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Development of pyRES: a Python library for time-dependent energy analysis and optimization of Renewable Energy Communities

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original. Some of the results presented in this dissertation were published on international journals or presented in national conference. In particular:

- The findings in Chapter 4 were published on Journal of Renewable Energy - Elsevier: Corsini, Alessandro, Giovanni Delibra, Pizzuti Isabella, Erfan Tajalli-Ardekani. *"Challenges of renewable energy communities on small Mediterranean islands: A case study on Ponza island." Renewable Energy* 215 (2023): 118986. (https://www.sciencedirect.com/science/article/pii/S0960148123008923 (accessed on 25 October 2023

- The findings in Chapter 5 were extracted from a work that is currently under review for the Energy Journal by Elsevier. Pizzuti Isabella, Erfan Tajalli-Ardekani, Alessandro Corsini, Giovanni Delibra. "Renewable energy communities based on solar panels and batteries: optimal aggregation of prosumers and consumers".

- The findings in Chapter 6 were presented at the 18th CONFERENCE ON SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS (SDEWES), Dubrovnik 2023. Pizzuti Isabella, Erfan Tajalli-Ardekani, Alessandro Corsini, Giovanni Delibra. *"Optimal integration of solar panels and Biomasses in an Italian Renewable Energy Community".* This work is currently under review for "*Energy Conversion and Management: X*" Journal by ScienceDirect.

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ISABELLA PIZZUTI

Summary

The subject of study is renewable energy communities (RECs), according to the European definition. The aim is to develop an open-source tool for the design, analysis and optimization of RECs. RECs serve as a tool for member States to achieve energy transition goals. The fundamental principles are the use of renewable sources, decentralized production, self-production and collective consumption, and direct consumer involvement. The REC is a complex energy system whose characteristics are influenced by several key factors, including the time scale, spatial scale, local context, stakeholders, technology, adopted business models, and the organizational models governing its activities. Currently, the activities of an REC involve the production, storage, sale, sharing, and consumption of energy. The adopted technologies can be classified into three categories: distributed generation systems powered by renewable sources, conversion systems, and storage systems. The geographical dimension where energy-related activities are implemented can vary significantly from groups of buildings to entire cities. the REC can be established in a wide range of contexts, ranging from small municipalities with fewer than 5,000 inhabitants to metropolitan cities with millions of residents, from mountainous areas to small islands, and from agricultural areas to industrial districts. The geographical context strongly influences the development of the RES due to factors as the availability of energy sources, climatic conditions, end-uses of energy, energy consumption patterns, type of existing technologies, type and number of available spaces to install renewable technologies. The main actors include, REC members (consumers and prosumers), technology suppliers, energy suppliers, ESCOs, Transmission system operators (TSO), Distribution

network operators (DNO), policymakers, regulatory bodies and aggregators. Organizational models are based on the horizontal cooperation and democratic decision-making. The introduction of RECs changes the paradigm of incentives for renewable sources: the incentive tariff is no longer proportional to the installed capacity but rather to the energy consumed on-site.

In the introduction, an analysis of changes in the energy system caused by policies against climate change is carried out with the aim to identify the circumstances which led to the spread of renewable sources and the definition of RECs. The interest in RECs as an emerging model for sustainable development, along with their potential applications, is supported through a literature analysis. In addition, a comparison between the traditional 'prosumer' model and the REC as a new model for the production and sharing of energy is conducted. The EU legal framework for RECs is analysed, with a focus on the Internal Electricity Market Directive (IEM) and The Renewable Energy Directive RED II which promote a competitive electricity market and, for the first time, establish an official definition of RECs. The status of the transposition of European directives into national legislation, is described, identifying good and bad practices. Focus is particularly given to the process of transposition of the RED II in Italy, which has launched an experimental phase with the aim of identifying the implications of the directive and facilitating the development of the final regulatory framework. Key responsibilities of entities introduced by the regulatory framework, including the Italian Regulatory Authority for Energy, Networks and Environment (ARERA), the energy services manager (GSE) and The Ministry of Economic Development (MiSE) are outlined. Virtual regulatory model introduced by ARERA, technical constraints and incentive mechanism are accurately described. Then the current spread of RECs in Europe and in Italy is mapped. The complexity of RECs is examined, focusing on several key factors, including the time scale, geographical scope, local context, stakeholders, technology, adopted business models, and the organizational models governing its activities. A comprehensive review is conducted with the aim of identifying the primary indicators for assessing the socioeconomic, environmental, and grid impacts of RECs. Subsequently, the investigation focuses on how the REC model can be applied in specific energy contexts such as smaller islands, and how the expansion of technical constraints may lead to the inclusion of additional energy vectors like heat, as well as the dissemination of RECs within the industrial districts. Elements of success and barriers preventing RECs spread are examined. Finally future pathways and policy recommendations are discussed.

