incentives have been implemented: one as a capital grant and one as an energy-based incentive. The eligible expenses for the capital grant contribution can amount to a maximum of 40% of the investment incurred and may include in this incentive the expenses for:

- the costs of construction and upgrading of the plant such as the infrastructures and machinery necessary for the management of the biomass and the anaerobic digestion process, for the storage of the digestate, the construction of the biogas purification plant, the transformation, compression and storage of the biomethane and CO_2, the construction of the systems and equipment for the company's self-consumption of biomethane[30], [31].
- the equipment for monitoring and oxidation of the biomethane, the exhaust gases and monitoring of fugitive emissions [30], [31].
- the costs of connection to the natural gas grid [30], [31].
- the costs for the purchase or acquisition of software programs functional to the management of the plant [30], [31].
- the expenses for design, project management, testing, consultancy, feasibility studies, purchase of patents and licenses, related to the realization of the above-mentioned investments, up to a maximum overall amount of 12% of the total eligible expenditure.
- the costs for the composting phase of the digestate [30], [31].

However, there is a ceiling for the capital grant contribution that can be requested based on the type of plant and its size. For the construction of new biogas upgrading plants on agricultural sites:

Capacity<= 100 Smc/h	13.200€/Smc/h
100< Capacity<= 500 Smc/h	11.600€/Smc/h
Capacity> 500 Smc/h	5.200€/Smc/h

TABLE 6: CEILING FOR THE CAPITAL GRANT FOR BIOMETHANE PLANT

About the incentivising tariff in the form of feed-in premium, it is determined starting from the reference tariff set as the base auction price in the respective competitive procedures. The reference tariff is identified according to the type of plant and its production capacity. For the years 2022 and 2023 the reference tariff value was:

Capacity <= 100 Smc/h	115 €/MWh
Capacity > 100 Smc/h	110 €/MWh

TABLE 7: REFERENCE TARIFF FOR BIOMETHANE IN 2022 AND 2023

Whereas, for the years 2024, 2025, 2026 the reference tariff is determined by applying a 2% reduction compared to the values previously indicated:

Capacity <= 100 Smc/h	112,7 €/MWh
Capacity > 100 Smc/h	107,8 €/MWh

TABLE 8: REFERENCE TARIFF FOR BIOMETHANE IN 2024, 2025 AND 2026

The offered tariff is calculated by applying to the reference tariff the percentage reduction offered by the applicant at the time of participation in the procedure, in order to benefit from the corresponding priority criterion in the auction base. This reduction can reach a maximum of -1% of the reference tariff. Finally, the entitled tariff is calculated by applying to the offered tariff a further reduction in case of failure to comply with the maximum entry-into-operation deadlines for the plant, which corresponds to -0.5% of the incentivising tariff for each month of delay, up to a maximum limit of nine months.

The Decree [30], [31] provides for two different incentive mechanisms based on the production capacity of the plant:

- All-Inclusive Tariff (TO) consisting of a single tariff corresponding to the entitled tariff, including the economic value of the sale of natural gas and the value of the Guarantees of Origin (GO). For plants benefiting from the TO, the GSE guarantees the purchase of biomethane injected into the grid with third-party connection obligation and the allocation of biomethane to the market.

- Premium Tariff (TP), calculated as the difference between the entitled tariff and the sum of the average monthly price of natural gas and the average monthly price of GO. For plants benefiting from the TP, the sale of biomethane is the responsibility of the plant.

The TO can be requested by the plant owner in the case of production capacity up to 250 Smc/h. Therefore, these can choose the provision of either TO or TP. In the case of plants with production capacity greater than 250 Smc/h, these can only access the TP. In the specific case of biomethane production plants directly connected to the grid with third-party connection obligation, we can define the algorithms for the calculation of the incentivising tariffs as follows:

For TO

$$I_n = (T - P_{GME}) * \text{MIN}(M1_n; M_s; M_{max}) * PCS1_n * (1 - \%SA) + M1_n * PCS1_n * P_{GME} \quad (1.5)$$

For TP

$$I_n = (T - P_{GME}) * \text{MIN}(M1_n; M_s; M_{max}) * PCS1_n * (1 - \%SA) - GO * P_{GO} \quad (1.6)$$

Where:

- I_n = incentive related to the production of month n.
- T = entitled tariff.
- $M1_n$ = monthly quantity of biomethane measured at the injection point into the grid with third-party connection obligation, expressed in Sm3.
- M_s = quantity of sustainable biomethane for month n, related to the specific configuration and reported in the sustainability certificate, expressed in Sm3. It is specified that for the purposes of applying the algorithm, biomethane that meets the value of greenhouse gas emission reduction is considered sustainable.
- M_{max} = maximum monthly producibility.
- $PCS1_n$ = monthly average value, weighted by quantities, of the higher heating value, expressed in kWh/Sm3, determined based on the chemical composition of the biomethane.

- %SA = percentage related to energy consumption attributable to auxiliary plant services.
- PGME = monthly average price of natural gas, weighted by quantities, recorded on the day-ahead natural gas market (MGP-GAS) in continuous trading and on the natural gas intraday market (MI-GAS) in continuous trading managed by the Energy Markets Operator (GME).
- GO = number of Guarantees of Origin of biomethane issued in agreement.
- PGO = monthly average price of the GOs.

Chapter 2 – Energy Load Analysis in Agricultural Enterprises and Renewable Energy Communities

2.1 Territorial Context

This section examines the characteristics of the Piedmont region from an agricultural and livestock farming perspective, with a particular focus on cattle husbandry. Specifically, the study will concentrate on the small rural municipality of Cardè (Province of Cuneo), with a population of fewer than 5,000 inhabitants, which has been selected as the proposed site for the farm enterprise.

2.1.1 The Agricultural Context of Piedmont: Key Characteristics and Trends

In Italy, the bovine livestock farming sector is concentrated in the northern regions, which account for approximately 71% of the roughly five and a half million heads of cattle in Italy. Piedmont holds 14.3% alone, ranking second only to Lombardy[32]. Moreover, Piedmonts farms are among the largest in terms of livestock numbers, with an average of around 83 cattle per farm in 2020. The trend in recent years, where the number of farms is decreasing while the total herd size remains stable, suggests that by 2025, a single farm may house around a hundred cattle. One of the areas with the highest concentration of livestock and bovine farming is the province of Cuneo. According to the *Anagrafe Agricola Unica* (Single Agricultural Register), updated to 2011, there are just under 5,000 farms specialised in cattle rearing, with over 400,000 heads, particularly concentrated in lowland areas [32]. However, this intensive farming activity exerts significant environmental pressure, primarily due to ammonia emissions and nitrates that seep into aquifers. Notably, nitrate concentrations in shallow groundwater exceed European directive standards. As a result, the Piedmont Region was compelled to designate *Nitrate Vulnerable Zones (NVZs)*, where manure application is restricted to 170 kg N/ha/year—half the standard limit[22]. Thus, the possibility of removing ammonia from manure through anaerobic digestion processes represents a major opportunity for the region in reducing groundwater and soil pollution. Additionally, the high density of cattle reduces feedstock supply distances for large cooperatives or consortia. In fact, since 2008, with the introduction of the *tariffa* *omnicomprensiva* (all-inclusive tariff) incentives, biogas plants in Piedmont have grown exponentially, reaching an annual production of 1 TWh by 2019[22].

2.1.2 Geographical Setting: The Case of Cardè

This study examines the potential for developing an integrated energy infrastructure in the municipality of Cardè, in the province of Cuneo, based on the local production and utilisation of renewable energy. While not referring to a specific farm, the initiative is founded on a hypothetical yet territorially coherent project design, modelled to represent either a single medium-sized farm or a consortium of local livestock farms. The project aims to assess the techno-economic feasibility and energy potential of establishing a Renewable Energy Community or, alternatively, a biogas plant utilising cattle effluent in a rural context. Cardè is a municipality located on the border between the provinces of Cuneo and Turin, with a population of 1,147 inhabitants and an area of 19 km². Despite its small population and limited size, according to the ARPA Piemonte report [33], Cardè hosts between 30 and 50 farms, with an estimated 5,000–10,000 head of cattle.

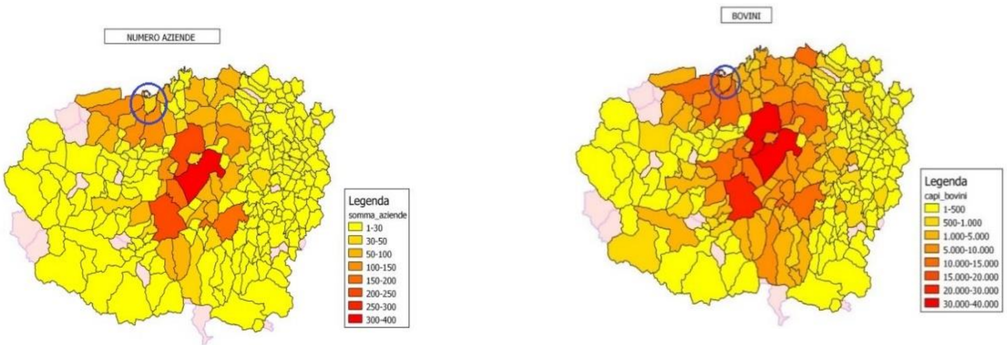


FIGURE 1;DISTRIBUTION OF AGRICULTURAL ENTERPRISES AND CATTLES IN THE PROVINCE OF CUNEO [SOURCE [33]]

This confirms the area's strong agro-livestock vocation and supports the hypothesis of farms with significant cattle numbers. Furthermore, it could justify the potential for collective energy and effluent management through cooperative models between adjacent farms or those integrated into shared production chains.

Being a municipality with a population below 5,000 inhabitants, the Renewable Energy Community (REC) to be established would be eligible for the 40% capital contribution allocated by the National Recovery and Resilience Plan (PNRR) for the construction of the electricity generation plant. It is also important to highlight that the entire municipality falls under the same primary substation, as demonstrated by the interactive map provided by the GSE. From an infrastructural perspective, the municipality has a well-distributed medium-voltage electrical grid across its territory. Additionally, a municipal gas network is accessible in the urban area, although there are no natural gas pipelines directly connected to peripheral agricultural zones. This does not preclude, in perspective, the possibility of evaluating biomethane injection into the grid. Thus, the simultaneous availability of large quantities of livestock effluents, surfaces suitable for photovoltaics, and a high number of potentially interested participating farms, makes Cardè an extremely suitable territorial context for testing an agro-livestock energy community model based on shared production, self-consumption and on-site exchange of renewable energy, with distributed environmental, economic and social benefits.

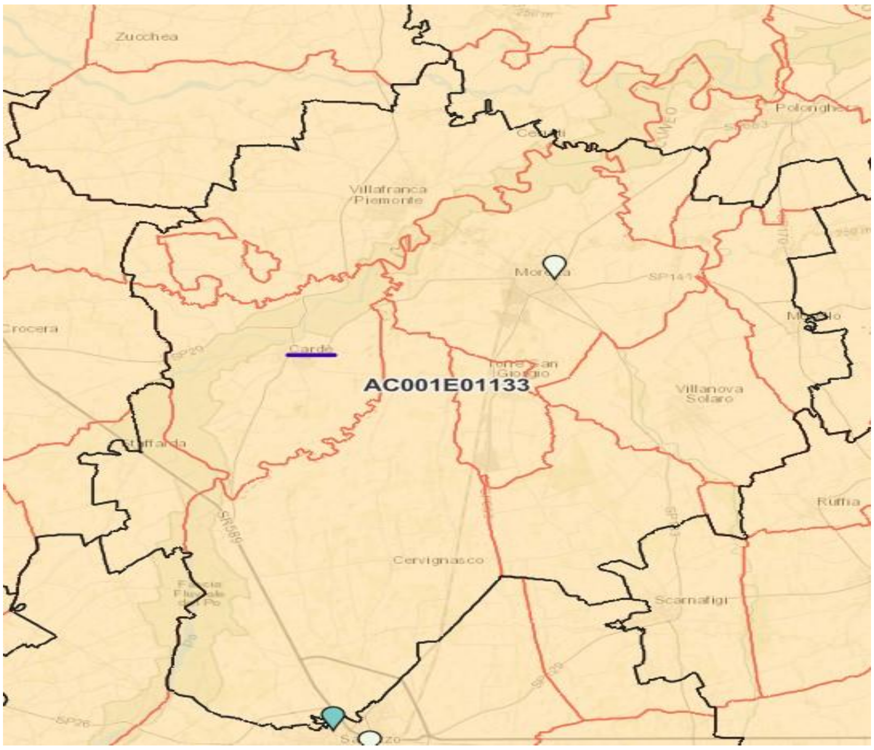


FIGURE 2: MAP OF THE PRIMARY SUBSTATION WHICH INCLUDES CARDÈ [SOURCE [GSE]]

2.2 Agricultural Enterprise Features

In estimating the energy potential obtainable from biomass produced in the livestock sector, a determining factor is represented by farm size: this directly affects both the technical feasibility of collecting and handling effluents, and the economic viability of their energy conversion through anaerobic digestion. National technical and regulatory literature identifies 50 head of cattle as the minimum threshold to begin considering energy recovery as technically feasible, although not always economically advantageous.

Below this threshold, in fact, the modest quantities of manure, the non-optimal material composition (e.g., low moisture or high straw content), and the structural simplicity of farms (lack of centralised collection systems, storage or separation facilities) make the integration of innovative biogas production technologies difficult or uneconomical. In these cases, the only viable path remains the consortium approach, based on multiple farms supplying effluents to a centralised plant, or co-digestion with other biomasses (OFMSW [Organic Fraction of Municipal Solid Waste], agro-industrial by-products).

However, above 100 head of cattle, a size threshold is reached that is considered, under certain conditions, already technically and economically suitable for the implementation of an on-farm plant. Supporting this threshold, the analysis conducted at national level shows that, while reducing the number of farms by 91% compared to the total (excluding those with fewer than 100 head), the reduction in terms of livestock numbers is much less pronounced, with a loss of only 42% of the total number of cattle. In the specific case of Piedmont, the effect is even less pronounced: at the same threshold (100 head), a reduction in livestock numbers of only 40% is observed[34].

2.2.1 Livestock Farming Activity and Effluent Production

The fictional farm under examination has a herd consisting of 840 cattle, raised for milk production purposes. The quantity of manure produced daily, and the associated electrical and thermal requirements of the livestock operation depend on a plurality of factors. Among the most significant are the live weight of the animals, the production purpose (meat, milk, or mixed), the type of housing adopted, as well as the methods of effluent removal and storage.

However, such specific information can only be obtained through a detailed technical analysis at farm level. To date, there are no national statistical sources providing standardised data on these parameters for individual livestock farms. For this reason, for the purposes of this study, the estimate of manure production was based on the values indicated in an ISTAT publication[34], which reports the quantities of liquid and solid manure produced as a function of live weight, age group and production purpose of the animals.

The herd has been divided into three age classes: 0 to 12 months, 12 to 24 months, and over 24 months. The herd composition, based on average data from actual operating livestock farms, is as follows:

- 324 calves (0–12 months)
- 60 heifers (12–24 months)
- 456 adult cows (over 24 months)

Each category corresponds to an average live weight of 200, 400 and 650 kg respectively, with an associated Livestock Unit (LU) value of 0.4 – 0.6 – 1. For the evaluation of the electrical and thermal loads of the barn, to be carried out in the next paragraph, the total number of LU is certified to be 621.6. The manure produced is divided into solid and liquid. For the quantity estimation, the presence of straw was also considered, amounting to 5 kg per tonne of live weight per day in the case of fixed housing, as it contributes to the volume of solid matter. The coefficients used for calculating daily production are:

- Liquid: 5.3 – 6.8 – 8.2 litres per 100 kg of live weight per day, respectively for the three age classes
- Solid: 0.66 – 0.82 – 1.05 kg of solid matter per 100 kg of live weight per day, respectively for the three age classes

The results obtained through these parameters are summarised in the following table:

	Liquid [kg/day]	Solid + Straw [kg/day]
0-12 months	3434,4	751,68
12-24 months	1632	316,8
>24 months	24304,8	4594,2
Total [t/day]	29,37	5,66

TABLE 9: LIVESTOCK TOTAL EFFLUENTS PER DAY

In conclusion, the total annual manure production amounts to 12,787 t.

2.2.2 Farm's Electrical and Thermal Loads Specification

For the determination of the farm's electrical and thermal loads, reference was made to a study conducted by the Animal Production Research Centre (CRPA) [35], [36]. This study shows that in Italy, the electrical energy consumption per Livestock Unit (LU) is 462 kWhel/LU, while the average annual consumption of methane for thermal energy is approximately 28 m^3/LU, equivalent to 567 kWhth/LU.

The energy consumption has been divided by usage type within the barn:

- Feeding: Represents one of the most energy-intensive operations in cattle farming. Most farms adopt total mixed ration (TMR) systems, which require electrical and thermal equipment for feed mixing and distribution. These are supplemented by devices for artificial calf feeding and automated feeders, particularly present in more modern facilities. The average electrical consumption for these operations is 79.3 kWh/year per LU, while thermal consumption stands at around 437.2 kWh/year per LU. The latter mainly derives from the use of thermal engines in TMR mixers, milk preheating or pasteurisation systems, and the operation of boilers or feed preparation plants.
- Summer ventilation: During hot months (May to September), emergency fans are necessary to prevent heat stress in livestock, especially in enclosed barns or those with high animal density. These systems, operating primarily during peak daylight hours,

consume on average 93.2 kWh/year per LU of electrical energy. The adoption of more efficient technologies remains limited, indicating potential for energy improvement. Nevertheless, forced ventilation is often essential to ensure animal welfare, preventing productivity drops or health issues during heatwaves.

- Bedding and effluent management: Effluent management represents a structural energy cost for every livestock operation. Activities include removal, handling, storage and distribution of slurry and manure, plus bedding management. Mechanical removal via tractors or fixed systems results in average electrical consumption of 38.2 kWh/year per LU. The thermal component is even more significant: an estimated 41,2 kWh/year per served animal for effluent removal, plus additional thermal demands for storage and bedding management. These consumptions are justified by operational complexity (loading/unloading with heavy machinery, pumping, tractors, etc.) and the large quantities of material to be handled, especially on large farms. Proper effluent management is essential both environmentally and for regulatory compliance, representing a priority area for energy efficiency.
- Lighting: Lighting represents a constant energy component, often underestimated but distributed across multiple operational areas. In housing areas (barns), the average annual consumption is 19.9 kWh per LU, supplemented by consumption for service buildings (6.2 kWh/LU) and external lighting (9.1 kWh/LU), totalling approximately 34.7 kWh/year per LU. The need to work safely during evening/night hours, prolonged use during cold seasons, and separate operational zones (barns, silos, warehouses, offices, yards) explain these values.
- Milking area: The milking parlour represents one of the most technologically equipped areas of the barn and consequently one of the most energy-intensive. Mechanical milking operations, plant washing, milk cooling and sanitary water heating generate significant consumption. The average annual consumption per lactating cow is: 76,1 kWh of electrical energy for milking and washing, 55,8 kWh for milk tank cooling, 54,3 kWh of thermal energy for hot water production.

The following table summarises the annual electrical and thermal energy consumption data per LU for the different usage types within the barn:

Operation	Electrical Load [kWh/yr/LU]	Thermal Load [kWh/yr/LU]
Feeding	79,3	437,2
Ventilation	93,2	0
Milking	76,1	54,3
Milk cooling	55,8	0
Manure removal	38,2	41,2
Lighting	34,7	0
Manure treatment	84,8	34,4
Total	462,1	567,1

TABLE 10: ELECTRICAL AND THERMAL LOAD FOR EACH APPLIANCE

To evaluating the daily load profile, two typical days of operation from an actual existing farm [37]were analysed. The days considered correspond to a summer day and a winter day respectively, to represent seasonal variations in energy consumption. These differences manifest significantly for certain specific loads: for example, emergency ventilation operates exclusively during hot months, while artificial lighting requirements are greater in winter months due to reduced availability of natural light.

The following table shows the operating time slots of main equipment, categorised by load type. For each item, in addition to activation and deactivation times, the operational load level is indicated to distribute electrical and thermal loads evenly throughout the day, providing a representative estimate of both absorbed power and actual usage duration.