The second chapter offers an overview of commercial software and open-source modelling tools for the optimal design of RECs, with the aim of identifying current trends in energy system modelling, challenges in simulating of RECs and requirements for new modelling tools. The modelling approach to develop a digital twin of the REC and the main steps of modelling are identified. Finally, methods to reconstruct production and demand curves along with the most used optimization method are described.

The third chapter provides a description of the python tool (pyRES) developed specifically to create digital twins of the RECs, starting with the rationale behind its development. An overview of the software's key features is presented, detailing how it can be effectively utilized to model RECs. Development phases, core components and main models are also presented. The chapter concludes with the description of the potential and future development of pyRES. In the last chapters case studies related to RECs analyzed in pyRES are presented.

In the first study the REC model is studied in a minor island disconnected from the national grid, with strongly seasonal energy load and water demand. Two sub-optimal REC configurations were defined using time-dependent simulations on pyRES. Results show the economical unfeasibility of REC when there is a poor mix of users. In contrast, REC can achieve economic profitability including industrial demand of a desalination unit (DES).

In the second work the REC model is studied in a small town of Lazio Region. The challenge is to stress the issues of assembling a profitable REC in this scenario, discussing the proper selection of prosumers and consumers, solar panels and battery storage. Major conclusions include the negative impact of BES on the economy of the REC and the benefits of the REC on CO_2 emissions and energy costs for the consumers. Finally, a sensibility analysis on these results was carried on discussing the effects of the fluctuations on the energy costs.

In the third work the REC model includes a mix of production characterized by the integration of solar panels and biomass plants for cogeneration, several residential and commercial users. Both thermal loads and electric loads are considered. Results show that with a biomass cogenerator prosumers have minor economic interest in being part of a REC as the incentives are proportional to shared energy. Increasing their share of the REC revenue, on the contrary, reduces the appeal to normal users, resulting in a difficult balance.

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Nomenclature

Abbreviations

ARERA	Italian Regulatory Authority for Energy, Networks and Environment
BES	Battery energy
CAPEX	CAP EXPenditure
CEC	Citizen Energy Community
CHP	Combined Heat and Power
DES	DESalinationSystem
DNO	Distribution network operators
EFSI	European Fund for Strategic Investments
EC	Energy Community
ESCO	Energy service companies
EU	European Union
GSE	Energy Services Manager
GIS	Geographical Information System
IEM	Internal Electricity Market Directive
ICE	Internal Combustion Engine
ICEs	Integrated Community Energy Systems
LCOE	Levelized Cost Of Energy
LV	Low voltage
MES	Multi-Energy Systems
MiSE	Ministry of Economic Development
MLP	Multi-Layer Perceptron
MV	Medium voltage
NPV	Net Positive Value

NSGA Non-dominated Sorting Genetic Algorithm

OPEX OPerational EXpenditure

OWC Oscillating Water Column

PNRR National Recovery and Resilience Plan

POD Point Of Delivery

PUN National Single Price

PV Photovoltaic

PVGIS Photovoltaic Geographical Information System

RED II Renewable Energy Directive

REC Renewable Energy Community

RES Renewable Energy Source

SME Small Medium Enterprise

TEC Thermal Energy Community

TSO Transmission system operators

ZEC Net Zero-Energy Community

Symbol Unit Quantity

D Demand

d Diameter

h Altitude

H Thermal power

i Current

I Solar radiation

lhv Lower heating value

m Mass

n Number of unit

$\breve{n}$ Mole

p Pressure

P Power

q State of charge

R Resistor

SOC State of charge

t Time

T Temperature

V Voltage

$\check{V}$ Volume

v Wind velocity

x Space

w Mass flow rate

ω Angular frequency

ξ Wave height

ρ Density

η Efficiency

1. Contribution of Renewable energy communities (RECs) to the energy transition

1.1 Exploring the context leading to the definition of RECs

Energy policies against climate change, the race towards renewable energy sources, the liberalization of the electricity market, the definition of the prosumer, and the beginning of the era of sharing economy contribute to the spread of renewable energy communities. The concept of an energy community refers to a group of people who spontaneously decide to collaborate on a collective project aimed at energy production. This concept includes different situations, but they all share the following fundamental principles:

- Freedom of participation
- Democratic decision-making processes
- Tangible benefits for community members
- Distinctive features that depend on the territory in which the community is established.

Evidence of energy communities (ECs) dates back to the mid-19th century. The first ECs emerged from the need to share production systems for powering small industrial activities. The collective ownership appeared as a solution to cut initial investment costs, especially in remote areas or on islands where resources were more expensive. Early forms of ECs could also be found in mining regions, where people organized around coal mining and use. ECs based on wind energy or small hydroelectric plants (typically from 5 to 100 kW) can be found worldwide. In some mountainous areas, communities shared electricity from small hydroelectric plants powered by local watercourses. In Italy, ECs could be associated with electric cooperatives, which originated between the 19th and 20th centuries and operated in remote areas of the Alpine region [1]. It wasn't until the 1970s that EC began to be associated with modern renewable technologies, and the concept of renewable energy communities (RECs) started to emerge. For the first time, this officially happened in Denmark with the establishment of the Danish Wind Turbine Owners and the first case of collective investment in the wind industry. By the end of the 20th century, starting from Germany and England, investments in community-owned solar energy projects spread across Europe, and RECs began to evolve [2][3].

Today, RECs are complex energy systems which include different production, transmission, distribution, and energy management configurations; types of actors; technologies; geographic scales; organizational and business models; and purposes. Furthermore, features of each community depend on local socioeconomic dynamics, territorial context, regulatory framework, available energy resources, environmental laws and regulations, infrastructure status, financial support, and member preferences. Main differences between RECs and ECs are presented in *Table 1* Bauwens et al. [4] have examined the concept of community within the context of energy systems in 183 cases. The existence of a community involves one or a combination of the following aspects: sharing the costs and revenues of an activity; development of a common identity sharing ideals; collaboration in the planning and management of projects; sharing technologies that physically connect members; geographical proximity; development of social relationships. In the context of energy systems, at least one of the activities among production, transmission, distribution, and consumption of energy must also be included. The energy configuration should include innovative elements in demand and production integration. Furthermore, the adjective "*renewable*" connects these communities to alternative energy sources. A survey conducted in the United Kingdom [5] has identified five categories based on the purposes of the renewable energy community: economic, environmental, social, political, and infrastructural. Economic objectives, such as savings on energy consumption costs, are the most frequently mentioned.

Table 1. Exploring differences between Energy Community (EC) and Renewable Energy Community (REC).

	Energy community (EC)	**Renewable energy community (REC)**
PURPOSE	cut initial investment costs through collective investment	increase the penetration of RES direct involvement of consumer
ACTIVITIES	local production, distribution and transmission of energy	local production, distribution and transmission of renewable energy
CONFIGURATIONS	small industrial activities small wind turbines small hydroelectric plants	adopting renewable technologies
CONTEXT	islands mining regions mountainous areas remote areas	everywhere
LEGAL FRAMEWORK	-	Clean Energy package
IMPACTS	social economic environmental	

Since 2008, there has been a marked increase in renewable energy community initiatives. In Europe, in 2015, more than 2800 energy cooperatives have been registered. The number of publications on this topic in scientific literature has significantly increased, ranging from 2 articles per year to 47 between 2000 to 2016 [4]. Using *Google Ngram Viewer's word* frequency calculator, it is possible to conduct research on 5 million books published between 1990 and 2019 that have been digitized. The frequency of use of 'renewable energy communities' has increased by around 200 times (*Figure 1*). These numbers are expected to keep growing. Kampman et al. [6] have explored the potential of European Union citizens in renewable energy production and demand-side flexibility and estimated that by 2050, approximately 83% of EU households could contribute to renewable energy production, with around 30% being part of an EC (*Figure 2*). As reported by the Directorate-General for Energy [7], by 2030, more than 50 GW of wind energy and over 50 GW of solar energy could be owned by ECs, corresponding approximately 17% and 21%, respectively, of the total installed capacity.