HOUR	FEEDING	VENTILATION	MILKING	MILK COOLING	MANURE REMOVAL	LIGHTING	MANURE TREATMENT
00:00	0	0	0	1.26	0	0	1
01:00	0	0	0	1.26	0	0	1
02:00	0	0	0	1.26	0	0	1
03:00	0	0	0	1.26	0	0	1
04:00	0	0	0	1.26	0	0	1
05:00	0	0	0	1.26	0	0	1
06:00	0	0	4	1.26	3.43	0	1
07:00	0	0	4	1.26	3.43	0	1
08:00	0	0	4	1.26	0	0	1
09:00	3	0	0	1.26	3.43	0	1
10:00	3	2	0	1.26	3.43	0	1
11:00	3	2	0	1.26	0	0	1
12:00	3	2	0	0	0	0	1
13:00	3	2	0	0	0	0	1
14:00	3	2	0	0	0	0	1
15:00	3	2	0	0	0	0	1
16:00	3	2	0	0	0	0	1
17:00	0	2	4	1.26	3.43	0	1
18:00	0	2	4	1.26	3.43	0	1
19:00	0	2	4	1.26	0	0	1
20:00	0	2	0	1.26	3.43	0	1
21:00	0	2	0	1.26	0	0	1
22:00	0	0	0	1.26	0	0	1
23:00	0	0	0	1.26	0	0	1

HOUR	FEEDING	VENTILATION	MILKING	MILK COOLING	MANURE REMOVAL	LIGHTING	MANURE TREATMENT
00:00	0	0	0	1.26	0	0	1
01:00	0	0	0	1.26	0	0	1
02:00	0	0	0	1.26	0	0	1
03:00	0	0	0	1.26	0	0	1
04:00	0	0	0	1.26	0	0	1
05:00	0	0	0	1.26	0	0	1
06:00	0	0	4	1.26	3.43	4	1
07:00	0	0	4	1.26	3.43	4	1
08:00	0	0	4	1.26	0	4	1
09:00	3	0	0	1.26	3.43	0	1
10:00	3	0	0	1.26	3.43	0	1
11:00	3	0	0	1.26	0	0	1
12:00	3	0	0	0	0	0	1
13:00	3	0	0	0	0	0	1
14:00	3	0	0	0	0	0	1
15:00	3	0	0	0	0	0	1
16:00	3	0	0	0	0	0	1
17:00	0	0	4	1.26	3.43	4	1
18:00	0	0	4	1.26	3.43	4	1
19:00	0	0	4	1.26	0	4	1
20:00	0	0	0	1.26	3.43	0	1
21:00	0	0	0	1.26	0	0	1
22:00	0	0	0	1.26	0	0	1
23:00	0	0	0	1.26	0	0	1

TABLE 11: DAILY SCHEDULE FOR FARM'S APPLIANCES IN TWO TYPICAL DAYS: SUMMER AND WINTER

In this way, knowing the number of LUs and the machinery usage routine during the days, it was possible to construct electrical and thermal load profiles for two different typical days:

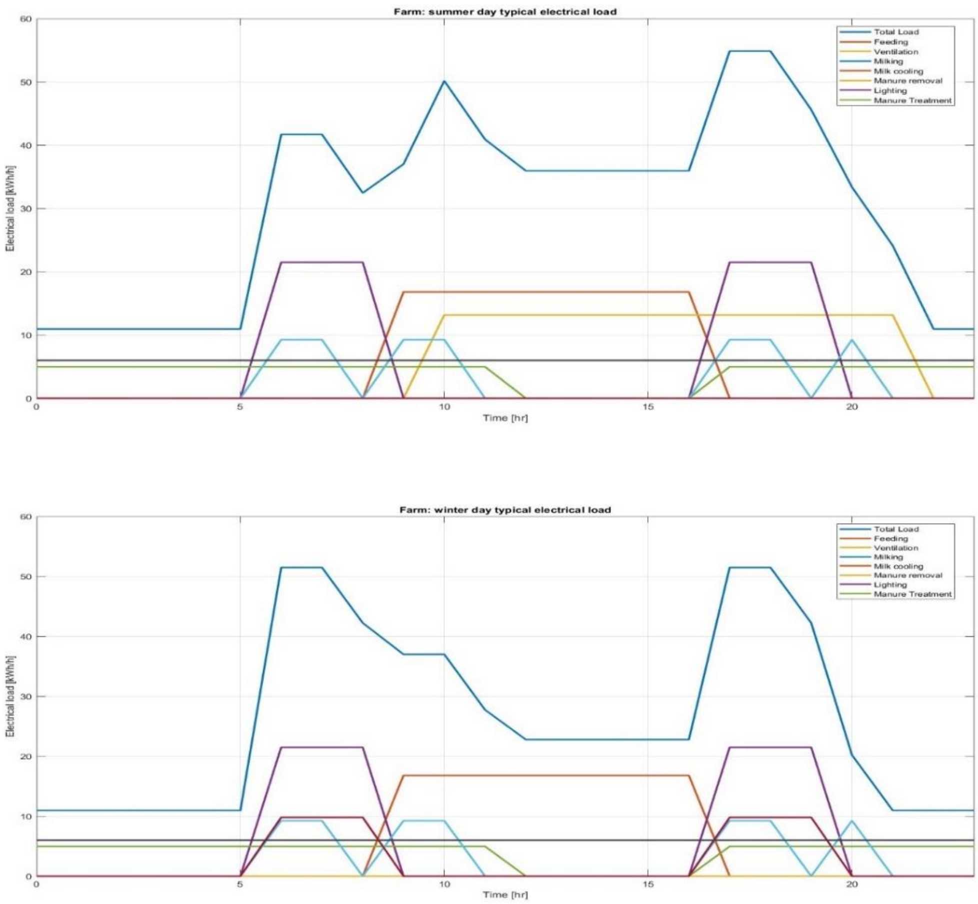


FIGURE 3: FARM ELECTRICAL LOAD FOR SUMMER AND WINTER DAY

From the analysis of the graphs, it clearly emerges that the daily electrical load does not vary significantly according to season. However, it can be observed that during summer days, electricity consumption is higher during daylight hours, primarily due to the activation of the ventilation system required to ensure environmental cooling and animal welfare. Conversely, in winter periods, two electrical consumption peaks are observed, occurring respectively in the morning and evening, attributable to the intensification of artificial lighting needed to compensate for reduced natural light availability.

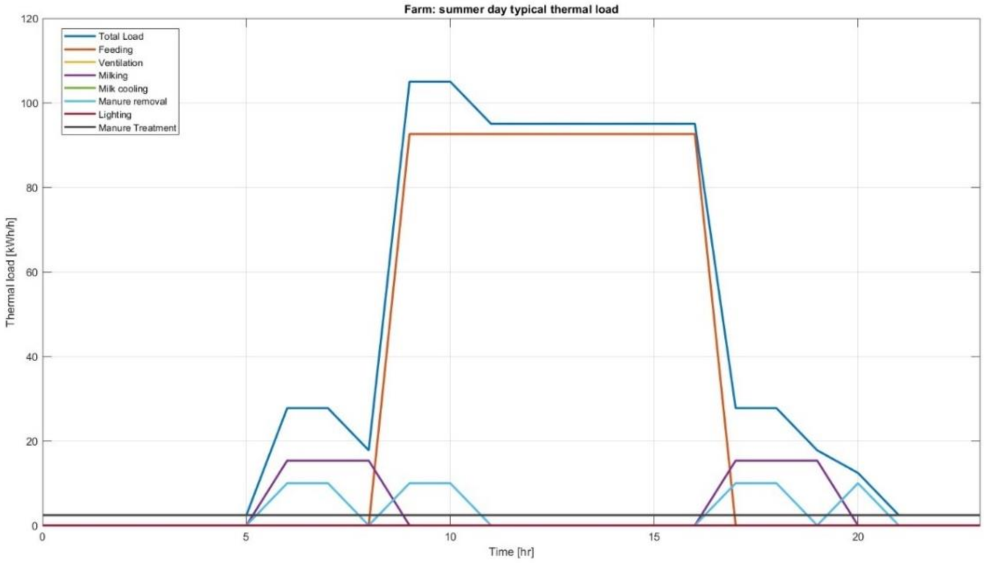


FIGURE 4: FARM THERMAL LOAD FOR SUMMER AND WINTER DAY

As for the thermal load, the two seasonal profiles are essentially overlapping. This behaviour can be attributed to the fact that summer cooling is performed exclusively by electric fans and therefore does not involve additional thermal consumption. The systems requiring thermal energy, such as those related to feeding, calf rearing or bedding management, maintain a virtually constant frequency and intensity of use throughout the year, resulting in a seasonally stable thermal demand.

Ultimately, the annual electrical load of the barn amounts to 246,780 kWh, while the annual thermal load amounts to 450,840 kWh.

2.3 Analysis of the Residential Context in the Municipality of Cardè

To define the composition of the Renewable Energy Community (REC) under study, the participation of 75 domestic users has been hypothesized, each with a committed power of 3 kW. This value represents a technical standard widely used among Italian residential users, particularly in rural contexts, and is adequate to cover the average needs of a household.

This choice is supported by demographic data provided by ISTAT, according to which the Municipality of Cardè has 1,134 inhabitants, with an average of 2.5 people per household. This results in an estimate of approximately 450 families. The hypothesis of involving 75 users therefore corresponds to a share of about 17% of the total, a value consistent with an initial phase of REC formation, in which limited but representative participation of the population is expected. To reinforce the social coherence of the hypothesized composition, it is useful to observe some percentages related to the family types present in the municipality, also taken from ISTAT data. Young couples with children represent 7.8% of the population, young couples without children 3.1%, young single-parent families 1.6%, and young individuals living alone 4%. These categories have been considered as the demographic groups most inclined to participate in a collective project based on sustainability, both for economic reasons and for a growing focus on environmental issues. Young people tend to show greater sensitivity to climate change and a marked tendency to adopt innovative solutions. Their participation in a REC can be seen as a social and cultural investment, as well as an economic one, and as a form of active protagonism in the energy transition, a crucial point in the establishment of a REC.

In this sense, the hypothesized composition of the 75 domestic users reflects a balance between technical realism, demographic consistency, and potential social involvement, constituting a solid basis for energy modelling and the simulation of shared energy flows.

2.3.1 Definition of Electrical Loads

For the evaluation of the electrical loads associated with the domestic users of the Renewable Energy Community, an open-source code developed in Python language by the CADEMA research group of the DENERG department at the Politecnico di Torino was used. The code is called RECOpt and is publicly available through a GitHub repository[7]

This tool is designed to optimize the combined operation of a photovoltaic system and a battery storage system, both of which can be configured with fixed or variable sizes. The main objective of the code is to conduct parametric analyses aimed at evaluating and optimizing the energy performance of groups of self-consumers or entire energy communities located in the Italian territory. As regards the estimation of photovoltaic production, the code requires as input a set of annual production data related to the plant under analysis. However, for the analysis of electricity consumption profiles, a dedicated module for the stochastic generation of load profiles is provided: the file *aggregate_load_profiler.py*. In this phase of the analysis, photovoltaic production was temporarily excluded to isolate and independently evaluate the aggregated electricity demand of the users. Therefore, only the Python module *aggregate_load_profiler.py* was executed, which is responsible for generating the load profiles. The module uses a bottom-up approach, initially constructing the usage profile of each appliance, then that of a single dwelling, and finally aggregating the profiles of a specified number of users.

The profile generator allows for the creation of typical days that are representative of user behaviour, distinguishing between weekdays and holidays and between the four seasons of the year. In total, the code returns eight daily profiles, each with high temporal resolution. The routine is based on real datasets derived from measurement campaigns conducted on a national scale. In particular, reference is made to the MICENE project (MIsure dei Consumi di ENergia Elettrica), promoted by the eERG (end-use Efficiency Research Group), which monitored the electricity consumption of 110 Italian households for several weeks with a resolution of 10 minutes, and to the REMODECE project, which provides additional data on appliances such as electric ovens and microwaves [5], [7]

To perform the simulation of the aggregated load profiles, it is necessary to provide the code with the following input parameters:

- Number of dwellings to simulate.
- Desired time resolution (from 1 to 60 minutes).
- Average number of people per dwelling.
- Average surface area of the dwellings.
- Maximum contractual power for each user.
- Geographic location (North, Central, South Italy).
- Prevalent energy class of the dwellings

This approach allows for the generation of realistic and representative electricity demand profiles, on a probabilistic basis, reflecting the geographic, behavioural, and technological variability of Italian households. These profiles constitute the basis for the subsequent energy analysis, in which demand will be compared with production from renewable sources within the framework of the REC.

For simulating the electrical load profiles using the module *aggregate_load_profiler.py*, it was necessary to define a set of input parameters capable of realistically representing the typical characteristics of domestic users involved in the Energy Community. The total number of dwellings simulated is 75, as defined in the previous paragraph. These dwellings were divided according to the energy class, referring to the data reported in the *Annual Report on the Energy Certification of Buildings* [38], drafted by ENEA in collaboration with the Regions and Autonomous Provinces. Climatic zone E was considered, which includes the territory of the Municipality of Cardè. In the report, the percentage distributions of the Energy Performance Certificates (APE) for each energy class in the various Italian climatic zones are shown. For zone E, it emerges that dwellings with classes lower than D (i.e., E, F, and G) constitute the absolute majority. However, since the simulator does not allow for direct representation of classes lower than D, these have been aggregated into the latter.

The final distribution used for the 75 simulated users is therefore the following:

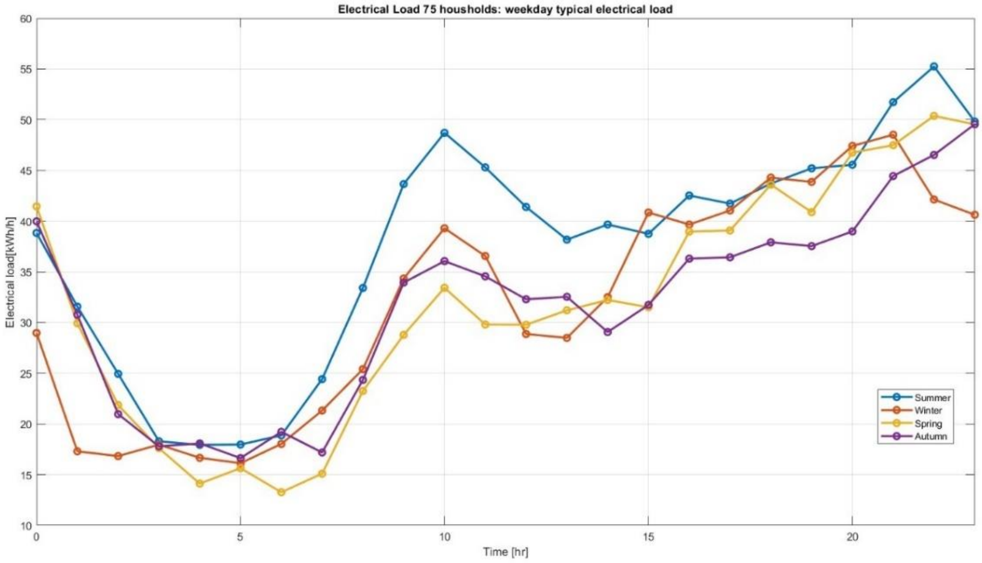
- 6 users in class A+++ (A4).
- 5 users in class A++ (A3).

- 5 users in class A+ (A2).
- 5 users in class B.
- 5 users in class C.
- 49 users in class D (including buildings actually in class D, E, F, and G).

The other parameters provided to the simulator were chosen in coherence with the territorial and sociodemographic context:

- Average number of people per dwelling: 2.5, value obtained from ISTAT data relating to the resident population of the Municipality of Cardè.
- Average dwelling surface area: 110 m^2, a typical value for single-family or two-family homes in rural settings.
- Geographical location: Northern Italy, to correctly reflect the climatic zone and the related energy use profiles.
- Contractual power: 3 kW per user, standard configuration for homes with average consumption.

These parameters allowed the generation of aggregated and seasonal electrical load profiles, distinguishing between weekdays and holidays, with a temporal resolution suitable for subsequent energy balance analyses of the REC. In the following images, the daily load profiles of the users for two typical days, weekday and weekend day, during the seasons are shown as examples:



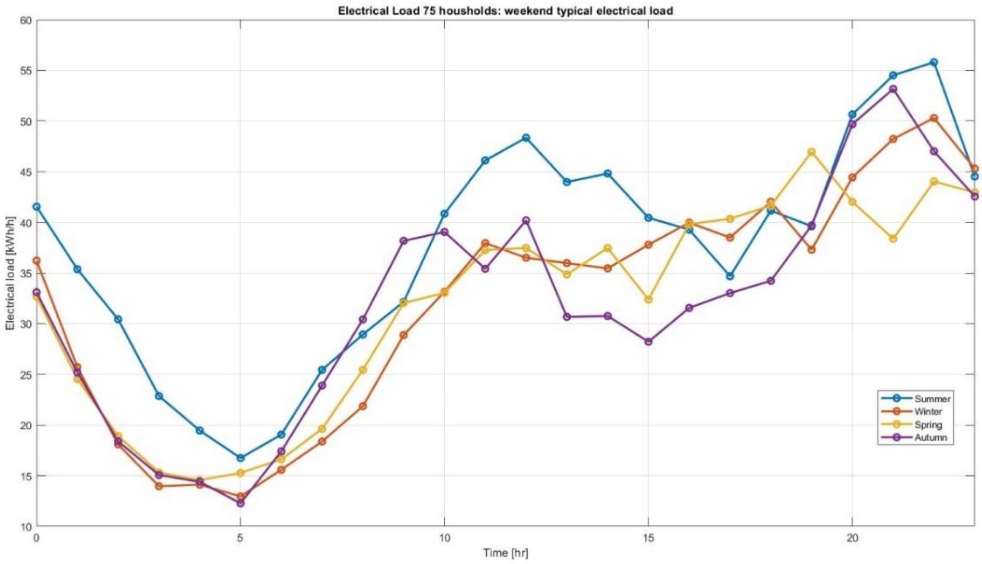
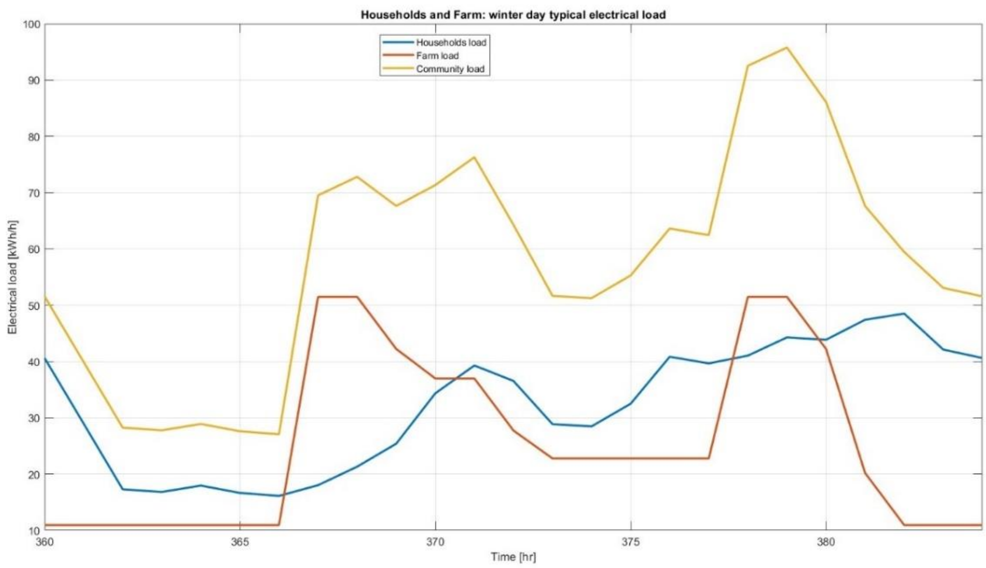


FIGURE 5: 75 HOUSEHOLDS LOAD FOR WEEK AND WEEKEND DAYS

From the analysis of the daily load profiles generated for the 75 domestic users, represented in the graphs, it is possible to observe how the summer season shows the highest values of electricity consumption, particularly during daylight hours. This behaviour is mainly attributable to the use of cooling systems, which significantly increase electricity demand during the hottest hours of the day. The profile clearly highlights the presence of two main peaks: one in the early afternoon hours and a more marked one in the evening period, as well as a significant reduction in consumption during nighttime hours. From the comparison between weekdays and holidays, a similar trend can be observed in the general shape, but with a reduction in consumption during the central hours of weekdays, presumably due to the absence of occupants for work-related reasons. On holidays, on the contrary, consumption is more evenly distributed throughout the day. Based on the aggregation of the simulated data for the different seasons and day types, it was possible to estimate the total annual electricity consumption of the 75 dwellings under study, equal to approximately 296,290 kWh/year.