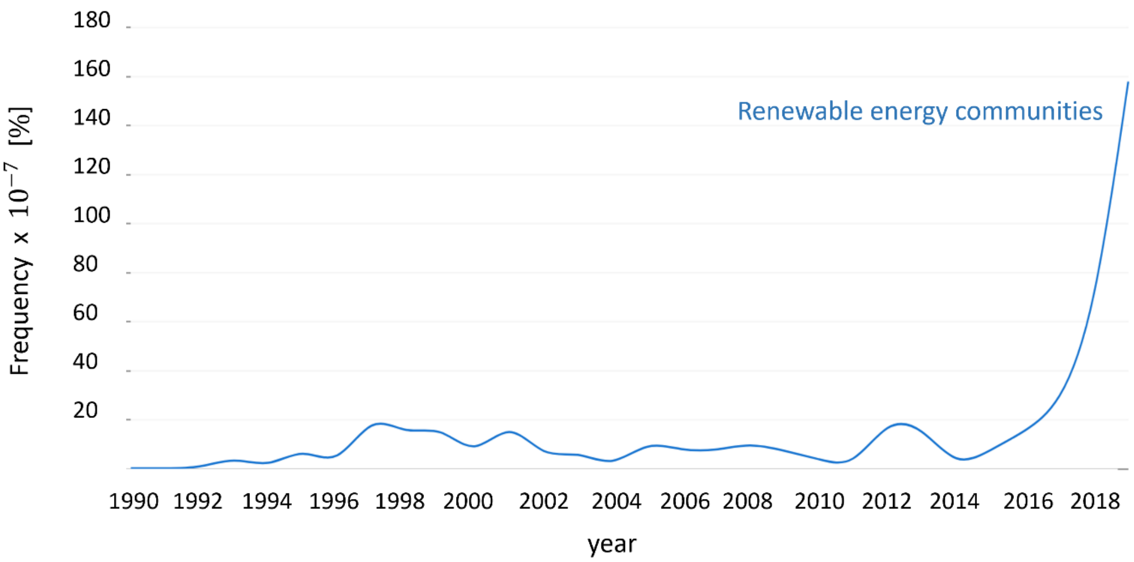


Figure 1. The frequency of use of 'renewable energy communities' between 1990 and 2019 according to Google Ngram Viewer's.

An analysis of changes in the energy system caused by policies against climate change is necessary to understand why there is a growing and indisputable renewed interest in ECs. The increase in ECs initiatives is driven by necessity of new energy models which promote the transition to renewables while overcoming integration challenges with the current energy system architecture. This increase is made possible by the liberalization of the electricity market. The negative impacts of fossil fuel use have been scientifically proven and measured. From 1850 to 2019, the increase in the global surface temperature caused by human activities such as energy supply, land use, and consumption patterns is of 1.07°C, compared to variations related to natural phenomena ranging from -0.1°C to +0.1°C [8]. This evidence has led to a radical transformation of the global energy system: at the 2015 Paris climate change conference (COP21), 195 countries established the ambitious goal of limiting the temperature increase below 2 degrees Celsius compared to pre-industrial levels. This marked the first international and legally binding agreement on global climate. According to [9], new energy market policies will result in a doubling of investments in clean energy by 2030, amounting to 2 trillion USD. From east to west, new objectives encourage the spread of renewable sources. By 2030, the United States anticipates more than doubling of solar and wind capacity, while China foresees reaching the peak of carbon and oil consumption. In Europe, the demand for natural gas and oil will be reduced by 20%, and the demand for carbon by 50%. These objectives become even more urgent due to the necessity of finding alternative sources to Russian gas. In Japan and Korea, the focus is on nuclear energy. In India, renewables will cover around two-thirds of the growing electricity demand. In the rest of the world, [10] have estimated that from 2008 to 2016, the number of people supplied by off-grid renewable installations has increased from 5 million to 133 million. Stand-alone systems are spreading in rural villages in Africa and South Asia and mostly consist of solar systems and mini-electric installations for household electricity production, including lighting and cooking. In such contexts, renewables are not only essential for water extraction from wells but also for improving basic public services, such as schools and hospitals. Access to electrical energy also promotes agriculture, communication, and dissemination of information.

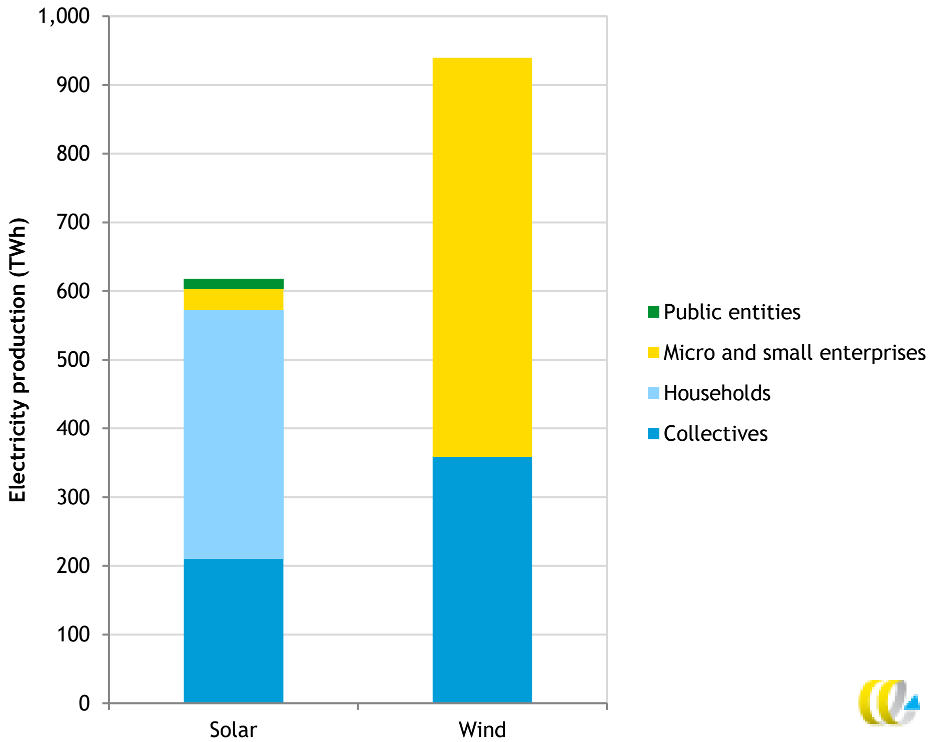


Figure 2. The potential of European Union citizens in renewable energy production and demand-side flexibility [6].

The transition to renewable energies is already underway. In the energy production sector, the main effect of the energy transition is the replacement of large-scale power systems (tens of MW), traditionally designed to supply large areas, with small-scale distributed power systems (tens of kW) powered by renewable sources. The current architecture of the electrical grid is transitioning from a system based on centralized generation and distributed consumption to a system where both generation and consumption are decentralized. Many studies have been conducted on a 100%

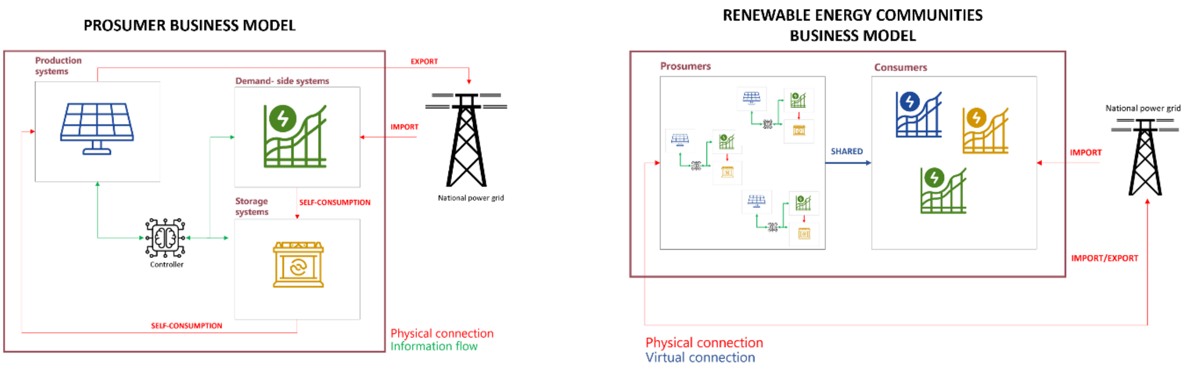
renewable scenario for Europe: Child et al [11] have argued that a 100% renewable scenario is technically feasible, economically advantageous, and consistent with the Paris agreement. However, Steinke et al. [12] have emphasized the necessity of substantial investments in balancing generation, grid expansion, and storage systems, and Rodriguez et al.[13] have highlighted the necessity of increasing interconnection capacity between foreign countries to facilitate demand and production balancing. This suggests that the transition involves not only a change in the type and size of systems but also in methods of energy production, transmission, and distribution: new energy configurations are required.

The diffusion of new energy configurations based on renewable sources has been facilitated by the liberalization of the electricity market, promoted by European directives on the internal electricity market (Directive 1996/92) and the internal gas market (Directive 1998/30). Through the opening of the electricity sector to competition in the production and sales segments, any consumer can now produce and sell electricity for the first time. The liberalization process has transformed the role of the consumer, evolving it into a prosumer. Hamwi et al. [14] have identified the prosumer as an emerging business model in the field of renewable energy production. The prosumer is mainly associated with privately-owned photovoltaic installations and is financially supported by government incentives such as tax reductions in the early years or a reduction in the feed-in tariff. Incentives ensure income and avoid financial risks. Hence, the prosumers create value through small-scale distributed production systems that they own. The collective actions of multiple renewable energy prosumers, which mainly include photovoltaic systems, are transforming the energy system: the centralized model of production is replaced by the locally distributed production. However, the prosumer model present challenges for two main reasons:

- Government incentives provided to encourage the installation of photovoltaic systems and boost economies of scale are coming to an end. New incentive mechanisms are based on a different paradigm: the incentive tariff is no longer proportional to the installed capacity but rather to the energy consumed on-site.
- Due to the non-programmable and intermittent nature of renewable sources, as the number of prosumers in an area increases, the dispatching and managing of energy flows along the power grid becomes more challenging. Additionally, the current stability of the grid depends on reserves of rotating power. As photovoltaic systems lack any rotating power components,

primary regulation cannot be guaranteed, thus restricting the penetration of photovoltaic installations.

The energy transition is advancing towards the end of the first phase, in which innovation consisted of the widespread adoption of renewable technologies and is now entering a second phase in which the use of renewable sources is a given, with innovation focus on demand and production integration. In this second phase, it is no longer possible to overlook the negative impacts of renewable sources on the power grid. The prosumer model which encouraged the transition in the first phase is currently being replaced by more complex energy models. Carlisle et al. [15] have introduced the concept of the 'net zero-energy community' (ZEC) as an extension of the zero-energy building concept: a community capable of meeting all energy needs through renewable sources. Mancarella [16] has proposed 'multi-energy systems' (MES) as a key option for decarbonizing the electrical system. These are integrated systems in which different energy carriers, such as electricity, heat, cold, and different types of fuels, interact on various scales, ranging from district to city, and even to the national level. Koirala et al. [17] have introduced "Integrated Community Energy Systems" (ICEs) as a new organizational model for distributed production systems, based on the integration of local resources and the community. Camargo et al. [18] have explored the potential of "hybrid renewable energy systems," systems consisting of the integration of photovoltaics, wind turbines, and community-level batteries to achieve electrical self-sufficiency. Lowitzsch et al. [19] have defined "renewable energy clusters" as the future energy systems based on the complementarity of multiple energy sources, bidirectional flows, Hamwi and Lizarralde [14] have identified emerging business models in the field of renewable energy production and demand management. Innovation in business models consists of co-operative initiatives and use of local resources. From the literature analysis, it emerges that dominant trends in energy systems are self-production, use of renewable sources, decentralization of energy production, source complementarity, introduction of storage systems, bidirectionality of energy flows, integration of multiple energy vectors and sector coupling. As regards business and governance models, trends suggest that a bottom-up approach is crucial for engaging of citizens. From the analysis of these trends appears why the spread of RECs is significantly increasing. Summarizing the factors renewing interest in RECs include policies aimed at fighting climate change and the liberalization of the energy market. The increased use of renewable energy sources involves the decentralization of the energy system and a redefinition of consumer ‘s role. Main differences between prosumer and REC business are presented in *Figure 3*.



Generate savings on energy bills	**PURPOSE**	Generate economic, social and environmental benefit
Local energy production	**ACTIVITIES**	Local energy production and sharing
Production systems + consumer	**CONFIGURATIONS**	Prosumer + consumers
Economic (+), environmental (+) on power grid (-)	**IMPACTS** Positive (+) Negative (-)	Economic (+), environmental (+), social (+), on power grid (+)
Initial investments, operation and maintenance, tax, network charges	**COST ITEMS**	Initial investments, operation and maintenance, network charges
Revenues from sold energy, tax reductions, savings on energy bills	**REVENUE ITEMS**	Incentives on energy consumed on-site, grid services/anicllary services, optional membership fee

Figure 3. Exploring differences between prosumer and REC business models [24][26][29].

ECs, which have existed since the 19th century, are now closely linked to the production of energy from renewable sources, constitute a model of energy production and sharing that directly involves citizens and include characteristics of future energy systems. REC is a distinct entity whose characteristics are closely depending on the context in which the community is established. Different energy systems can fit this definition. Given the complexity of the REC, this work focuses on REC recently defined by the European Union, examining key aspects *Figure 4*. The aim is to develop an open-source tool (pyRES) for the design and optimization of RECs. pyRES is a python tool has been developed to create digital twins and simulate the energy-economic-environmental behaviour of the RECs.

The work is organized as follows:

- **In the first chapter**, an analysis of the European regulatory framework and the transposition processes in various states is carried out, with a particular focus on Italian national regulations. The current state of spread in Europe and Italy is investigated. In the Italian case, the role of public institutions and regional-level projects are also examined. Additionally, the complexity of the system is analysed, examining the temporal and spatial scales, technologies, stakeholders, organizational and business model. The role of RECs is analysed in specific energy contexts such as small islands and industrial districts. Key socioeconomic, environmental, and grid-related impacts are briefly discussed, along with the key success factors and barriers to diffusion. Potential developments are hypothesized, and some recommendations are suggested.