2.4 Total Electric Load and Energy Expenditure

Once the daily and seasonal electric load profiles were defined for the 75 domestic users considered in the Energy Community, it was possible to proceed with an estimate of the total annual energy consumption. This assessment represents a fundamental step to understand the aggregate energy needs of the community and to carry out a preliminary analysis of the costs incurred in the absence of self-production or self-consumption systems. In the following images, the daily load curves for two typical days are presented: one winter day and one summer day:



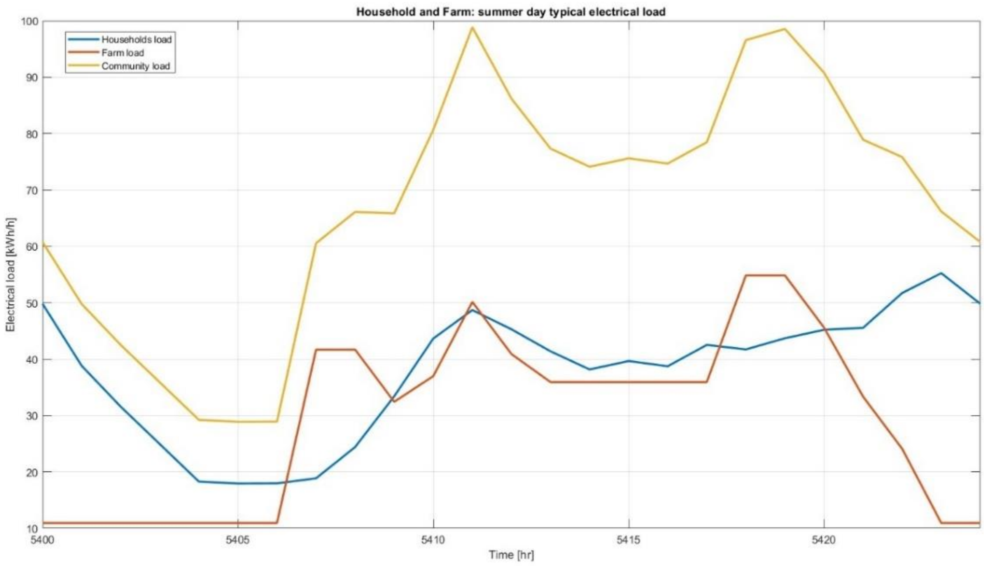


FIGURE 6: FARM AND 75 HOUSEHOLDS CUMULATE ELECTRICAL LOAD FOR WINTER AND SUMMER DAYS

Once the annual electric loads of all users were defined, the annual energy expense was established. For the residences, only the expense related to electric energy was evaluated, while for the agricultural company, the expense for natural gas used to provide thermal energy for various company processes was also assessed. The price of electric energy was derived from the average cost of electricity in the variable tariff retail market in Italy in 2024, communicated by ARERA, amounting to 227.4 €/MWh, while the gas cost, also obtained from ARERA, is 1.129 €/sm3 for industrial customers with a natural gas consumption between 5,000 and 50,000 standard cubic meters per year, with reference year 2022.

For each residence, therefore, the total annual expense for the supply of electric energy corresponds to 898.36 €, while for the agricultural company it is about 56,117 €. Regarding the gas consumption expense in the agricultural company, it amounts to 47,570 €.

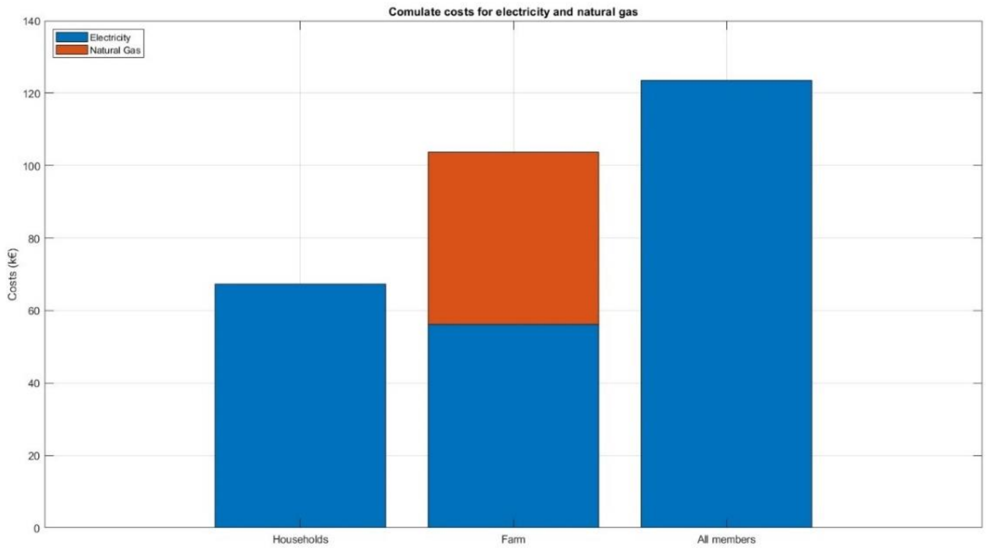


FIGURE 7: ENERGY SUPPLY YEARLY EXPENDITURE

Chapter 3 – Energy System Configuration Design

In the next chapter, the energy and economic performance of a renewable energy community composed of a farm, acting as a prosumer, and 75 households, which will act as consumers of the produced electricity, will be analysed, along with another scenario in which the farm, not being part of the energy community, produces and sells biomethane. Therefore, the configurations considered will be three:

- The first includes only a photovoltaic system installed on the roof of the farm's barn.
- The second includes, in addition to the photovoltaic system, an anaerobic digestion plant coupled with an internal combustion engine. This system enables the combined production of electricity and thermal energy. The thermal energy generated will be used to reduce the consumption of natural gas from the grid, contributing to covering the thermal demand of the farm's processes.
- In the third, the biogas produced will be used to produce biomethane and its subsequent sale.

In order to determine the optimal size of the photovoltaic system, a parametric analysis will be conducted on the plant's power, evaluating two fundamental energy Key Performance Indicators (KPIs):

- the Self-Consumption index (SC).
- the Self-Sufficiency index (SS).

These indicators will be represented on a Pareto chart, where the point (1,1) represents the utopia, i.e., the theoretical maximum energy efficiency. The configurations closest to this point will be selected for further analysis, in particular the evaluation of economic performance, expressed through:

- the Net Present Value (NPV).
- the Internal Rate of Return (IRR).
- the Payback Time (PBT).

with the aim of identifying the most economically advantageous solution[5]

Once the optimal size of the photovoltaic system is defined, the simulation of the combined plant with anaerobic digestion will be carried out. Also in this case, the analysis will be parametric, considering a range of power values for the internal combustion engine and a variable photovoltaic production, keeping the maximum value determined in the simple photovoltaic configuration.

The economic performance of both configurations will then be compared with an additional alternative: the direct sale of the biomethane produced to the grid, after purification of the biogas through a Pressure Swing Adsorption (PSA) process. This latter process was simulated using a tool developed in the MATLAB environment, called toPSAil [39]

3.1 Model of Renewable Energy Communities

As previously mentioned, RECs are composed of a set of users connected to the same primary substation, which can inject or withdraw electricity from the grid depending on the role they play within the community itself. Each user is uniquely identified by their POD (Point of Delivery).

The users can be divided into two main categories:

- active.
- passive.

An active user is one that has a renewable energy generation plant and is able to inject energy into the grid. A user can also be considered active if it is equipped exclusively with a storage system, capable of withdrawing energy during the charging phase and returning it to the grid during the discharging phase. These storage systems help to improve the energy performance of the community by storing energy in the presence of a production surplus and releasing it during demand peaks.

The type of consumption by the users also varies according to when the energy is used:

- We speak of physical self-consumption when the energy produced by a plant is directly consumed by the user connected to it.
- The excess energy is fed into the national electricity grid and, if used by another user belonging to the same community, it is referred to as shared energy.
- The remaining portion is simply fed into the grid and accounted for as non-shared energy.

The sharing of energy among community members, through the national electricity grid, is called virtual self-consumption.

Ultimately, within a REC, three main figures can be identified:

- the consumer, i.e., the one who withdraws energy from the grid.
- the producer, i.e., the one who injects energy into the grid thanks to the availability of a renewable source plant.
- the prosumer, a subject who plays both roles, that is, produces and consumes energy, characterized by a bidirectional energy flow.

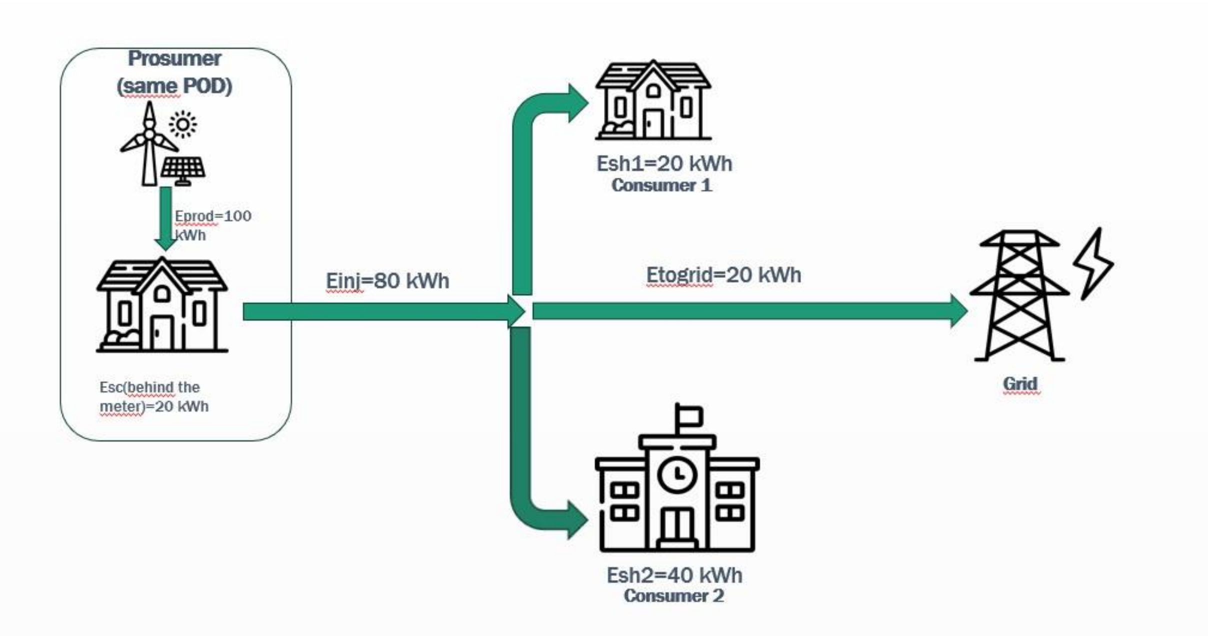


FIGURE 8: REC MODEL

3.1.1 Energy Flows and KPIs

For evaluating energy flows, the presence of a renewable energy generation plant installed at the farm is assumed. As previously described, the considered plants in which the energy produced is shared are of two types:

- a configuration with only a photovoltaic system.
- a configuration with an internal combustion engine, capable of generating both electricity and thermal energy, in cooperation with a photovoltaic system.

In both configurations, the farm is considered as a prosumer, i.e., a user capable of producing electricity and physically self-consuming the produced energy before any injection into the grid. In this specific scenario, there is only one node acting as a producer. However, more generally, the different energy flows can be defined as:

- the total hourly electricity production of the community can be defined as the sum of the hourly productions of all the plants belonging to the REC[5], [13]:

$$E_{prod,h} = \sum_i E^i_{prod,h} \quad (3.1)$$

- The hourly self-consumed energy is equal to the minimum between the energy produced and the energy consumed by the prosumer j and is calculated 'behind the meter', i.e., before the injection into the grid [5], [13]:

$$E^j_{selfcons,h} = \text{MIN}\left(E^j_{prod,h}; E^j_{cons,h}\right) \quad (3.2)$$

- The energy injected into the grid is equal to the difference between the energy produced and that self-consumed by the prosumer j [5], [13]:

$$E_{inj,h} = \sum_j E^j_{prod,h} - E^j_{selfcons} \qquad (3.3)$$

- The energy withdrawn from the grid corresponds to the sum of the energy withdrawn by the various PODs of the community [5], [13]:

$$E_{with,h} = \sum_j E^j_{with,h} \qquad (3.4)$$

- The hourly shared energy, within the REC, is equal to the minimum between the injected energy and the withdrawn one [5], [13]:

$$E_{sh} = \text{MIN}\left(E_{inj,h}; E_{with,h}\right) \qquad (3.5)$$

- The energy injected into the grid but not shared, i.e., not virtually self-consumed by other users, is equal to the difference between the injected energy and the shared energy [5], [13]:

$$E_{to\,grid,h} = E_{inj,h} - E_{sh,h} \quad (3.6)$$

- The energy withdrawn from the grid is equal to the difference between the withdrawn energy and the shared one [5], [13]:

$$E_{from\,grid,h} = E_{with,h} - E_{sh,h} \quad (3.7)$$

- The energy consumed by the community is instead equal to the sum of all the consumptions of the users belonging to the REC and corresponds to the electrical demand as also defined in the previous chapter [5], [13]:

$$E_{cons,h} = \sum_j E^j_{cons,h} (3.8)$$

Once the energy flows are defined, it is now possible to introduce the energy performance indicators of the community: the Self-Consumption Index (SCI) and the Self-Sufficiency Index (SSI). These two indicators represent distinct concepts:

- The Self-Consumption Index describes the local use of the produced energy, i.e., the share of generated energy that is physically consumed by the prosumer or virtually by the other users belonging to the energy community and is defined as:

$$SC = \frac{E_{selfcons} + E_{Sh}}{E_{prod}} = 1 - \frac{E_{to\,grid}}{E_{prod}} \quad (3.9)$$

  Where the numerator includes the amount of energy consumed 'behind the meter' by the prosumer and the share of energy shared by the other users, and the denominator the amount of energy produced by the renewable source plants. This index takes values between 0 and 1: a value equal to 1 indicates that all the energy produced by the REC systems is consumed internally by the community; values close to 0 indicate that most of the produced energy is not used locally, but injected into the grid without self-consumption, thus requiring the purchase of external energy to meet the community's needs[5], [40].

- The Self-Sufficiency Index, instead, represents the community's ability to meet its own energy demand through local production. It indicates how much of the energy consumed by the users is directly supplied by the renewable production plants, and how much, instead, is withdrawn from the electricity grid. This index is defined as:

$$SS = \frac{E_{selfcons}+E_{sh}}{E_{cons}} = 1 - \frac{E_{from\,grid}}{E_{cons}} \quad (3.\,10)$$

Where in the numerator, as before, are the amounts of energy consumed by the prosumer and shared with the other users, while in the denominator this time is the amount of energy consumed by all users. This index also ranges from 0 to 1: a value equal to 1 implies that all the consumed energy is covered by local production (self-consumed or shared); values close to 0 indicate that the plant is not properly sized, making it necessary to extensively rely on grid energy to meet the loads [5], [40].

These two indices, although indicative of the REC's energy performance, are inversely correlated: as one increases, the other tends to decrease. The compromise between these two indicators can be effectively represented by a Pareto chart, in which the point (1,1) — called the "utopia point" — represents the ideal condition of maximum self-consumption and maximum self-sufficiency. The goal of the energy analysis is therefore to identify, among the examined configurations, the one closest to the utopia point, as it is potentially the most advantageous for the entire community from an energy perspective[5].

3.1.2 Energy Flows and KPIs

Even though renewable energy communities were not conceived with the primary goal of generating financial profits for their members, it is still essential to evaluate the economic profitability of the investment. This allows for an understanding of whether the initiative is sustainable over time and capable of repaying the initial investment, contributing to the reduction of energy costs for the participants.

To carry out this evaluation, three widely recognized economic indicators are used: the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Payback Time (PBT). These tools make it possible to quantitatively estimate the expected economic returns and, therefore, the convenience of the project.

The Net Present Value (NPV) represents the algebraic sum of all expected cash flows over time, discounted to present value through a discount rate. It is based on the principle of the time value of money, according to which one euro today is worth more than one euro received in the future[41]. The formula is:

$$NPV = -CAPEX + \sum_{i=1}^{N} \frac{CF_n}{(1-r)^n} \quad (3.11)$$

Where:

- CAPEX corresponds to the initial investment, preceded by a minus sign since, in cash flow analysis, the money spent is negative while profits are positive. The CAPEX includes all initial expenses for the establishment of the REC and for the purchase of the plant that will produce the energy made available to the REC.
- CF corresponds to cash flows: positive cash flows are those deriving from the sale of electricity to the grid including the incentives for shared electricity as defined in the CACER Decree and summarized in Chapter 1. As for the energy injected into the grid, that is, after the prosumer's meter, all the energy is sold at market price as defined by ARERA and GSE. The National Single Price (PUN) considered is that of 2024 and the hourly values of the reference year were used. Shared energy, on the other hand, also has a premium tariff that can reach up to €120/MWh for the plant sizes considered. This premium tariff depends on the Zonal Price (Pz), which was obtained from GSE for the year 2024. For photovoltaic production in the Northern and Central regions, a corrective factor is also provided for the level of insolation, equal to €10/MWh and €4/MWh respectively. Finally, there is also a reimbursement from ARERA for the production and consumption of energy on-site equal to €9/MWh. Negative cash flows, instead, are those deriving from operation and maintenance expenses of the plant (OPEX), which for photovoltaics correspond to a minimal outlay, while for the anaerobic digestion plant have a significant weight during the year. These expenses will be addressed in more detail in Chapter 4.
- n corresponds to the year in which the cash flow is considered. This ranges from 1 to 20 since the twentieth year is the one in which the premium tariff stops being provided.
- r is the investment discount rate and is assumed to be 5%.

The Internal Rate of Return (IRR) is the discount rate that brings the net present value of the project to zero considering the investment years [41]:

$$0 = -CAPEX + \sum_{i=1}^{N} \frac{CF_n}{(1-IRR)^n} \quad (3.12)$$

The IRR represents the intrinsic profitability of the project and can be interpreted as the annual rate of return generated by the investment's cash flows. If the IRR is higher than the cost of capital, the project is considered profitable. However, in the presence of irregular cash flows (i.e., those that change sign more than once), the IRR can yield ambiguous or multiple results.

Finally, the Payback Time (PBT) is the number of years needed for the accumulated, non-discounted cash flows to cover the initial investment [41]. More formally, the PBT is defined as the time such that:

$$0 = -CAPEX + \sum_{i=1}^{PBT} \frac{CF_n}{(1-r)^{PBT}} \quad (3.13)$$

In conclusion, although each indicator offers a different perspective, the integrated evaluation of NPV, IRR, and PBT provides a more complete view of the economic sustainability of a project. In REC analyses, these metrics are essential to compare different technological configurations and highlight the most economically advantageous one.

3.2 Sizing of the Photovoltaic System

For sizing the photovoltaic system, a farm located in the Municipality of Cardè, in Piedmont, situated at coordinates 44°44'55" N, 7°29'19" E, was taken into consideration. As highlighted in Chapter 2, the farm is to be considered fictitious regarding the number of cattle; however, to obtain a more accurate and realistic assessment, it was decided to base the analysis on an actual existing structure, identified via Google Earth.

FIGURE 9: CARDÈ MUNICIPALITY [SOURCE: GOOGLE EARTH]

From the analysis of satellite images, it is observed that the farm is already equipped with tanks for the storage of livestock waste, which will later be used to produce biogas through anaerobic digestion. The main barn has a roof with a usable surface area of approximately 1500 m², oriented about 20° westward. Considering an average value of 5 m² for each installed kWp, it is estimated that the maximum theoretically installable photovoltaic capacity on the roof is equal to 300 kWp. This surface has been selected as a reference for the installation of the photovoltaic system considered in the study.

FIGURE 10: FARM

3.2.1 Photovoltaic System Production

The electricity production of the photovoltaic system was estimated using PVGIS (Photovoltaic Geographical Information System), a tool developed by the Joint Research Centre of the European Commission. This tool makes it possible to obtain hourly data on solar radiation components and on the electric power produced by photovoltaic systems with different nominal peak capacities. For the simulation, a system loss of 14% was considered, as standardized by PVGIS, with an efficiency of 21% in solar radiation conversion and with module inclination automatically optimized. The azimuth angle was set at -20°, in accordance with the actual orientation of the roof identified at the farm. The PVGIS-SARAH2 database, referring to the year 2020, was used as the data source. The data obtained in terms of hourly electric power were converted into kWh, to be compared with the hourly electricity demand profiles of the energy community.

The following figures show the daily electricity production trends on two typical days, related to the different system sizes considered, ranging from 100 kWp to 175 kWp. The decision to remain below the 200 kWp threshold per single system is motivated by the intention to access the increased premium tariff, as provided for by the current regulatory framework:

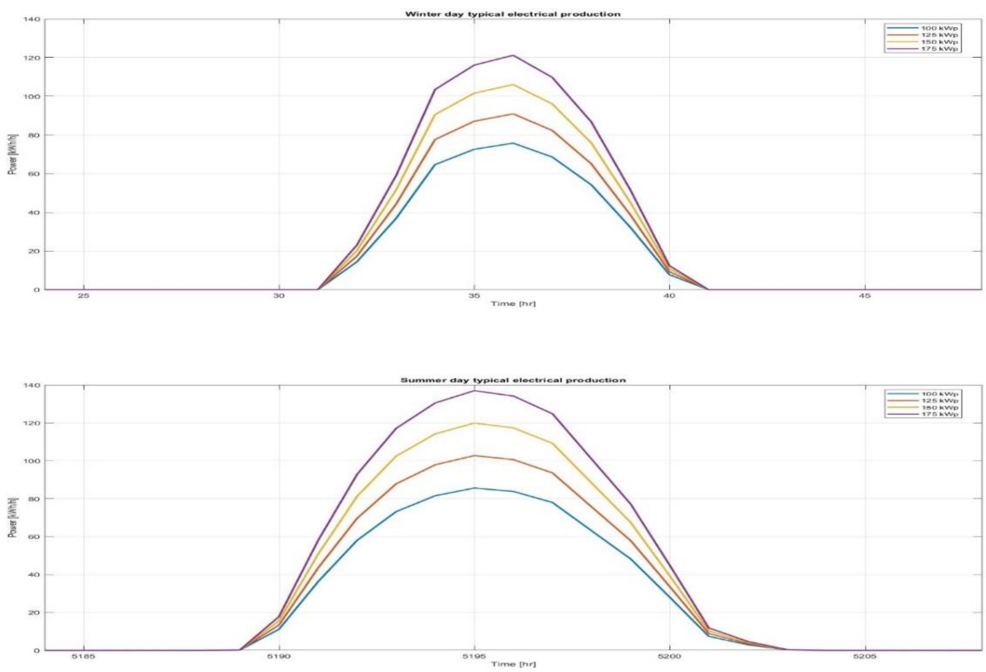


FIGURE 11: PV PLANT PRODUCTION FOR DIFFERENT SIZES IN WINTER AND SUMMER

In the following image, instead, the data on electricity production from photovoltaics for different sizes in 2020 are shown. The production trend, as can be observed, might appear anomalous since in the spring months, especially April, the production is higher compared to the summer months. However, by comparing the data with the weather in Cardè in 2020, it can be noted that it was a predominantly cloudy year during the summer months [cit. Weather Spark], limiting the electricity production from photovoltaics, and this also has repercussions on the economic analysis that will be carried out later. This leads to the conclusion that the performance of the photovoltaic system could be even better when considering an increase in electricity production, especially during the summer period.