- **The second chapter** focuses on REC modelling, considering the tools and methodologies currently available, explaining why the development of a customized tool was necessary.

- **The third chapter** provides a detailed description of pyRES. The software's key features,steps for RECs modelling, development phases, core components and main models are presented. The chapter concludes with the description of the potential and future development of pyRES.

In the last chapters case studies related to RECs analyzed in pyRES are presented.

- **In the fourth chapter** the REC model is tested in a minor island disconnected from the national grid, with strongly seasonal energy load and water demand.

- **In the fifth chapter** the REC model is tested in a small town of Lazio Region. The study investigates whether it is more convenient for a prosumer with an excess of photovoltaic production to install an electrochemical storage or to share the excess in a REC.

- **In the sixth chapter** the REC model includes a mix of production characterized by the integration of photovoltaic and biomass plants for cogeneration, several residential and commercial users. Both thermal loads and electric loads are considered.

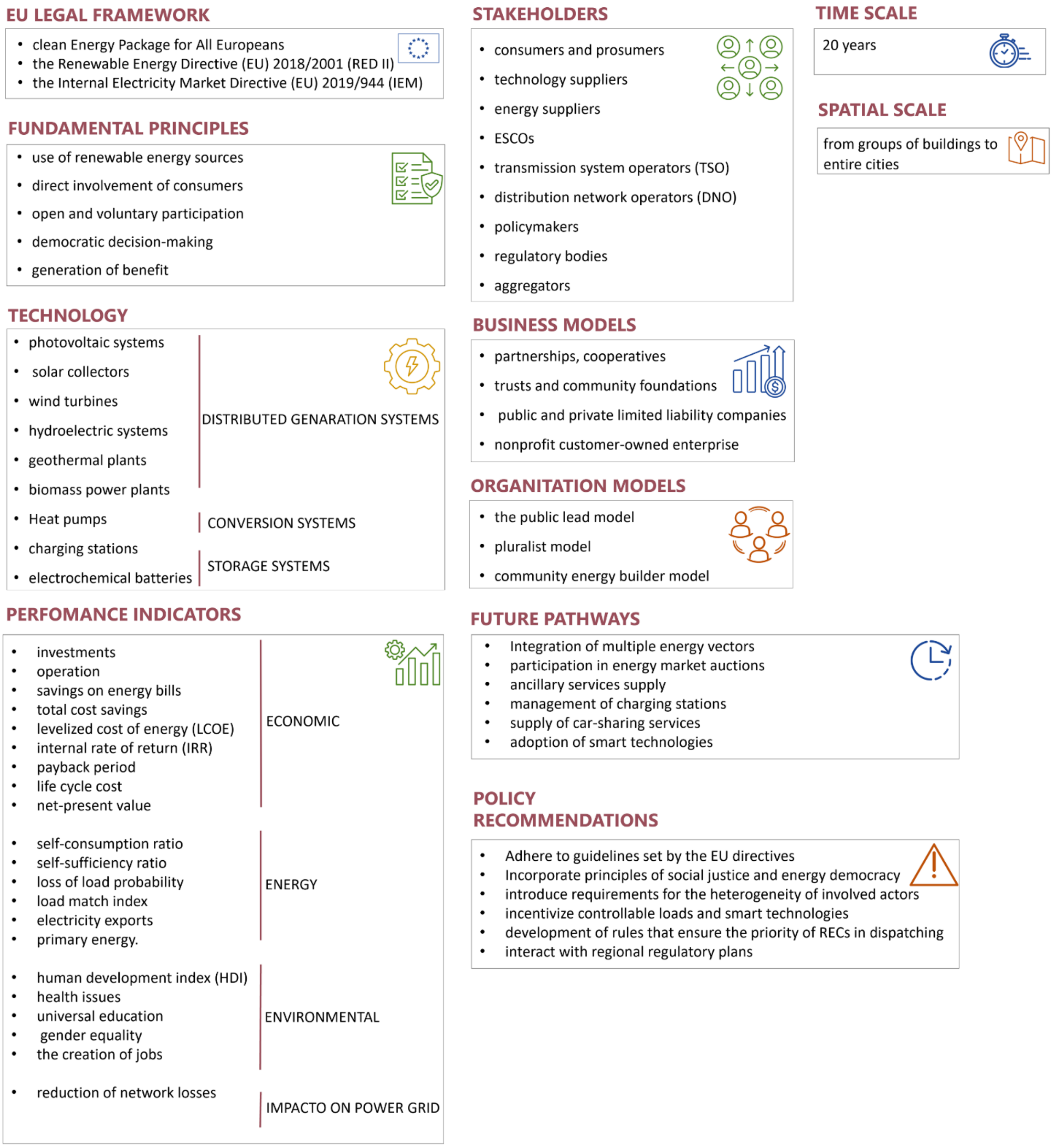


Figure 4 . Key aspects of a Renewable energy community (REC): A Visual Overview.