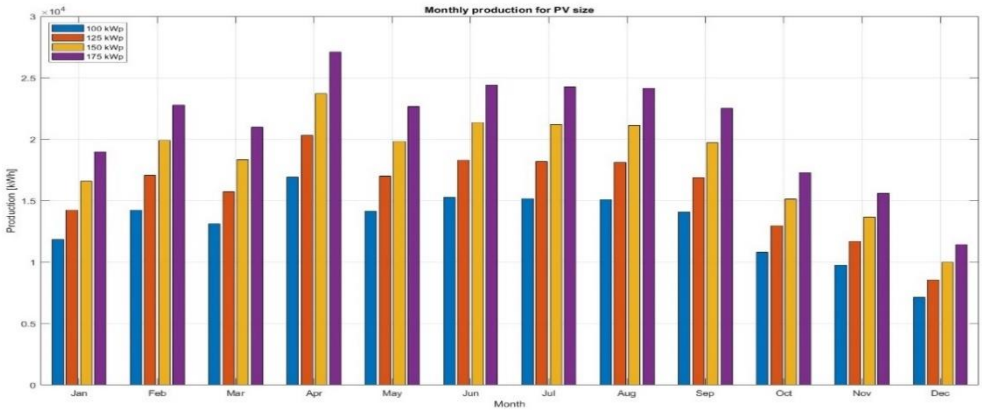


FIGURE 12: YERALY PV ENERGY PRODUCTION FOR DIFFERENT SIZES IN 2020

Therefore, we can summarize the annual electricity produced by the different configurations in the following table:

PV size [kWp]	Yearly PV production [MWh/yr]
100	157,59
125	189,10
150	220,62
175	252,14

TABLE 12: YEARLY PV PRODUCTION FOR DIFFERENT SIZES

3.2.2 Analysis of Energy Performance and Selection of the Optimal Size

At this point, having evaluated the annual photovoltaic system production on an hourly basis and having the load curves of the energy community available, it was possible to assess the energy performance of the REC using the equations presented at the beginning of this chapter. In the following table, the data of the energy shared within the community, self-consumed by the farm, the energy sold to the grid, and the energy absorbed are reported:

PVsize [kWp]	E_{SC} [MWh/yr]	E_{SH}[MWh/yr]	E_{TOGRID}[MWh/yr]	$E_{FROMGRID}$[MWh/yr]
100	108,23	43,34	6,01	252,95
125	114,16	56,68	18,27	239,61
150	118,62	65,63	36,37	230,67
175	121,96	72,08	58,10	224,21

TABLE 13: ENERGY FLOWS

To determine the optimal power of the photovoltaic system to be installed, a comparative analysis of the different configurations was carried out by evaluating two fundamental indicators for each: the self-consumption index and the self-sufficiency index. The analysis aims to identify the solution that best balances these two parameters, ensuring both a good local use of the energy produced and a significant coverage of the community's demand. The result is shown in the following image:

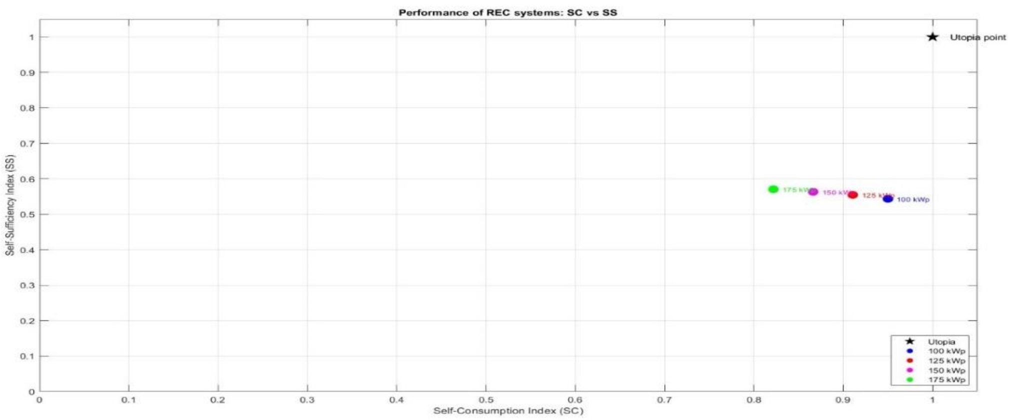


FIGURE 13: PARETO CHART: SS VS SC

And the results summarized in the following table:

PVsize [kWp]	SC [%]	SS [%]
100	96,18	53,42
125	92,74	54,65
150	88,63	55,61
175	84,33	56,38

TABLE 14: SCI AND SSI FOR DIFFERENT SIZES

From the results, it emerges that the self-sufficiency for the 4 system sizes is not very different, while the self-consumption varies over a wider range, showing that the difference lies in the amount of energy injected into the grid. As can be seen from the performance index values, the optimal solution from an energy perspective is the installation of 125 kWp, which presents a self-consumption index of 0.9274 and a self-sufficiency index of 0.5465. However, the chosen configuration was the one with 150 kWp because the energy performance does not differ significantly; in fact, as highlighted in the previous paragraph, there is a higher production of electricity and, consequently, better utilization of the available surface area. Moreover, the economic performance improves significantly, which is essential to evaluate the feasibility of an investment, as will be demonstrated in the next chapter. Below, therefore, the production curves of the 150 kWp photovoltaic system are presented in comparison with the electrical load of the REC:

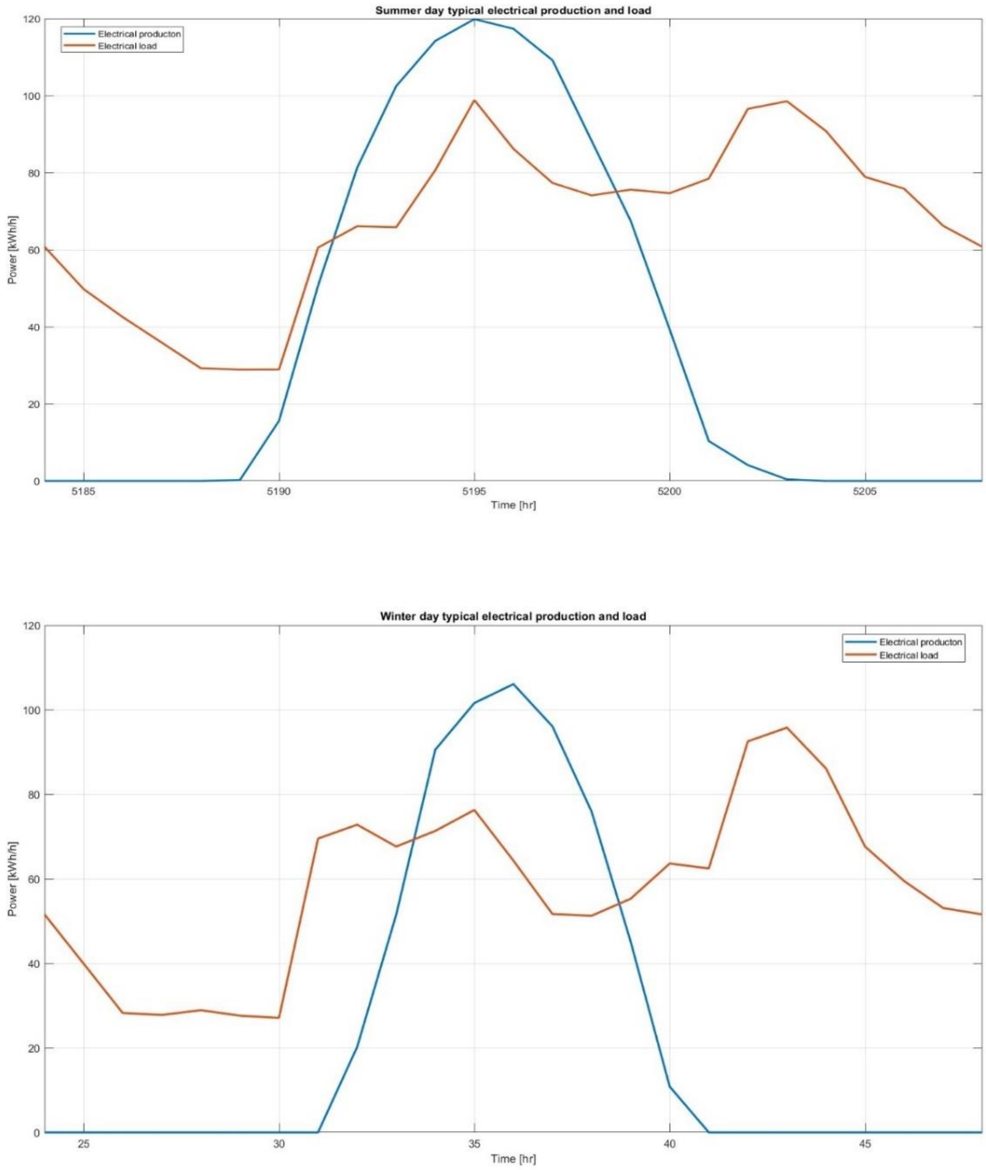


FIGURE 14: 150 KWP PHOTOVOLTAIC PRODUCTION VS ELECTRICAL LOAD OF THE CER IN WINTER AND SUMMER

It can be observed that during the central hours of the day there is a production surplus, while the morning and evening consumption peaks require energy integration. This result could be achieved through the use of storage systems, but in this study, an alternative solution has been proposed: using a photovoltaic system with lower power and integrating a CHP system, which will allow not only the production of electricity but also the coverage of the thermal needs of the farm and the coverage of consumption peaks throughout the entire day.

3.3 CER with Biogas-Fueled CHP and Photovoltaic System

To improve the overall energy performance of the community, as an alternative to the use of an electrochemical storage system, the implementation of a biogas-fueled cogeneration plant (CHP) was considered, taking advantage of the biomass availability generated by the farm. The proposed solution involves the integration of an internal combustion engine, capable of providing electrical energy to the community and, at the same time, thermal energy to meet the needs of the livestock facility.

The incentive framework defined by the CACER Decree, in fact, is not limited to photovoltaic only, but also includes other renewable sources such as wind, hydroelectric, and biomass and biogas plants, thus promoting the adoption of CHP systems in agricultural contexts. One of the main advantages of this configuration lies in the cogeneration's ability to produce electrical energy continuously throughout the day, overcoming the intermittency of photovoltaic systems, which operate exclusively during daylight hours. In this way, the community can more effectively cover the electrical loads, especially during the demand peaks that occur in the morning and evening hours. To support this configuration, a parametric analysis was carried out starting from the previous configuration in which a photovoltaic system of 150 kWp was installed and considering a variation in the CHP power from 150 kW down to 100 kW. This is made possible by the presence of a buffer tank that allows the anaerobic digester size not to be changed but enables the management of electricity production according to the available biogas. The size of the buffer tank chosen is 500 m^3 at constant because typically they operate at or below atmospheric pressure. The size of 500 m^3 was selected as a compromise to optimize the operating hours of the cogenerator by making efficient use of the biogas produced. This volume allows for temporary storage of excess biogas during periods of low energy demand, so that it can be used later when the demand increases avoiding waste and improving the overall energy efficiency of the system.

In this analysis, the power not covered by the congenator is supplemented by a photovoltaic system of smaller size compared to the initial configuration, with the aim of keeping the entire project economically sustainable. Finally, the valorisation of the produced biogas generates further benefits for the farm itself, which can reuse the digestate as fertilizer, helping to reduce both the costs related to the treatment of livestock waste and the overall environmental impact.

3.3.1 Principles of the Biological Process for Biogas Formation

To understand and optimize the anaerobic digestion process, knowledge of the chemical and biological processes involved is necessary. The degradation of organic matter in the absence of molecular oxygen leads to the formation of two gases: methane and carbon dioxide. This process involves different microbial groups: hydrolytic bacteria, acidifying bacteria, and methanogenic bacteria, each of which plays a fundamental phase in the process. The latter are the ones that produce methane and CO_2 with an average composition of two parts to one, respectively. Methane, not soluble in water, passes directly to the gas phase, while carbon dioxide can be found in both the gas and liquid phases. A typical example of anaerobic degradation is that of glucose presented in the following reaction:

$$C_6H_{12}O_6 \rightarrow CH_3COOH$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

The conversion of substrates into methane occurs through an anaerobic trophic chain. The biodegradation process consists in three main phases[42]:

- Hydrolysis: large organic molecules are degraded into simpler compounds such as enzymes and amino acids. The presence of cellulose or other slowly hydrolysing materials can inhibit the process. The enzymes produced can bind into short chains of volatile fatty acids, while the co-products can ferment to produce alcohols, CO_2, and H_2.
- Acetogenesis: starting from the substrates formed in the previous phase, acetogenic bacteria produce acetic acid, formic acid, CO_2, and H_2. The presence of molecular hydrogen can lead to inhibition problems, but if it is maintained at low concentrations thanks to the presence of methanogenic bacteria, the degradation of fatty acids to H_2 by acetogenic bacteria is made more probable.
- Methanogenesis: this phase represents the last stage of the anaerobic trophic chain. Methane, in fact, is the only non-reactive compound in the entire process. Methanogenic bacteria convert acetic acid and hydrogen into methane and carbon dioxide.

From these reactions, it can be observed that the anaerobic digestion process must be kept well under control to avoid process inhibition and thus the non-formation of methane, the desired product. The main parameters that must be kept under strict surveillance are[42]:

- Temperature: there are three temperature ranges to classify the anaerobic digestion process: psychrophilic with temperatures between 5 and 25°C, characterized by a slow methane production and consequently a long residence time inside the reactor; mesophilic with temperatures between 30 and 40°C, the most used among the three; thermophilic from 50 to 60°C, the temperature range in which the most methane is produced but very sensitive to temperature variations due to the presence of few bacterial species.
- Volumetric organic loading rate: expressed as the weight of volatile solids (VS) per unit volume of the digester per unit of time. The load usually varies between 1 to 11 kg $VS/m^3/day$.
- Hydraulic retention time: it is the average residence time of the liquid phase inside the digester. Usually, the lower the operating temperature, the greater the retention time and it lasts in average 30 days.
- Solids concentration: usually expressed as the percentage of volatile solids on the total dry matter. The solids concentration is necessary to establish the organic load and the type of digester to be used.
- Alkalinity and pH: the optimal pH condition for methanogenic bacteria varies in the range between 6.4 and 7.6 pH.

Over time, different types of digesters have been developed for biogas production. In Italy, the most widespread are the continuous stirred tank reactors without recirculation, known as Continuous Stirred Tank Reactors (CSTR). These reactors operate in continuous mode, with an average residence time of the substrate defined as hydraulic retention time (HRT – Hydraulic Retention Time). Anaerobic digestion processes can be structured in one or two stages.

- In single-stage processes, all biological reactions of digestion take place inside a single reactor. In this case, the slowest phase of the process becomes the limiting element and determines the sizing.
- In two-stage processes, on the other hand, two separate reactors are used, one for each main phase of the process (hydrolysis/acidogenesis and acetogenesis/methanogenesis). This configuration allows optimizing the sizing of each reactor based on the different bacterial kinetics, improving overall efficiency and biogas yield.

Both configurations generally operate under mesophilic conditions (about 35°C). CSTR reactors usually have a cylindrical shape and are equipped with an internal mechanical stirrer, whose purpose is to keep the substrate homogeneous, prevent sediment formation at the bottom, and ensure uniform distribution of bacteria in the manure[42].

3.3.2 Sizing of the Digester

The CSTR-type digester is commonly used for the anaerobic digestion of wastewater, urban organic waste, or for the co-digestion of livestock effluents with energy crops such as maize or triticale. However, there are numerous application examples in which the digester is fed exclusively with livestock effluents, with the aim of limiting the use of agricultural land for energy crops and reducing potential conflicts between food and energy production.
In the specific case analyzed, the digester will be fed solely with bovine livestock manure, both in solid and liquid form. As reported in Chapter 2, in Table 9, the total daily amount of bovine effluents available is equal to 35.03 tonnes per day. Starting from this value, it is necessary to determine the volatile solids (VS) content, an essential parameter for calculating the daily biogas production [43]:

	Liquid [kg/day]	Solid + Straw [kg/day]
Total wastewater [t/day]	29,37	5,66
Volatile solids [%]	6,88	18,45
Volatile solids [t/day]	2,02	1,04
Biogas [Nm3/kg VS]	0,38	0,38

TABLE 15: DAILY VOLATILE SOLIDS PRODUCTION

From the production of volatile solids, we can state that the amount of biogas produced, assuming the digester operates at full capacity, is equal to 1,164.41 Nm^3/day and therefore 48.52 Nm^3/hour.

At this point, it is essential to proceed with the sizing of the digester volume in order to correctly estimate the thermal and electrical demand of the plant. A single-stage digester has been assumed, with a cylindrical shape and a top dome, where the livestock effluents accumulate in the cylindrical part, while the biogas produced is stored in the dome. The sizing of the cylindrical part was carried out based on the Hydraulic Retention Time (HRT), equal to 30 days, as recommended for bovine livestock effluents. The useful volume of the cylindrical part was calculated using the following expression [44]:

$$V_{cyl} = q_{fs} * HRT * SF \quad (3.14)$$

Where:

- q_{fs} = volumetric flow rate of the incoming feedstock (m^3/day).
- HRT = Hydraulic Retention Time (30 days).
- SF = Safety factor equals to 1.3 (-).

By applying the formula, a cylinder volume of 1440 m^3 is obtained, corresponding to a height of 6.5 m and a diameter of 13 m, considering a height-to-diameter ratio equal to one-half [44]. Based on this diameter, the volume of the upper dome was then determined using the formula for the volume of a hemisphere, so the volume of the entire digester is 2015 m^3. The geometric characteristics of the digester are crucial, as they allow for the calculation of the exposed surfaces that influence thermal losses, due to the temperature difference between the external environment and the inside of the vessel, where the anaerobic digestion process takes place. These surfaces are equivalent to:

Base = 132.86 m^2

Lateral surface = 265.71 m^2

Dome surface = 265.71 m^2

3.3.3 Thermal and Electrical Demand of the Digester

Once the digester has been sized, it is possible to estimate the thermal and electrical demand required for the biogas production process.

The thermal demand consists of the heat required for preheating the biomass and the heat necessary to compensate for thermal losses through the digester surfaces.

The heat required for preheating the biomass is calculated with the following equation[44]:

$$Q_{ph} = m_{ph}c_p\left(T_{dig} - T_{sub}\right) * t_p \qquad (3.15)$$

Where:

- m_{ph} = mass flow rate of the biomass (kg/sec).
- c_p = specific heat of the substrate assumed equal to that of water, 4.186 kJ/kg/K.
- T_{dig} = temperature of the digester operating under mesophilic conditions, 40°C.
- T_{sub} = temperature of the substrate considered as the average ambient temperature throughout the year.
- t_p = time to heat the substrate before entering the digester.

The amount of heat needed to compensate for thermal losses through the outer walls has been calculated with the following equation [44]:

$$Q_{loss} = \left[\left(A_{floor} * U_{floor}\right) + \left(A_{walls} * U_{walls}\right) + \left(A_{dome} * U_{dome}\right)\right] * \left(T_{dig} - T_{air}\right) \qquad (3.16)$$

Where:

- A_{floor} = floor surface of the digester in m².
- U_{floor} = thermal transmittance of the floor equal to 0.465 W/m²/K.
- A_{walls} = surface of the outer walls of the digester in m².
- U_{walls} = thermal transmittance of the walls equal to 0.320 W/m²/K.
- A_{dome} = surface area of the digester dome in m².
- U_{dome} = thermal transmittance of the dome equal to 1 W/m²/K.
- T_{dig} = temperature of the digester operating under mesophilic conditions, 40°C.

- T_{air} = ambient temperature in °C.

The preheating of the biomass occurs twice a day (at 11:00 and 21:00), when the previously collected slurry is fed into the digester. Thermal losses, instead, are distributed throughout the day.

As for the electrical energy required by the digester, this also consists of two terms referring to the electrical energy for pumping the biomass into the digester and the electrical energy for the internal agitator, necessary to ensure adequate mixing of the substrate.

The electrical energy for pumping is estimated with the following equation[45]:

$$P_{pump} = m_{ph} H \rho g t_p \frac{1}{\eta} \quad (3.\ 17)$$

Where:

- m_{ph} = mass flow rate of the biomass (kg/sec).
- H = height of the conveyor belt considered equal to that of the digester cylinder (m).
- ρ = density of the substrate assumed equal to that of water, 1000 kg/m³.
- g = gravitational acceleration [m/sec^2].
- t_p = time to feed the substrate into the digester.
- η = pump efficiency considered equal to 0.7 (-).

The energy for mixing the substrate is calculated with[45]:

$$P_{stir} = V_{liq} S t_s \quad (3.\ 18)$$

Where:

- V_{liq} = Volume of the liquid in m³.
- S = specific mixing power assumed equal to 0.005 kW/m³.
- t_s = time for mixing.

The daily load distribution for the pump was considered twice a day at 11:00 and 21:00 for fifteen minutes, while the mechanical agitator works throughout the day.

In this way, it was possible to evaluate the new electrical and thermal load profiles:

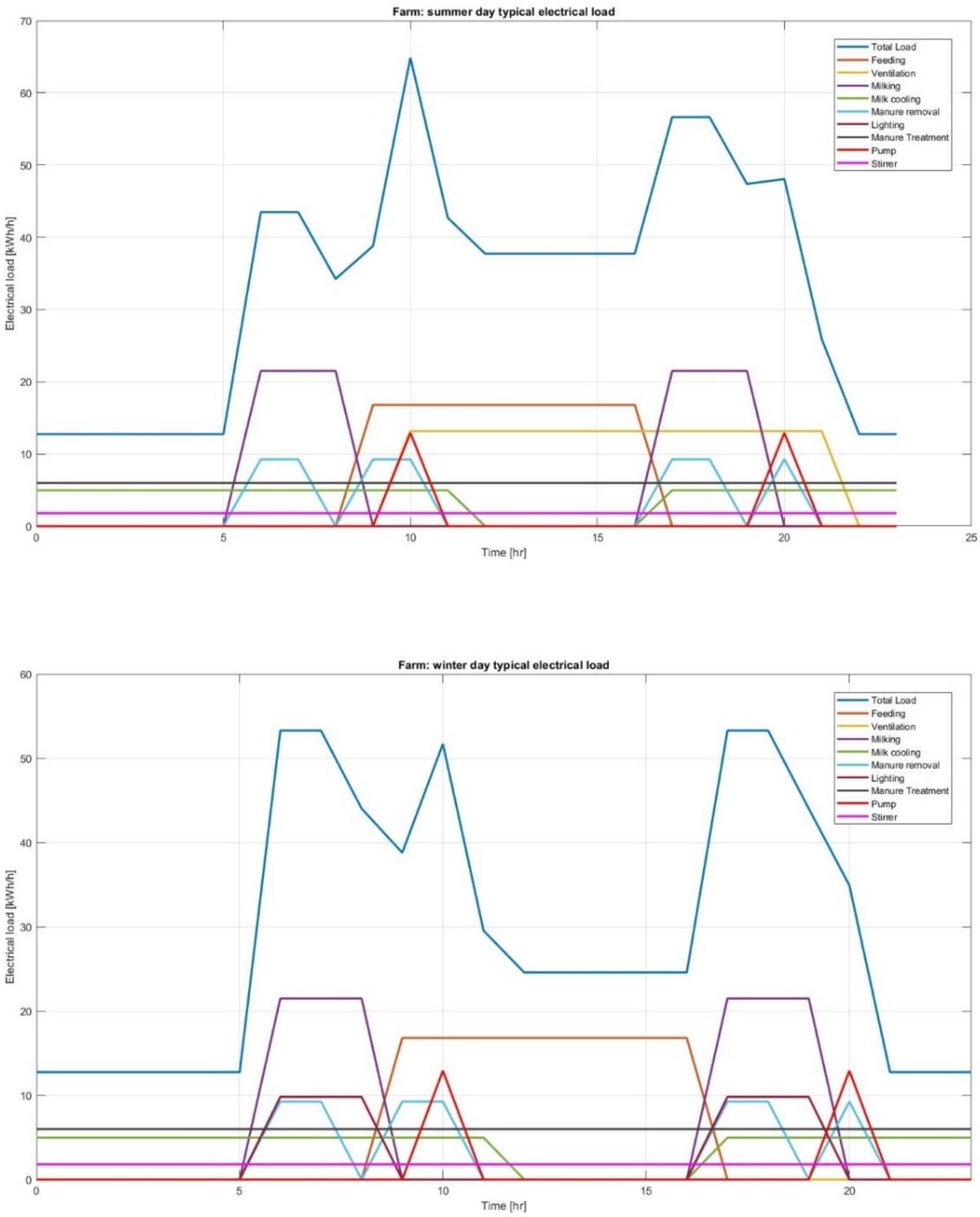


FIGURE 15: FARM PLUS ANAEROBIC DIGESTER ELECTRICAL LOAD PROFILE FOR SUMMER AND WINTER DAYS

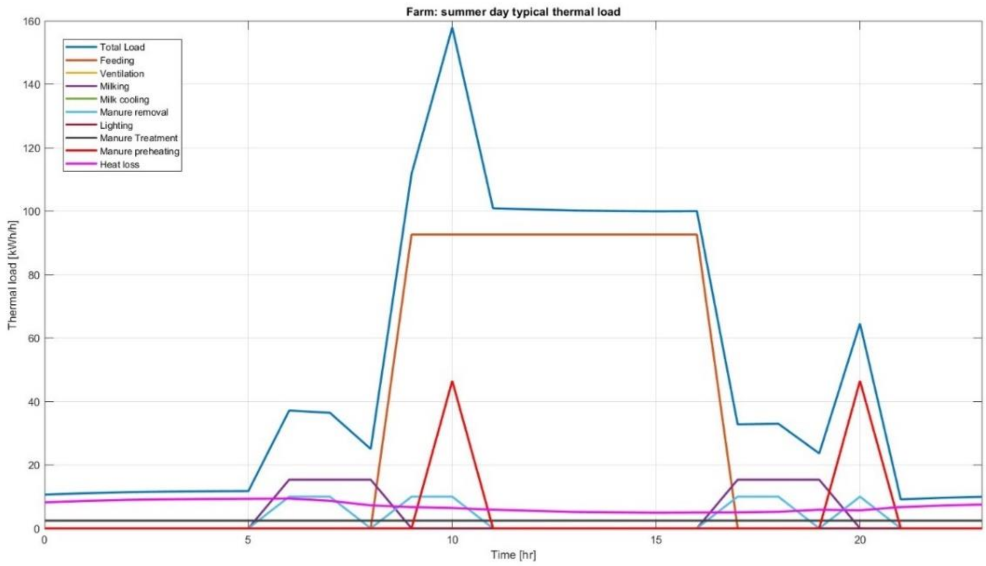


FIGURE 16: FARM PLUS ANAEROBIC DIGESTER THERMAL LOAD PROFILE FOR SUMMER AND WINTER DAYS

3.3.4 Analysis of the energy performance of the REC powered by biogas and photovoltaics

Once the new load profile of the agricultural company was defined, including the contribution of the anaerobic digester, it was possible to develop the annual production curves of the plant. Considering the characteristics of the biogas, composed of 60% methane and 40% carbon dioxide, typical results for biogas produced from bovine effluents with a lower heating value of 6,4 kWh/m^3, and an engine electrical efficiency of 0.355 and thermal efficiency of 0.498. The biogas flow rate required for electricity production was calculated as:

$$Q_{biogas} = \frac{P_{el,CHP}}{LHV_{biogas} * \eta_{CHP}} \quad (3.19)$$

The volumetric flow of biogas for the different CHP sizes is reported in the following table:

Electrical Power [kW]	Q [Nm3/sec]
100	44,01
110	48,51
120	52,82
130	57,22
140	61,62
150	66,02

TABLE 16: BIOGAS FLOW RATE BURST WITH RESPECT TO CHP ELECTRICAL POWER

To assess the economic and technical sustainability of the investment, a maximum peak power output of 150 kWp was maintained, while the power of the cogenerator was varied from 150 kW down to 100 kW. The missing power share, resulting from the downsizing of the engine, was supplemented by installing a photovoltaic system.

Subsequently, to compare this hybrid configuration with the one based exclusively on a photovoltaic system, the main energy indicators, SS and SC were calculated. The results of the energy flows and the energy KPIs are shown in the following tables:

CHP + PVsize [kW]	E_{SC} [MWh/yr]	E_{SH}[MWh/yr]	E_{TOGRID}[MWh/yr]	$E_{FROMGRID}$[MWh/yr]
100 + 50	271,96	296,09	251,04	0,21
110 + 40	271,96	296,19	305,18	0,10
120 + 30	271,92	296,12	365,16	0,17
130 + 20	263,78	283,49	397,89	1,28
140 + 10	254,88	262,80	409,06	3,35
150	239,04	247,23	421,01	4,91

TABLE 17: CHP PLUS PV ENERGY FLOWS IN THE CER

CHP + PVsize [kW]	SS [%]	SC [%]
100 + 50	97,06	60,04
110 + 40	96,48	58,55
120 + 30	95,60	57,11
130 + 20	94,15	55,85
140 + 10	92,40	54,75
150	90,97	53,60

TABLE 18: SSI AND SCI IN THE REC SUPPLIED BY CHP PLUS PV

It is observed that, in the cogeneration configuration, the self-consumption and self-sufficiency indices are reversed compared to the configuration based exclusively on a photovoltaic system. This behavior is due to the greater regularity of electricity production guaranteed by the cogenerator, which allows for a more continuous and reliable coverage of the community's energy demand. Self-sufficiency values between 0.90 and 0.97 are reached, highlighting the system's ability to almost entirely meet local electricity consumption. On the other hand, the self-consumption index tends to decrease, since the electricity produced more than demand is fed into the grid. The integration with a photovoltaic system proves effective in further improving overall energy performance, reducing dependence on external sources and increasing the efficiency of the entire system.

In the configuration where the cogeneration engine has a power of 150 kW (without photovoltaic), it is observed that, operating at full load, the engine consumes a biogas flow greater than the amount generated daily. To simulate more realistic operating conditions, a management constraint was introduced: when the volume of biogas in the 500 m^3 atmospheric pressure storage tank (buffer) falls below 30% of the total volume, the cogenerator is shut down for 3 hours to allow for the restoration of the minimum gas reserve. This strategy results in a reduction in annual electricity production due to shutdown cycles but avoids biogas waste, improving the overall sustainability of the system. Furthermore, it was assumed that, when the community's electrical load—also reduced by the photovoltaic production if present—is lower than half of the engine's maximum power, the latter can operate at half load with lower efficiency, producing less power but allowing biogas savings to be used during peak demand hours.

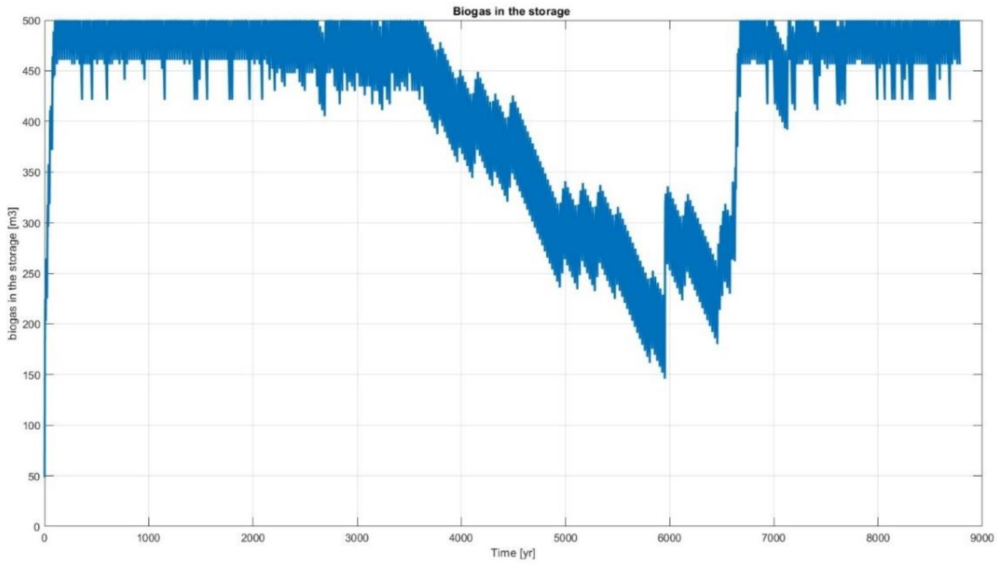


FIGURE 17: YEARLY VARIATION OF THE BIOGAS IN THE BUFFER TANK WITH 120 KW CHP AND 30 KWP PV

The following table shows the number of hours in which the buffer tank is full, the capacity factor, and the amount of biogas wasted for the various configurations:

CHP + PVsize [kW]	Tank full [h]	CF [-]	Biogas wasted [Nm3/h]
100 + 50	8752	0,99	78845
110 + 40	8734	0,99	47127
120 + 30	1096	0,99	16915
130 + 20	15	0,97	190
140 + 10	0	0,91	0
150	0	0,87	0

TABLE 19: TIME OF WORK OF THE DIFFERENT CONFIGURATIONS WITH CHP

From an economic point of view — as will be illustrated in the next chapter — the combined presence of the CHP unit and the photovoltaic system proves to be more advantageous, even in the case where a portion of the biogas produced is not fully utilized. The following images show the load curves and the production curves for two typical weeks, one in summer and one in winter, in the configuration with 120 kW of CHP and 30 kWp of photovoltaic system:

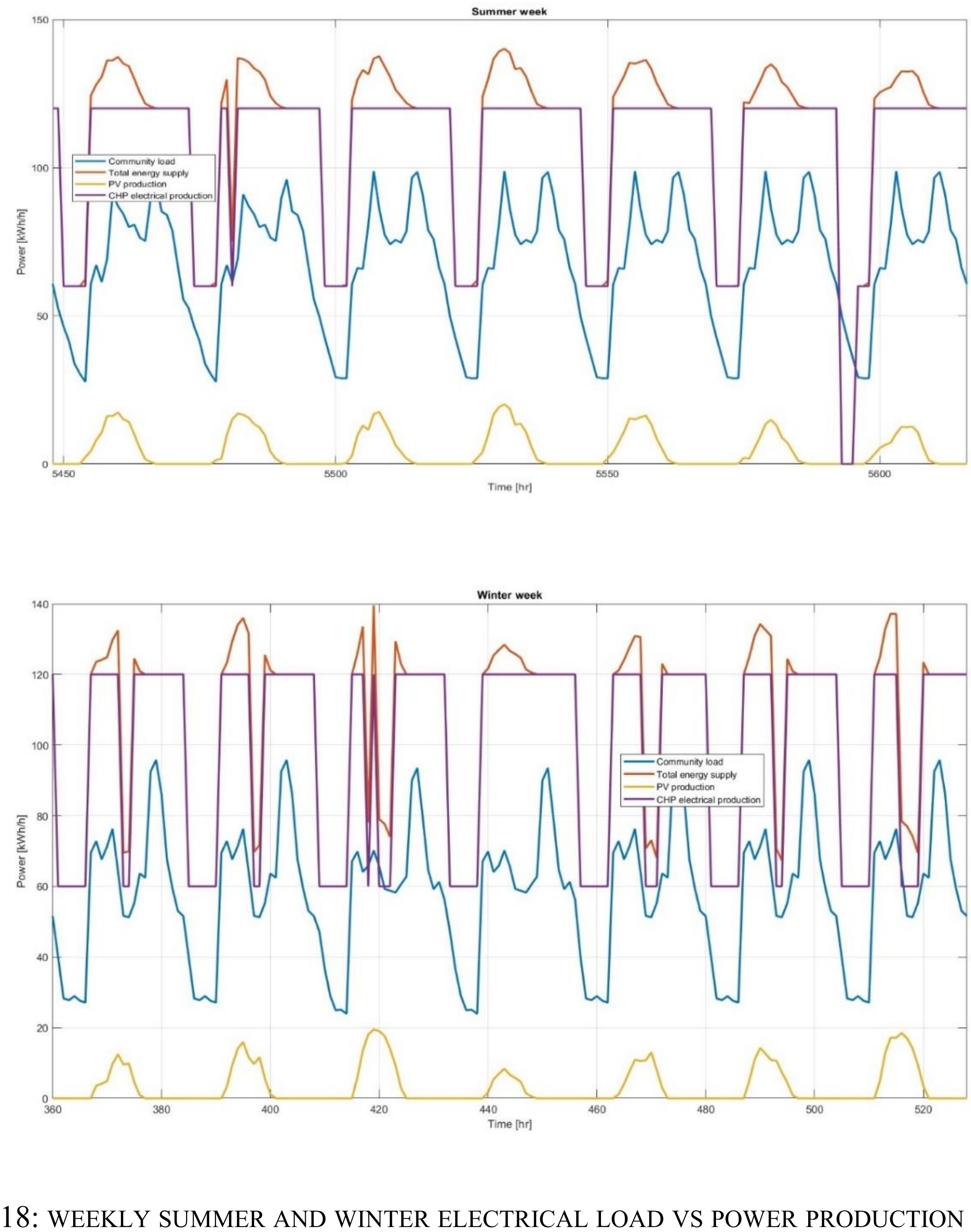


FIGURE 18: WEEKLY SUMMER AND WINTER ELECTRICAL LOAD VS POWER PRODUCTION IN A REC SUPLLIED BY CHP PLUS PV

The advantage of having a cogeneration plant also lies in its heat production. In this case, it has been considered that the heat generated is used to reduce the natural gas demand from the grid for the farm, thereby lowering costs. Below is the thermal load curve of the farm overlaid with the thermal production curve:

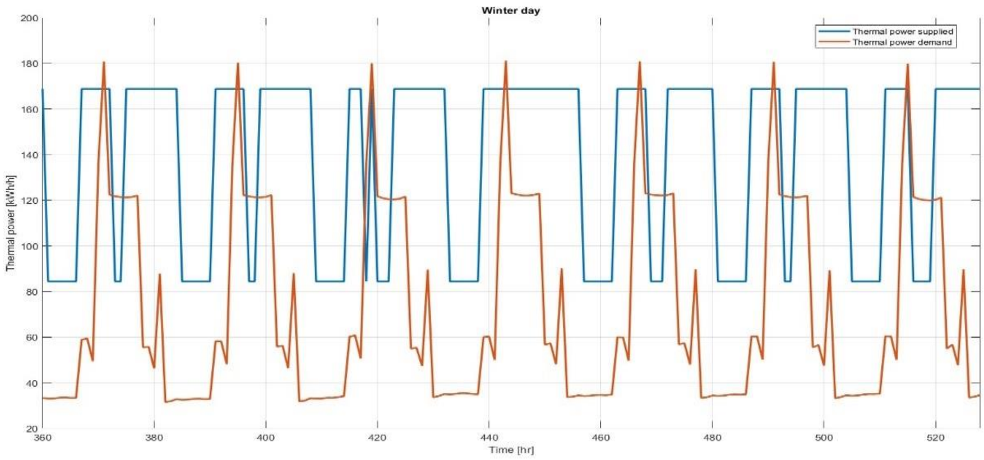


FIGURE 19: WEEKLY FARM'S THERMAL LOAD VS THERMAL POWER SUPPLIED BY THE CHP

In conclusion, it can be stated that a hybrid configuration with a downsized cogeneration engine supported by a photovoltaic system is capable not only of ensuring high levels of energy self-sufficiency, but also of meeting the energy needs of a larger community compared to a configuration powered solely by solar energy.

3.4 Upgrading to Biomethane with PSA Technology

In this chapter, the process of biomethane production through biogas upgrading is analysed. In recent years, incentives for electricity production from biogas have progressively decreased, making way for new support policies aimed at biomethane production, intended both for injection into the natural gas grid and for use as fuel in the transport sector.
In 2017, despite thousands of active biogas plants across the national territory, only 7 of them were equipped with upgrading systems for biomethane production. However, by the end of 2024, the number of upgrading plants had increased to 115, with a total production capacity of approximately 67,000 Smc/h. This growth highlights a significant increase in interest in biomethane, particularly in the northern regions of Italy, where the availability of biomass and agricultural by-products is higher. Despite this positive trend, Italy is still far from reaching the target set by the PNIEC (Integrated National Plan for Energy and Climate), which foresees an annual production of 5.7 billion Smc of biomethane. To accelerate the development of the supply chain, the Ministerial Decree of 15 September 2022 introduced a new incentive strategy, also supported by PNRR funds. The measure provides for two main instruments:

- a capital grant for the construction or conversion of plants.
- an incentive tariff on biomethane production, granted for a defined period [see Chapter 1].

Starting from the hourly biogas production generated by the anaerobic digester described in Chapter 3.3, an upgrading model was developed using the open-source simulation tool called toPSAil (Totally Open Pressure Swing Adsorption Intensification Laboratory). The model involves the use of a PSA (Pressure Swing Adsorption) cycle for the removal of carbon dioxide contained in raw biogas, to obtain a gas with purity characteristics compliant with grid injection standards. To make the simulation realistic, the biogas conversion reactor was dimensioned using pressure values as boundary conditions, suitable for achieving biomethane with the desired characteristics.

Subsequently, the main economic flows associated with this type of investment were analyzed and calculated. The results obtained will be compared with the other two configurations analyzed, as illustrated in Chapter 4.

3.4.1 Technologies for Biogas Upgrading

The percentage of biomethane (CH_4) contained in the biogas produced by an anaerobic digester strongly depends on the digester's feedstock and can vary approximately between 40% and 75%. The remaining portion is made up of a mixture of unwanted gases, primarily carbon dioxide (CO_2), as well as traces of hydrogen sulphide (H_2S), water vapor, ammonia (NH_3), and other minor contaminants in lower concentrations. To obtain biomethane with the required purity levels for grid injection or use in transportation, it is necessary to remove these impurities. Minor concentration contaminants, such as H_2S, are eliminated in a preliminary phase through pretreatment systems, with the aim of protecting the upgrading equipment from corrosion or damage [46].

The most common technologies for removing H_2S include:

- adsorption on activated carbon.
- biological oxidation.
- chemical scrubbing.

For the removal of CO_2, technologies derived from the industrial sector of Carbon Capture are used, historically applied for the treatment of combustion gases. The main adopted solutions include:

- chemical or physical adsorption.
- membrane separation.
- solvent scrubbing (physical or chemical).

The final goal of these treatments is to obtain biomethane with a methane content above 96%, in line with the technical specifications required for end use.

Focusing on physical adsorption, the main technologies available on the market are:

1. TSA (Thermal Swing Adsorption): The TSA process is based on regenerating the adsorbent material through an increase in temperature. In practice, the saturated adsorbent is passed through by a flow of hot gas, which causes the desorption of the previously retained molecules, particularly CO_2. For effective regeneration, the temperature must be raised, but without exceeding the thermal limits of the adsorbent material, otherwise its structural integrity may be compromised. A typical TSA system uses two fixed beds operating alternately: while one is active for adsorption (usually at ambient temperature), the other is regenerated with a hot flow, generally of inert gas or steam. Continuous operation is possible if adsorption and regeneration times are similar, but this affects efficiency since desorption takes longer than adsorption, leading to a progressive reduction in adsorption capacity over time and an increase in the adsorbate concentration in the bed. Furthermore, the long heating and cooling times make this process less dynamic and require larger dimensions to ensure operational continuity. Consequently, TSA is usually employed only when PSA (Pressure Swing Adsorption) systems cannot ensure the required methane purity. One advantage of TSA is that it does not require pressure changes, resulting in a less complex system with lower electricity consumption. However, the main drawback is the high energy cost, especially when temperatures above 400–450 °C are needed for effective regeneration of the adsorbent. Recent studies are exploring the use of multistage fluidized beds, which allow for better heat exchange and higher energy efficiency, also thanks to heat recovery systems such as high-temperature heat pumps. These solutions make it possible to transfer heat from the adsorber to the regeneration column, thereby reducing overall consumption. However, fluidized beds present challenges related to mechanical wear of the adsorbents, which can degrade quickly (e.g., zeolite 13X) [47].
2. PSA: The PSA technology (Pressure Swing Adsorption) is based on the alternation of adsorption and desorption in a fixed bed of adsorbent material, exploiting pressure variations to separate carbon dioxide (CO_2) from the methane present in the biogas. Desorption occurs by reducing the pressure compared to that used during adsorption: this allows the release of CO_2 molecules from the adsorbent material, enabling its

regeneration. The classic PSA cycle, known as the Skarstrom cycle, consists of four main phases:

1 Adsorption – the compressed biogas (between 4 and 10 bar) enters the column where CO_2 is retained by the adsorbent bed, while methane (CH_4) passes through and is collected as a pure product.

2 Blowdown – when the bed reaches the saturation point (breakpoint), the feed is stopped and the pressure inside the column is gradually reduced to atmospheric pressure. In this phase, the adsorbed CO_2 is released as “off-gas.”

3 Purge – a part of the purified methane is reintroduced into the bed to remove the remaining CO_2, completing the regeneration of the adsorbent.

4 Pressurization – the column is brought back to operating pressure to be ready to resume the adsorption cycle. This phase can be conducted co-currently or counter-currently (back-fill).

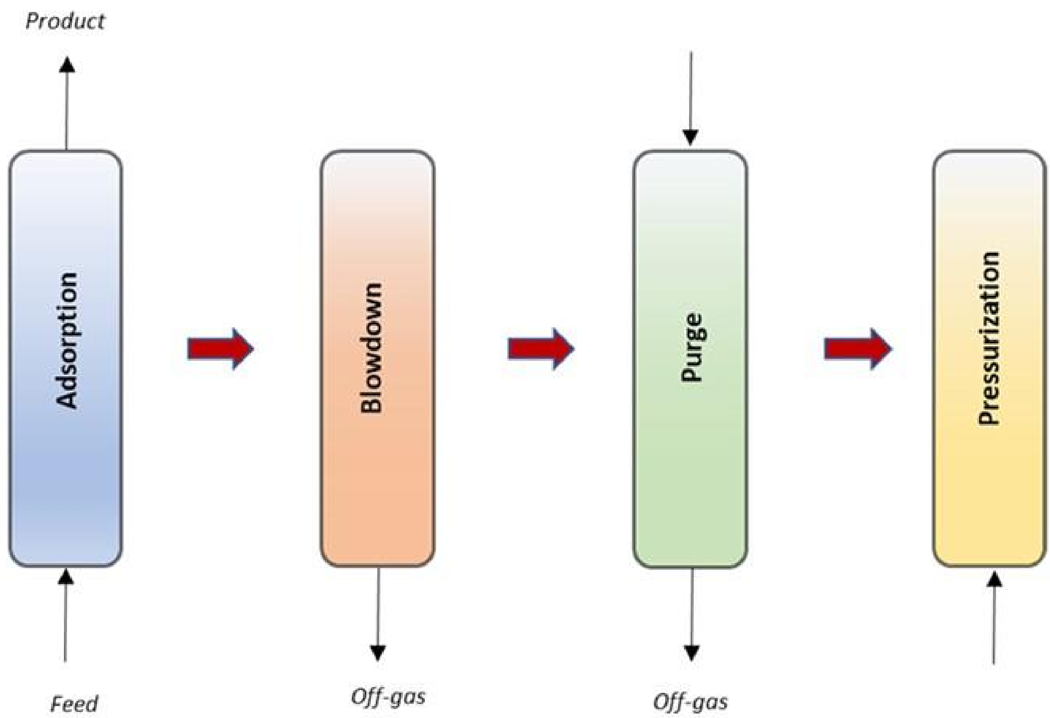


FIGURE 20: SKRSTROM CYCLE [SOURCE [47]]

To ensure continuous operation, the PSA system uses multiple columns in parallel: while one column is in the adsorption phase, the others are in the regeneration phases. Depending on the complexity of the cycle, PSA systems can have from two up to nine columns operating simultaneously. A common strategy to improve process efficiency and reduce methane losses during blowdown is the implementation of pressure equalization phases between columns. In practice, the gas from the blowdown of one column is used to partially pressurize another, reducing both CH_4 emissions (a potent greenhouse gas) and energy consumption. However, the introduction of these phases requires a greater number of columns, since during equalization the biogas supply must be interrupted. Another strategy to contain losses is to perform blowdown in multiple depressurization stages, recirculating the initially released methane back to the process inlet. The purge phase can also contribute to CH_4 losses if not managed properly. From an operational point of view, PSA technology allows achieving excellent separation results under different operating conditions, but requires careful optimization of some key parameters: Adsorption Pressure: increasing this pressure increases the adsorption capacity of the bed and thus the methane purity and the purge/feed ratio (P/F), which, if high, favors better bed regeneration and higher methane purity but reduces the amount of recovered gas; conversely, a P/F that is too low leads to incomplete regeneration and reduced efficiency. In summary, PSA represents a highly efficient technology for biogas upgrading, but presents an important trade-off between purity, methane recovery, and energy efficiency. Unlike TSA, which uses thermal energy, PSA uses mechanical energy, allowing faster cycles but potentially higher energy costs. For this reason, especially on an industrial scale, finding the right balance between process performance and energy consumption is essential [47].

- VSA: The VSA (Vacuum Swing Adsorption) technology is conceptually very similar to PSA, as it also uses pressure variation as the main operating parameter to achieve the separation of biogas components. The fundamental difference between the two processes lies in the desorption phase: while in PSA the pressure is reduced to atmospheric level, in VSA it is lowered further, operating under vacuum (sub-atmospheric) conditions. This characteristic makes VSA particularly advantageous when using adsorbent materials with very steep adsorption isotherms in the low-pressure region. In these cases, applying vacuum allows more efficient regeneration of the adsorbent bed, improving CO_2 removal and increasing the purity of the produced methane [47].

3.4.2 Operating Principles of PSA/VSA Processes

In the most common adsorption processes, the adsorbent is brought into contact with a fluid inside a packed bed column. Understanding the dynamic behaviour of this system is fundamental for a rational design and optimization of the process. The dynamic behaviour of adsorption columns depends on two main factors:

- The gas-solid equilibrium relationship, which describes how the gas components distribute between the gas phase and the solid phase.
- The mass transfer from the gas to the adsorbent.

The gas-solid equilibrium determines the maximum capacity of the adsorbent to retain a given solute. Since the composition and temperature of the gas vary over time and along the column, these changes influence the adsorption equilibrium. For this reason, it is necessary to adopt a complete gas-solid equilibrium model, capable of accurately representing real operating conditions. Experimental studies have confirmed how the equilibrium is influenced by these variations, especially in the presence of microporous adsorbents.

The complexity of the mathematical model depends on various factors:

- the concentration level of the components in the gas.
- the choice of the kinetic equation (i.e., the adsorption rate model).
- the flow model chosen to represent the movement of the gas in the column.

Moreover, temperature also plays a crucial role: for high-concentration feed streams, the heat generated by the adsorption process can cause thermal waves both along the column axis and in the radial direction. This entails the need to include in the model also the phenomena of heat generation and transfer in the adsorbent bed. Finally, along the column, an axial pressure drop may occur, which requires the inclusion in the model of the momentum balance for a more accurate description of the system.

To simulate the transient behaviour of the adsorption and desorption phases, several mathematical models have been implemented. These models are based on complex partial differential and algebraic equations (PDAE) built to describe:

- Mass conservation
- Energy conservation
- Momentum conservation
- Adsorbate diffusion into the adsorbent
- Equilibrium isotherms

The transient mass balance of the gas phase includes terms to describe axial dispersion, flow convection, accumulation in the gas phase, and a source term caused by the adsorption process, and can be represented by the following equation [48]:

$$\frac{\partial Ci}{\partial t} = -\frac{\partial (uCi)}{\partial z} + Dax\frac{\partial^2 Ci}{\partial z^2} - \frac{1-\varepsilon}{\varepsilon}\rho_{ads}\frac{\partial ni}{\partial t} \quad (3.20)$$

Where:

Dove:

- C_i: represents the concentration of the adsorbate in the fluid phase, that is, the amount of component i present in the gas or liquid flowing through the adsorption bed.
- z: indicates the position along the length of the bed, i.e., the spatial coordinate that describes the point considered inside the column.
- u: is the fluid velocity, that is, the speed at which the gas moves through the column.
- t: represents time, a fundamental variable to analyze the dynamic and transient behavior of the system.
- ϵ: s the bed void fraction, i.e., the portion of the total column volume that is occupied by the fluid (and not by the solid particles).
- ρ: represents the particle density, that is, the mass per unit volume of the solid adsorbent material.

- $n_{i:}$: indicates the average concentration of component iii inside the adsorbent particle and is the parameter that connects the mass balance in the fluid phase with that in the solid phase.
- D_{zi}: is the effective axial dispersion coefficient, which represents in an aggregated way all the mechanisms that contribute to mixing along the axis of the column (such as molecular diffusion and mechanical dispersion).

This equation is used to find the gas distribution along the bed assuming only the axial component and not the radial component of gas concentration in the solid is considered. The last term of the equation represents the approximation of mass exchange between the gas phase and the solid phase. The most used approximation in this sense is the so-called Linear Driving Force (LDF), represented by the following equation [48]:

$$\frac{\partial ni}{\partial t} = k_s(n^* - n_i) \qquad (3.21)$$

Where:

- n^*= Represents the equilibrium concentration of the adsorbent that can be captured in the adsorbate.
- k_i= Represents the mass transfer resistance in a single coefficient called the LDF coefficient.
- n_i Is the amount of adsorbate captured inside the porous structure which is described by the adsorption isotherm models.

There are different adsorption isotherms that depend on the pressure and temperature of the process. The most used is the Langmuir isotherm, but to describe the adsorption of CO_2 in biogas, for greater accuracy, the multisite Langmuir model is used [48]:

$$n^* = \sum_{i=1}^{n} \frac{q_{max} b P_i^n}{1 + b P_i^n} (3.22)$$

Where:

- q_{max}: maximum amount of the adsorbed element.

- b,n: parameters for the isotherm fitting.
- P: partial pressure of the adsorbed component.

This model allows the adsorption to be described as a linear variation of concentrations between the gas phase and the solid phase. Furthermore, as the gas flows through the porous material, it undergoes a pressure drop due to viscous losses and kinetic energy dissipation. This pressure drop is described by the Ergun equation [48]:

$$\frac{\delta P}{\delta z} = -K_D u - K_V u^2 \quad (3.23)$$

Where:

- K_D= coefficient accounting for kinetic losses.
- K_V=coefficient accounting for viscous losses.

The presence of pressure drops reduces the performance of the system. The other equations governing the process describe the thermal energy exchange during the process [48]:

$$-\lambda_L \frac{\partial^2 T_g}{\partial z^2} + \rho_g C_g \frac{\partial (u T_g)}{\partial z} + \rho_g C_g \frac{\partial T_g}{\partial t} + \left(\frac{1-\varepsilon}{\varepsilon}\right) h_f a_s (T_g - T_s) + \frac{4 h_w}{\varepsilon d_{int}} (T_g - T_w) = 0 \quad (3.24)$$

Where:

- T_g: represents the bulk gas temperature, i.e., the average temperature of the gas in the column.
- C_g: is the heat capacity of the gas, i.e., the amount of heat required to increase the temperature of a certain mass of gas by one degree.
- ρ_g: indicates the mass density of the gas, i.e., the mass per unit volume of the gas in the bed.
- h_f: is the film heat transfer coefficient between the gas and the adsorbent, which quantifies the thermal exchange by convection at the surface of the particles.
- a_s: expresses the ratio between the external surface area of the particles and their volume, a fundamental geometric parameter to calculate heat and mass flows.

- T_s: represents the temperature of the solid, i.e., the temperature of the adsorbent material.
- h_w: is the internal convective heat transfer coefficient between the gas and the inner wall of the column.
- d_{int}: indicates the internal diameter of the column, a geometric parameter necessary to evaluate radial heat exchange.
- T_w: is the wall temperature of the column, which can significantly influence the thermal distribution of the gas.
- λ_l: represents the effective axial heat dispersion, i.e., the measure of heat diffusion along the axis of the column. It can be estimated through empirical correlations.

Heat exchange of the solid phase [48]:

$$\rho_p C_s \frac{\partial T_s}{\partial t} = h_f a_s (T_g - T_s) + \sum_{i=1}^{n} -\Delta H_i \frac{\partial ni}{\partial t} \quad (3.25)$$

Where:

- ΔH = isosteric heat of adsorption.

Heat exchange along the reactor wall [48]:

$$\rho_w C_w \frac{\partial T_w}{\partial t} = h_w a_w (T_g - T_w) + U a_a (T_\infty - T_w) \quad (3.26)$$

Where:

- C_w: is the heat capacity of the column wall, i.e., the amount of heat required to increase the temperature of one unit mass of the wall by one degree.
- ρ_w: represents the density of the column wall, i.e., the mass per unit volume of the material constituting the wall.
- a_w: indicates the ratio between the internal surface and the volume of the column wall. This parameter is important to calculate the internal heat exchange between gas and wall.
- a_a: represents the ratio between the external surface and the volume of the column wall, used to calculate the heat exchange with the external environment.

- U: is the overall heat transfer coefficient from the wall to the external environment (ambient air), which accounts for all external heat transfer mechanisms (conduction, convection, and radiation).
- T_{inf}: represents the temperature of the external environment, i.e., the temperature of the air surrounding the column.

3.4.3 toPSAil

In the context of gas-solid separation process simulation, particularly for biogas upgrading through pressure swing adsorption, the tool toPSAil[39] stands out as an extremely advanced and versatile open-source resource. Developed in the MATLAB® environment, toPSAil was designed to offer a valid alternative to commercial PSA simulators, which are often closed, not very adaptable, and limited in the possibility of customization by the researcher. The model implemented in the software is based on a dynamic approach that uses a network of CSTR reactors arranged in series to discretely represent the behaviour of the adsorbing column along the axial axis. This methodology allows for detailed simulation of the different phases of the PSA cycle — adsorption, blowdown, purge, and pressurization — considering mass transfer phenomena, thermal exchanges, and pressure variations. A particularly relevant aspect of the tool is the management of dynamic boundary conditions, which can be imposed either in pressure-controlled mode or flow rate-controlled mode. This allows for flexible simulation of complex cycles, including flow reversal phases, commonly present in real PSA processes. Furthermore, toPSAil allows the integration of realistic thermodynamic models, calculation of pressure drops along the column, and consideration of the interaction between the physical properties of the adsorbent materials and the operating conditions. The software also provides the possibility of calculating key performance parameters such as methane purity, recovery, productivity, and energy efficiency, described by the following equations [49], [50]:

$$PURITY = \frac{\int_0^{tfeed} c_{CH4}u|_{z=L}dt}{\int_0^{tfeed} c_{CH4}u|_{z=L}dt+\int_0^{tfeed} c_{CO2}u|_{z=L}dt} \quad (3.27)$$

$$RECOVERY = \frac{\int_0^{tfeed} c_{CH4}u|_{z=L}dt-\int_0^{tpurge} c_{CH4}u|_{z=L}dt}{\int_0^{t} c_{CH4}u|_{z=0}dt} \quad (3.28)$$

$$PRODUCTIVITY = \frac{y_{CH4,feed}n_{feed}*RECOVERY}{n*PURITY} \quad (3.29)$$

$$SPECIFIC\ ENERGY\ CONSUMPTION = \frac{ENERGY\ CONSUMPTION}{PRODUCTIVITY} \quad (3.30)$$

Thanks to its modular structure, full code transparency, and the ability to easily customize models and cycles, toPSAil represents a powerful tool for the design, simulation, and optimization of PSA systems, both for academic research purposes and for industrial applications. Its applicability to biogas upgrading processes makes it an ideal choice for simulating realistic methane purification scenarios, evaluating the effectiveness of new adsorbent materials, or comparing alternative operating strategies based on sustainability and efficiency goals.

Once the basic parameters necessary for the simulation were defined, the setup of the model to be executed was carried out. The adopted cycle is an improved variant of the Skarstrom cycle, which includes not four but five operating phases. The considered phases are:

1. First repressurization using the refined product coming from the tank, up to an intermediate pressure of 2.5 bar (starting from initial conditions close to atmospheric pressure).
2. Second pressurization with the raw gas (feed), until reaching the operating pressure of 8 bar;
3. Feed phase at constant pressure of 8 bar, during which the selective adsorption of CO_2 occurs.
4. Blowdown phase, that is the first depressurization down to 0.15 bar, which allows the desorption of CO_2. Since the final pressure is subatmospheric, this case is referred to as a VPSA (Vacuum Pressure Swing Adsorption) process and not simply PSA;
5. Purge phase, at constant pressure of 0.15 bar, aimed at improving the methane purity in the product.

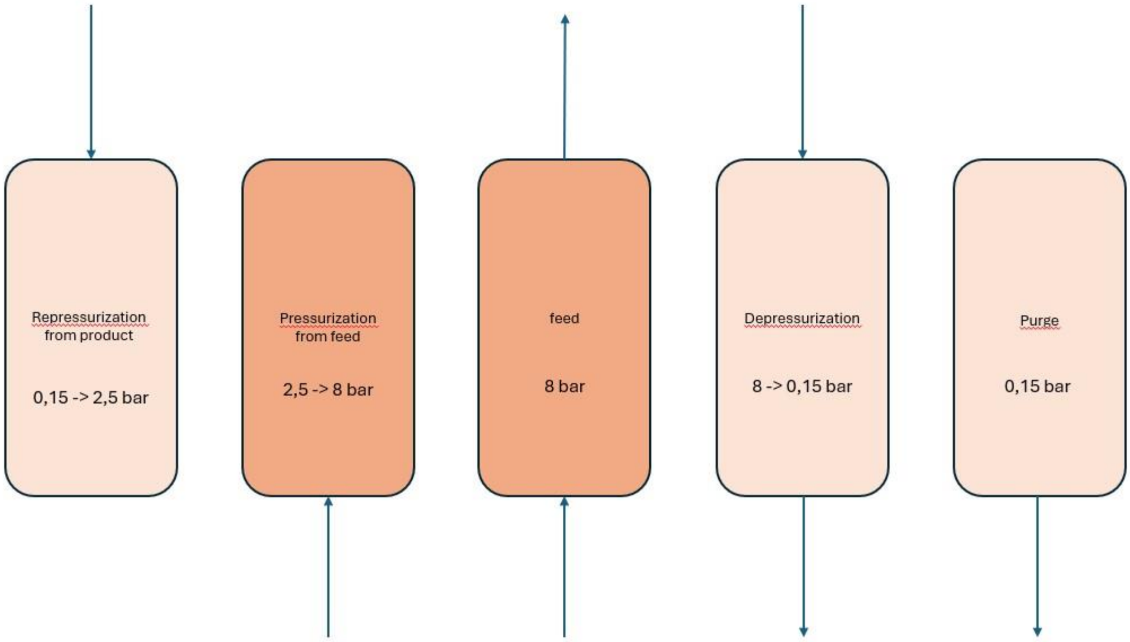


FIGURE 21: IMPROVED SKARSTROM CYCLE

The simulation was carried out assuming the presence of a single adsorbent bed, with step durations of 120, 120, 240, 120, and 120 seconds respectively. To simplify the model, isothermal conditions and no axial pressure drop along the column were assumed. The adsorption behaviour was described using the multisite Langmuir model, suitable for representing systems with heterogeneous surfaces. The properties of the incoming gas were defined assuming a typical composition of biogas obtained from anaerobic digestion of bovine manure, consisting of 60% methane and 40% carbon dioxide. From this composition, the thermophysical properties of the biogas, in particular molar weight and density, were derived.

As for the adsorbent material, Carbon Molecular Sieve 3K was used, which demonstrates the best performance from an energy point of view, whose main properties were defined within the model, including those necessary for the parameterization of the multisite Langmuir isotherm. These characteristics are reported in the following table [49], [50]:

Gas	q_{max} [mol/kg]	b [kPa^{-1}]	n [-]	K_i [sec^{-1}]
CO2	8,974	1,73E-8	8,287	-
CH4	11,797	2,48E-10	6,303	1E-4

TABLE 20: FITTING PARAMETER FOR MULTISITE LANGMUIR ISOTHERM FOR CMS 3K

Finally, the volumes of the auxiliary components of the system were also defined. The buffer tank, positioned upstream of the reactor where adsorption takes place, was considered to operate at a pressure of 8.4 bar, slightly higher than the internal pressure of the adsorption bed, in order to ensure the correct flow of gas. The volume of the vessel intended for CO_2 capture was also sized. To this end, the flow rate of biogas entering the feed tank during the depressurization and repressurization phases was calculated, as these are necessary to bring the reactor back to the desired operating conditions.

Similarly, the volume of the reactor was calculated considering the amount of product introduced during the first pressurization phase (up to the intermediate pressure of 2.5 bar), coming from the products, and subsequently the pressurization phase up to 8 bar, obtained from the feed tank, based on the pressure difference between the reactor and the upstream tank. The volumes are respectively of 385 and 19,2 litres and the and it is considered that the ratio among the diameter and the length is 0,2 [50]

Thanks to the model setup and the definition of the operating parameters, it was possible to simulate the CO_2 capture process within the adsorbent bed. The pressure trend over time and the amount of carbon dioxide adsorbed in the material were monitored throughout the different phases of the cycle. The results obtained allow for the analysis of the dynamic behaviour of the system in response to the cyclic pressure variations and the defined operating conditions. The curves related to the evolution of pressure and the CO_2 loading in the adsorbent material are shown in the following figures and represent a fundamental support for evaluating the efficiency of the process.

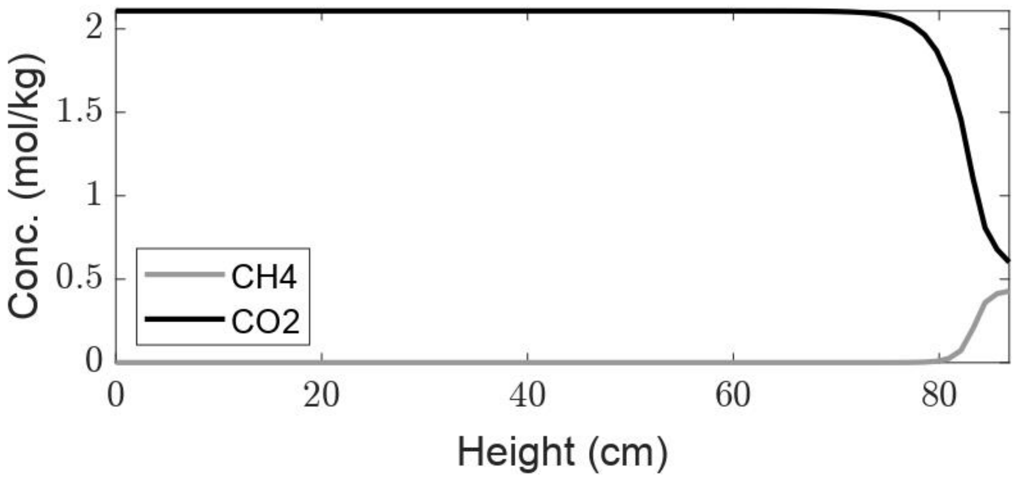


FIGURE 22: CONCENTRATION OF CH4 AND CO2 IN THE COLUMN

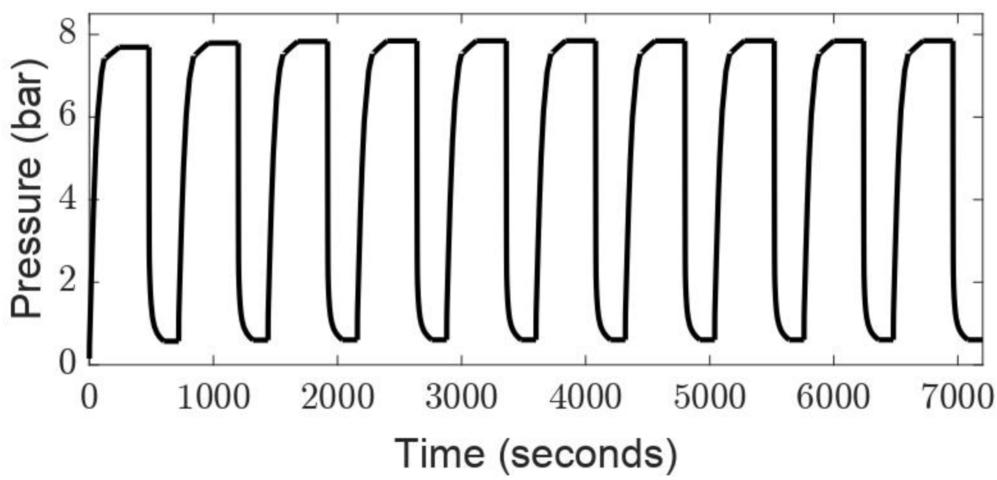


FIGURE 23: PRESSURE VARIATION IN THE COLUMN

From the analysis of the simulation results, it is observed that, regarding the concentration profile of carbon dioxide in the adsorbent bed, the material appears almost completely saturated along most of the column. Only in the last centimetres of the bed is there a noticeable increase in methane concentration, indicating that the CO_2 has reached the local saturation capacity and that the adsorption front is advancing toward the outlet. This behaviour is typical of a well-dimensioned system, in which the separation efficiency is high.

As for the pressure profile, during the first simulated cycles, a value slightly lower than the 8 bar expected as the operating condition is recorded. However, as the cycles progress, the system reaches a steady-state regime in which it is possible to stably maintain the desired pressure, confirming the good balance between the repressurization phases and the gas release phases. In order to evaluate the effectiveness of the simulated adsorption cycle, the main performance indicators of the process were calculated and analysed, namely productivity, biomethane purity, recovery, and specific energy consumption. These parameters make it possible to quantitatively assess the efficiency of the system and its potential application on a real scale. To further deepen the analysis, a parametric evaluation was carried out, keeping constant the volumes of the reactor and the buffer tanks, but varying the maximum pressure reached in the cycle. In particular, the operating pressure of 8 bar was progressively reduced to 6 bar and subsequently to 4 bar, to observe the impact of this variation on the process performance. The results obtained from these comparative simulations are shown in the following graph and represent a useful tool for understanding the behaviour of the system as a function of the maximum pressure, highlighting any trade-offs between energy efficiency, product quality, and separation capacity.

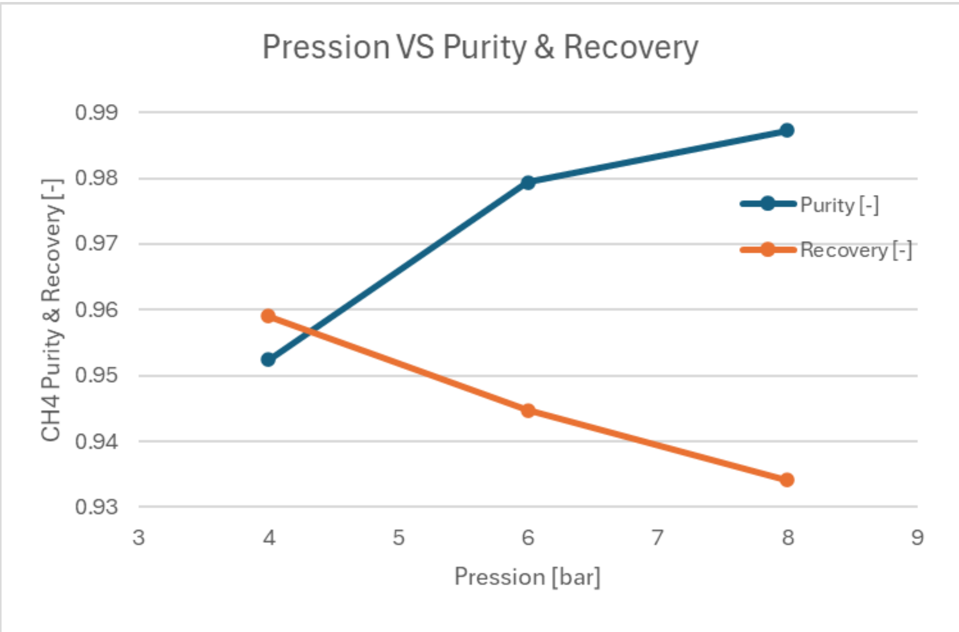


FIGURE 24: PURITY AND RECOVERY OF CH4 CHANGING THE MAXIMUM PRESSURE OF THE CYCLE

As also demonstrated in [49], the results confirm that the increase in adsorption pressure leads to an increase in methane purity in the final product. However, this condition also results in a greater retention of CH_4 inside the adsorbent bed, with a consequent decrease in the recovery rate. In particular, it is observed that the recovery ratio decreases more rapidly than the purity increases with increasing pressure, highlighting a greater sensitivity of the recovery to changes in operating pressure. This result underlines the existence of a technical trade-off between purity and recovery, which must be considered during the process optimization phase. Considering that the required purity must be greater than 0.97, the configurations taken into consideration are those with maximum pressures of 6 and 8. Also considering the specific consumption reported in the following table, it was decided to adopt a system operating between 8 and 0.15 bar, since considering the objectives of the study, it was decided to maximize the production of biomethane at the expense of the energy spent.

	P = 4 bar	P = 6 bar	P = 8 bar
Productivity [Nm3/h]	21,11	24,29	27,54
Specific power consumption [kWh/m3]	0,13	0,18	0,22

FIGURE 25: PRODUCTIVITY AND SPECIFIC POWER CONSUMPTION OF THE PSA CYCLE VARYING THE MAXIMUM PRESSURE

Chapter 4 – Economic Analysis And Final Considerations

So far, the establishment of the Renewable Energy Community (REC) has been analysed with the related energy flows, identifying the most advantageous configuration. Furthermore, a CO_2 capture model based on PVSA technology has been presented, with the aim of also considering the production of biomethane, a possible alternative for a farm producing biogas. In this chapter, therefore, an economic analysis will be proposed based on the KPIs defined in Chapter 3, with the aim of identifying the optimal configuration and providing concrete guidelines for implementation. The analysis will examine the capital expenditures (CAPEX) and operational expenditures (OPEX) of the plants, calculating the annual cash flows derived from the sale or sharing of energy, or from the direct sale of biomethane into the grid. Finally, possible future developments that a farm can undertake will be outlined, in order to further improve economic and energy parameters, contributing to transforming these realities into sustainable models capable of generating value, innovation, and autonomy in rural areas.

4.1 REC Business Model

To quantify the costs of a Renewable Energy Community (REC), it is essential to consider the ways in which it is established. As provided by the CACER decree and reported in the literature, a REC can adopt different business models. The main configurations are described below[5]:

- Model fully self-managed by citizens: In this case, the REC is entirely established by citizens, who bear the initial investment costs, operating costs, and management activities. However, this model can be complex to implement, as community members may not possess sufficient technical or legal knowledge. The possible involvement of public bodies or institutions could help to overcome legislative barriers. An advantage of this configuration is that all proceeds from incentives, such as the feed-in tariff, would remain entirely available to the REC itself.

- Model with external technical support: In this configuration, the REC entrusts a third party with the technical management of the plant and the operation & management activity. This party receives a fee for the services offered, covered by the REC. This approach allows overcoming difficulties related to the lack of specific skills within the community but involves a partial reduction in revenues for the REC members, as a share of the incentives must be allocated to the payment of the external manager.
- Model with external investment (third-party ownership): In this scenario, a third party fully covers the initial investment costs. REC members do not have to bear capital expenditures and, in fact, use the plant in a sort of "energy lease" regime. In this case, the REC and the investor enter into a contract for the distribution of revenues. Most of the proceeds go to the third party, who must recover the investment made. This is the least profitable solution for community members but also the easiest to implement: citizens do not have to worry about technical or bureaucratic aspects and still benefit from a, albeit limited, reduction in their energy bills.

In the specific case analysed in this study, the REC fully bears the initial investment for the construction of the plant. However, to ensure efficient management and overcome any lack of technical or organizational skills, an external party is involved, entrusted with operation & management activities, to whom the related service costs are paid. This configuration represents an effective compromise: on one hand, the community maintains full ownership of the plant and fully benefits from the proceeds deriving from energy production and sharing; on the other hand, it can rely on professional support in technical management [5][11], avoiding compromising operational efficiency. It is, therefore, the most profitable model for REC members, although it involves a recurring expense for external management services.

4.1.1 CAPEX of Photovoltaic Plant, Anaerobic Digester, VPSA System

To calculate the economic KPIs of the configurations, we initially need to evaluate the initial investment cost. This varies greatly between photovoltaics, which turns out to be the least expensive renewable energy technology, and the anaerobic digester for biogas production, which also requires the installation of auxiliary machinery for its operation. In all three cases, however, since the CER was located in a municipality with fewer than 5,000 inhabitants, it was possible to benefit from the capital contribution made available by the PNRR, which amounts to a maximum of 40% of the initial investment, and this share was reached in all three configurations, considering for the CER a 50% reduction in the feed-in tariff.

As for the photovoltaic modules, monocrystalline silicon has gained an increasing market share in recent years thanks to its higher efficiency compared to polycrystalline silicon. The transition to this technology has been crucial in increasing the average efficiency of photovoltaic modules, which went from 14.7% in 2010 to 20.9% in 2021, with an average efficiency of 21% in 2023 [51]. From 2009 to 2023, the prices of crystalline silicon modules dropped between 92% and 98%, with an average reduction of 93%. In 2023 alone, the prices of monocrystalline modules dropped by up to 55%, with an average cost of 0.16 USD/W, and minimum values as low as 0.11 USD/W for the least expensive modules. However, Italy represents an exception in the European landscape: while most European countries recorded a decrease in total installed costs between 2018 and 2023, in Italy an increase in costs was observed from 2022 to 2023. Despite this, Italian values in 2023 remain lower than in 2018 and stand at around 809€/kWp [51]. This represents the Total Capital Investment (TCI) for photovoltaic modules including: the module, the inverter, the installation, and other soft costs. The CAPEX values of the photovoltaic plant are reported in the following table:

PV size [kWp]	Total PV cost [€]	PV cost with capital grant [€]
100	80.931	48.559
125	101.160	60.698
150	121.400	72.838
175	141.630	84.978

TABLE 21: PV CAPEX

In the economic analysis model for biogas production, it was taken into consideration that the costs refer to the entire installation of the plant. These depend on various technical and economic factors, including the characteristics of the anaerobic digestion process, the size of the plant, and the type of biomass used. In particular, the installed power plays a central role:

as the size of the plant increases, a progressive reduction in the unit investment cost, expressed in euros per installed electric kW, can be observed. This scale effect represents a fundamental element in the economic planning of the plants. The unit cost can vary significantly: from about 3,500–4,000 €/kW up to 7,500–8,000 €/kW, mainly depending on the adopted feedstock and the plant's power. The feedstock affects both the design configuration of the plant and the complexity of the necessary equipment, thus having a direct impact on the initial capital required. An analysis based on a sample of 35 [52], [53] real plants made it possible to validate a mathematical estimation model, based on a scale law commonly used in design practice, which adopts an exponent equal to 2/3 for the cost variation as a function of power. Starting from a reference plant with a power of 999 kW and an average cost of about 4 million euros, it is possible to estimate the cost of plants of different sizes by applying the following formula:

$$C = (\frac{P}{P_0})^{\frac{2}{3}} * C_0 \quad (4.1)$$

Where:

- P = plant power, which in this case varies between 100 and 150 kW.
- P_0 = reference plant power equal to 999 kW.
- C_0 = reference cost of the 999 kW plant equal to 4 million euros.

These values refer to a study conducted in 2012. The construction and installation costs of the plant may have decreased over time, but to remain in an unfavourable condition, these slightly higher-than-current-market values were considered. Furthermore, the costs related to the anaerobic digestion plant were supplemented by the costs of the photovoltaic system, if present. The total costs are reported in the following table:

CHP + PVsize [kW]	Total Plant cost [€]	Plant cost with capital grant [€]
100 + 50	902.816	722.810
110 + 40	951.292	771.290
120 + 30	998.079	818.080
130 + 20	1.043.386	863.360
140 + 10	1.087.293	907.290
150	1.130.000	950.000

TABLE 22: CHP PLUS PV CAPEX

To evaluate the total cost of the upgrading plant for biomethane production, the estimation already carried out for the anaerobic digestion plant was used as a starting point. However, since in this configuration all the biogas produced is sent to the upgrading process to obtain biomethane, no cogeneration unit (CHP) is present. Therefore, the cost of the cogenerator [54] was subtracted from the initial capital (CAPEX) of the reference plant. The cost of the CHP was evaluated through the following equation and amounts to approximately €187,270:

$$C_{CHP} = 6229{,}1 * P_{el,CHP}^{0{,}676} \quad (4.2)$$

Once the correct cost of the plant without CHP was defined, the complete economic evaluation of the entire upgrading system was carried out. To this end, the Total Capital Investment (TCI) was estimated, that is, the total investment required for the construction and start-up of the plant (IC: construction and installation costs). The TCI [55] represents a broader value than the sole cost of the installed equipment, as it includes:

- the Fixed Capital Investment (FCI), which includes direct (on-site and off-site) and indirect costs related to construction, engineering, and installation.
- the working capital necessary for the start-up and initial management of the plant.

- the start-up costs, related to the commissioning phase. For the calculation of the TCI, consolidated empirical correlations from the literature were used, which provide the following ratios:

$$TCI = 2{,}36 * IC \quad (4.3)$$

$$FCI = \frac{TCI}{1{,}30} \quad (4.4)$$

These correlations are based on the following assumptions:

- the off-site direct costs are equal to 45% of the on-site direct costs.
- the indirect costs represent 25% of the total direct costs.
- the working capital is estimated as 15% of the TCI.
- the start-up costs correspond to 10% of the FCI.

To calculate the plant costs, the configuration presented in Chapter 3 was used, in which the upgrading plant includes: a buffer vessel, a reactor where the CO_2 capture reaction takes place, a compressor for the initial compression of the biogas, and a vacuum pump for the reduction of the pressure below ambient. The equation used for the calculation of the plant components was derived from [56] and describes elements operating at ambient pressure with a steel structure:

$$log_{10}C_p^0 = K_1 + K_2 log_{10}(A) + K_3[log_{10}(A)]^2 \quad (4.5)$$

Where:

- A= capacity or size of the appliances.
- K1, K2, K3: values for the equation fitting.

Subsequently, for the compressors, the evaluation of the Bare Module Factor (Fbm) was carried out, which considers the material with which the machinery was built. In addition, a scale factor equals to 0.84 was used, since the power of the compressor is lower than the minimum described by the cost curve available in the literature. On the other hand, for the pressure vessels, it is necessary to consider, in addition to the factor that accounts for the material, also the operating pressure with the equation reported below:

$$C_{BM} = C_P^0 F_{BM} = C_P^0 (B_1 + B_2 F_M F_P) \quad (4.6)$$

$$F_{P,vessel} = \frac{\frac{(P+1)D}{2[850-0{,}6(P+1)]}+0{,}00315}{0{,}0063} \qquad (4.7)$$

The fitting parameters are reported in the following table:

	K1	K2	K3	B1	B2	F_{BM}
Compressors	5,0355	-1,8002	0,8253	-	-	5
Tanks	3,4974	0,4485	0,1074	2,25	1,82	-

TABLE 23: FITTING PARAMETERS FOR THE CALCULATIONS OF THE CAPEX FOR TANKS AND COMPRESSORS

All the reported values are referred to the year 2001, therefore, through the CEPCI, it was possible to update the values to 2024. Moreover, a conversion from USD to EUR was carried out to consider the expense made in Europe. Finally, for the vacuum pump, a commercial price of €11,160.51 was found, and for the adsorbent material, CMS 3K, which does not need replacement during the 20 years lifetime of the plant, a specific cost of €17.5/kg [54]was considered, corresponding to a total of €1,358. In this way, it was possible to evaluate the entire TCI to be added to the investment for the anaerobic digester, equal to €347,514.72. In the following table is reported the cost for the AD plant with the PSA system:

Biomethane upgrading	Total Plant cost [€]	Plant cost with capital grant [€]
	1.293.200	929.710

4.1.2 OPEX Photovoltaic Plant, Anaerobic Digester, VPSA system

Regarding the operational costs (OPEX) within the Renewable Energy Community (CER), the cost of management and coordination of energy flows, entrusted to an external operator, was initially considered. This management cost was set at 25 €/kW[11] and applies to both configurations analysed. Being a cost proportional to the installed power, its absolute value varies depending on the size of the photovoltaic system.

Since the size of the photovoltaic system can vary depending on the scenario considered, the related management costs are also variable. On the contrary, as regards the biogas plant, the installed power was set at 150 kW; therefore, the operational costs for this section of the plant are constant for all the parametric configurations analysed.

In addition to the management costs, the Operation & Maintenance (O&M) costs of the photovoltaic plant were also included in the operational costs. For these, a reference value of 7.76 €/kW[51] per year was adopted, including ordinary technical activities, insurance, corrective operations, periodic cleaning of the panels, and other minor expenses related to the operation of the plant. The following table shows the OPEX for different sizes of photovoltaic systems:

PV size [kWp]	O&M PV cost [€]
100	3.276
125	4.095
150	4.914
175	5.733

TABLE 24: PV OPEX

For the configuration that includes the integration between the photovoltaic system and the biogas plant with cogeneration (CHP), it is necessary to carefully consider the operational costs associated with the management of the anaerobic digestion plant, as they represent a significant portion of the overall OPEX. The optimal operation of a digestion plant requires careful and continuous management, both to ensure the stability of the biological process and to obtain a constant and reliable production of electricity. Under ideal conditions, the plant should operate for about 8,000 hours per year, corresponding to almost all the available hours, excluding only short stops for maintenance or technical interventions. Based on [52], for a plant with installed power equal to 100 kW, the annual operational cost is estimated at around 0.011 €/kWh of electricity produced, mainly due to company labour and routine maintenance of the plant, equal respectively to 0.006 €/kWh and 0.005 €/kWh. The equation for the estimation of the OPEX for the CHP plant is:

$$OPEX_{CHP,PV} = Worker\ salary + AD\ maintenance + OPEXpv \quad (4.8)$$

Theoretically, the operational costs should also include the costs for biomass supply, but since the farm itself produces livestock waste, this type of cost was considered equal to zero. The following table shows the operational costs for the different configurations:

CHP + PVsize [kW]	Total O&M costs [€]
100 + 50	12.455
110 + 40	13.112
120 + 30	13.832
130 + 20	14.025
140 + 10	13.883
150	13.730

TABLE 25: OPEX CHP PLUS PV

Regarding the configuration based on biomethane production, the operation costs take into account three main components: the electricity consumed by the biogas upgrading unit, the labour cost associated with the presence of an operator, this is a specialist worker, paid more than the one of only the AD [54], dedicated to the management of the plant, and the maintenance cost of the anaerobic digester considered equal to the previous configuration. Also, in this case the costs for the biomasses is neglected. It is calculated with the following equation [55] and the results are shown in the table below:

$$OPEX_{biomethane} = P_{el,upgrading} * c_{el} + Worker\ salary + AD\ maintenance \quad (4.9)$$

Biomethane Plant	Total O&M for biomethane [€]
	77.153

TABLE 26: OPEX BIOMETHANE PLANT

4.2 Parametric Comparison of the Configurations

Once the investment costs (CAPEX) and operational costs (OPEX) were defined and analysed in detail, both for the renewable energy community and for the biomethane production plant, it was possible to proceed with the evaluation of the main economic indicators (KPI), as introduced in Chapter 3. These indicators, including the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Payback Period (PBP), represent fundamental tools for measuring the economic profitability of the two proposed configurations and allow for an objective comparison between the analysed alternatives, supporting the choice of the most economically efficient solution.

4.2.1 Economic KPIs Comparison of REC with Photovoltaic Plant

As also illustrated in Chapter 3, the configurations analysed include photovoltaic plants with a variable power between 100 and 175 kWp. From an energy perspective, the best performance was achieved by the 150 kWp configuration, which showed a good balance between production and self-consumption. However, the economic analysis highlighted that the 175 kWp configuration is the most advantageous in terms of economic return. Nevertheless, it is important to underline that the primary objective of a Renewable Energy Community (REC) does not lie exclusively in profit maximization, but in social, environmental, and territorial enhancement through increased sustainability, energy autonomy, and emission reduction. For this reason, the 150 kWp configuration was chosen, as it represents an optimal compromise between energy performance, economic sustainability, and social impact. Moreover, this choice allows for a reduction in initial investment costs, promoting broader participation and inclusiveness within the community. The figure shows the trend of the NPV over the 20 years of the investment:

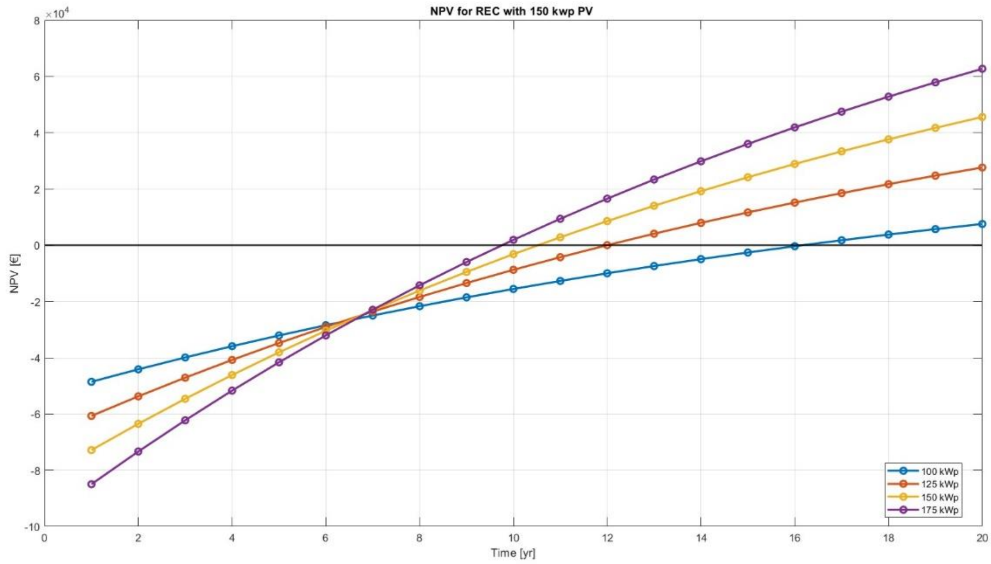


FIGURE 26: REC NPV FOR DIFFERENT SIZES OF PV

In the following table are reported the values of the economic KPIs for the REC supplied by the PV plant:

PV size [kWp]	NPV [€]	PBT [yr]	IRR [%]
100	9.284	17	7
125	30.361	13	10
150	49.258	11	12
175	67.310	10	13

TABLE 27: REC ECONOMIC KPIS WITH PV PLANT

From the analysis of the Internal Rate of Return (IRR), the investment is sustainable, as the value obtained is higher than the current depreciation rate, equal to 0.05. This figure indicates a positive profitability of the project in the long term. As for the Payback Time, it is observed that it is slightly higher than the average reference values, generally around 8 years. This deviation is mainly attributable to the reduced electricity production during the summer months, as also highlighted in Chapter 3. During this period, which usually represents the peak production phase for a photovoltaic system, energy production is lower, resulting in less energy sharing than expected and therefore a lower economic return. This phenomenon slightly extends the investment payback time, while not compromising the overall economic sustainability.

Moreover, within the economic analysis carried out, the reduction in the farm's electricity bill due to the direct self-consumption of the energy produced by the photovoltaic system was not included. However, this aspect represents a significant economic benefit that deserves to be considered. In the case of the 150 kWp configuration, the annual savings estimated thanks to self-consumption amount to €29,764, corresponding to about 53% of the farm's initial energy expenditure. Consequently, the new energy costs of the farm would be reduced to €26,353 per year. This saving significantly contributes to the improvement of the overall economic balance, further strengthening the financial sustainability of the intervention and encouraging the adoption of shared energy models.

4.2.2 Economic KPIs Comparison of REC with AD and CHP

With the introduction of the anaerobic digestion plant, it is observed that the initial investment assumes a significantly greater weight in the overall economic analysis. In particular, in the case of the installation of the CHP (Combined Heat and Power) system alone, and despite the current incentive tariff in force, it is not possible to obtain a positive Net Present Value (NPV). This highlights that, for small-scale plants, the exclusive use of available biomass is not sufficient to ensure the economic sustainability of the investment. In this context, the integration of photovoltaics with the CHP system proves to be fundamental to improve the economic feasibility of the initiative by reducing both capital investment costs and operating expenses. As already discussed in Chapter 3, this configuration also allows for the optimization of the energy performance of the energy community, thanks to the greater continuity in the availability of self-produced energy compared to photovoltaics. Therefore, among the different configurations analyzed, the one that ensures the best balance between economic sustainability and energy performance was found to be the one composed of a 120 kW electric CHP and a 30 kWp photovoltaic system.

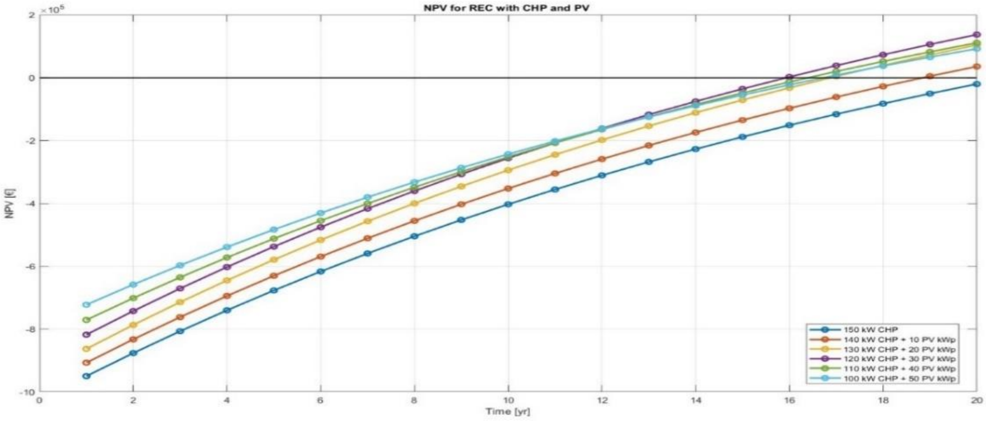


TABLE 28: REC NPV FOR DIFFERENT CHP AND PV PLANT

In the following table are reported the values of the economic KPIs for the REC supplied by the CHP and PV plant:

CHP + PVsize [kW]	NPV [€]	PBT [yr]	IRR [%]
100 + 50	117.190	15	7
110 + 40	138.020	15	7
120 + 30	166.480	14	7
130 + 20	133.890	15	7
140 + 10	64.668	17	6
150	8.434	19	5

TABLE 29: REC ECONOMIC KPIS FOR CHP PLUS PV PLANT

As highlighted also by the Internal Rate of Return (IRR), the configurations that include, even minimally, a photovoltaic system prove to be economically sustainable. The integration of photovoltaics, in fact, allows for a significant improvement in profitability indicators, making the overall investment more solid and less exposed to risk. As for the Payback Time (PBT), this is significantly higher compared to the configurations based solely on photovoltaics. This difference is attributable both to the higher initial investment required for the anaerobic digestion plant and the CHP system, and to the structure of the incentive tariff, which was not specifically designed to enhance electricity production from biogas, partly penalizing this type of configuration compared to other renewable sources.

Quantifying the economic benefits related to the self-consumption of electricity and the replacement of natural gas drawn from the grid, a significant impact on the energy balance of the farm is evident. In the configuration that includes a 120 kW CHP plant and a 30 kWp photovoltaic system, with the CHP operating for about 8,500 hours/year, there is a reduction in electricity costs of 96.6% compared to the situation without any plant. In absolute terms, the annual expenditure for electricity is reduced to only €1,873. Similarly, with regard to natural gas consumption, the cost reduction is 96.76%, bringing the annual expenditure to €2,119. These results demonstrate the high effectiveness of the integrated CHP-photovoltaic system not only in terms of energy sustainability but also in terms of reducing dependence on external energy sources and enhancing the economic resilience of the farm.

4.2.3 Economic KPIs for Biomethane Injection into the Grid

Regarding the injection of biomethane into the grid, this undoubtedly represents the most advantageous configuration from an economic point of view for the farm. Unlike the Renewable Energy Community (REC) configuration, where incentives extend for twenty years, in the case of biomethane the incentive lasts fifteen years. This aspect is clearly reflected in the trend of cumulative cash flows, where a change in the slope of the curve is observed at the fifteenth year, corresponding to the end of the incentive support.

In the reference graph, two distinct hypotheses are compared: one where no incentive is provided for biomethane production and one where the currently available incentives are recognized. The analysis highlights how the presence of the incentive is decisive: in its absence, the investment is not economically sustainable, while its activation allows the achievement of a favourable economic balance, justifying the investment also in terms of financial return for the farm. In the following table are reported the values of the economic KPIs for the biomethane injection into the grid by the farm:

	NPV [€]	PBT [yr]	IRR [%]
No-incentives	650.530	7	14
Incentives	<0	-	-

TABLE 30:FARM ECONOMIC KPIS FOR BIOMETHANE INJECTION IN TO THE GRID

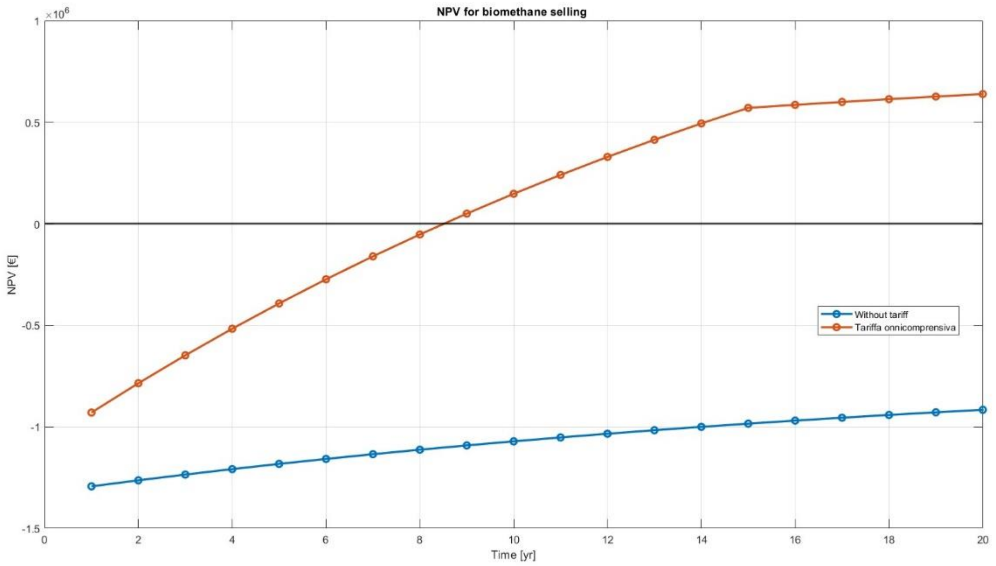


FIGURE 27: FARM NPV FOR BIOMETHANE INJECTION INTO THE GRID

4.3 Comparison of Economic KPIs Between the Selected Configurations

Finally, a comparative analysis of the three selected configurations was conducted, whose main economic and energy KPIs are reported in the following table:

	NPV [€]	PBT [yr]	IRR [%]
PV: 150 [kWp]	49.258	11	12
CHP + PV: 130 [kW] +20[kWp]	166.480	14	7
Biomethane injection with TO	650.530	7	14

TABLE 31: ECONOMIC KPIS COMPARISON OF THE DIFFERNT CONFIGURATION CHOSEN

From the comparison, it emerges that, within the Renewable Energy Community, the configuration with only the photovoltaic plant allows for a faster economic return compared to the hybrid configuration that also includes the anaerobic digestion plant. However, in the long term, particularly at the end of the twenty-year cycle, the hybrid configuration guarantees a significantly higher overall economic gain, thanks to the continuous production of electricity throughout the year. From an energy point of view, the two configurations have different characteristics: the photovoltaic plant maximizes self-consumption, using energy at the moment it is produced, while the hybrid configuration with CHP and photovoltaic optimizes energy self-sufficiency, ensuring energy availability also during nighttime hours and winter months. This aspect opens up the possibility, in the hybrid configuration, of integrating additional users, such as homes or other businesses, within the energy community, so as to better valorise the excess energy produced.

In addition, the hybrid configuration offers a direct advantage for the farm, allowing a drastic reduction in energy costs up to nearly total self-sufficiency, both for electricity and heating. Conversely, in the configuration dedicated to biomethane production, energy indicators were not considered as no electricity or thermal energy is produced on site; on the contrary, the plant consumes energy for the upgrading of biogas. However, the incentive provided for the injection of biomethane into the grid proves more consistent and advantageous compared to those provided for electricity production from biogas within the REC framework. This is reflected in a significant increase in profits for the farm, making this solution economically sustainable and particularly interesting in a perspective of valorising the agricultural-biological supply chain.

4.4 Enhancements and Implementation Opportunities

To further improve the study, it would be appropriate to apply the analyzed configurations to a real case, for example an energy community located near an agricultural company. In the analysis carried out, the agricultural company was considered as the only prosumer, but in a real context, citizens could also take on the role of producer-consumers, thus contributing to increasing the overall efficiency of the system.

A significant contribution could come from the integration of battery storage systems, which, during periods of CHP generator shutdown, would be able to provide the energy needed to meet the community's demands.

Moreover, if the tariff conditions made it convenient, the coexistence of the biomethane upgrading system with the energy community could be considered. In this case, even the electricity consumed for the upgrading process, if shared, could generate economic benefits for the biomethane producer, who would thus have access to two different forms of incentive, thereby encouraging both the production of biomethane and the sharing of electricity.

Finally, a comparative analysis of the costs of the different energy sources and the available business models could prove useful in order to identify the best economic compromise between third-party management and direct citizen management.

4.5 Future developments

The development of renewable energies has brought about a profound change in the energy sector, steering it towards new economic and productive models. In particular, the principles of the circular economy and environmental sustainability goals today constitute the cornerstones of the transition towards a low-carbon society. In this scenario, all involved actors — citizens, businesses, researchers, and policymakers — are called to actively collaborate in defining effective solutions to face the climate crisis. Among the most relevant strategies is the recovery of residues and waste, which allows closing the material cycle, reducing waste, and at the same time generating new economic and employment opportunities. In this perspective, energy communities based on the use of anaerobic digesters and biogas production can become true energy hubs in rural areas, ensuring both electrical and thermal independence.

However, to fully exploit this potential, significant infrastructural investments are necessary, such as the development of district heating networks, in line with what is foreseen by the 2023 revision of the RED II Directive. As also highlighted in this study, a considerable portion of the heat produced in such plants would otherwise be lost, whereas it could instead be used to supply an entire rural community, increasing the overall system efficiency. Finally, the introduction of new technologies and targeted incentives opens further possibilities, such as the production of hydrogen from biogas through technologies like rSOC, PEM, and PEMWE[57]. In this way, hydrogen could act both as an energy carrier for storage and as a clean fuel for agricultural vehicles, making rural areas not only sustainable but also potential centres of technological development.

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