1.2 The EU legal framework for RECs

The EU was the first country to translate into binding laws the goals established in the Paris COP. These goals include a 40% reduction in greenhouse gas emissions by 2030 and the achievement of a climate-neutral economy by 2050. The EU's strategy is based on the creation of an *energy union*. The guidelines aim to adopt a common approach and achieve coherence among central, national, and local decision-making processes without compromising independence in selecting the energy mix and technological solutions. This approach aims to standardize objectives while preserving autonomy at different levels. Among the decisive actions to realize the energy transition of member States are: the emanation of directives for the development of a common regulatory framework; the establishment of research and development programs; the creation of control centers to monitor progress and ensure the conformity to with standard international practices; the development of tools such as the European Fund for Strategic Investments (EFSI), where public funds attract private investments; and the supply financing. These actions involve different stakeholders, from private enterprises to public institutions, from citizens to non-governmental organizations and research institutes.

The goal-setting framework for the EU's new environmental energy policies in the modernization of the energy system was defined in the "Clean Energy Package for All Europeans": a set of 8 legislative acts published by the European Commission in November 2016. The Clean Energy Package defines future actions up to 2050 are defined to achieve the goals. The main themes are energy efficiency, the penetration of renewable sources, the electricity market, supply security, and involving citizens in energy production. Among the main innovative elements are the implementation of integrated national plans for energy and climate, the modification of the internal electricity markets' framework, the evolution of the consumer's role, and the introduction of RECs.

[7] have illustrated the benefits of Clean Energy Package in terms of the environment, economy, supply security, consumers, and international aspects. The analysis considers two-time horizons: the short term up to 2030 and the long term with focused on 2050. The European Union is a leader in energy transition and the benchmark for many countries worldwide. The new European policies contribute to the evolution of energy systems and increase the cohesion, international collaboration, and homogeneity of the economies of the Member States. The advantages include more than just the reduction of greenhouse gas emissions. The diversification of energy sources and

the spread of renewables reduce dependence on foreign supply and improve energy security. Reduced susceptibility to global geopolitical influences preserves a greater political stability. The modification of energy market structures and the promotion of competition increase flexibility and stability, avoiding sudden price fluctuations. All these factors have a direct effect on consumers who can access to improved services. An additional positive impact is the reduction of energy poverty. The strengthening of interconnections and infrastructure promotes cross-border exchanges and cooperation among states. The combination of these changes improves the quality of life for individual citizens and creates fairer conditions for EU businesses in global energy markets. The EU clearly aims to achieve a radical shift in energy production and sales, with a focus on the role of consumers and the definition of EC.

The Clean Energy Package contains two definitions of energy community: Citizen Energy Community (CEC) and Renewable Energy Community (REC), differences are summarized in

Table 2. [20][21] have underlined analogies and differences. Both communities are legal entities which are established to increase environmental, economic, or social benefits to their members, stakeholders, or local areas in which they operate, rather than for generating financial profits. Community members can be citizens, local authorities, including municipalities or small and medium enterprises. The attendance is open and voluntary. Both communities are involved in the production, consumption, storage, sharing, and sale of energy. They may also be involved in providing energy efficiency services, electric vehicle charging, and aggregation. Among the main differences are REC is closely linked to renewable energy sources, while CEC is technologically neutral; REC operates in proximity to renewable energy projects, whereas CEC is not geographically constrained; any actor can participate in CEC, with the only condition that members for whom the energy sector constitutes their primary economic activity cannot hold decision-making power. On the contrary, REC allows participation exclusively for individuals, local authorities, small and medium enterprises, provided that the energy sector is not their primary economic activity. RECs can be controlled by small and medium enterprises located near the renewable energy project, while CEC excludes medium and large enterprises from the control.

Table 2. Exploring differences between Citizen Energy community (CEC) and Renewable Energy Community (REC).

		Citizen Energy Community (CEC)	**Renewable Energy Community (REC)**
Analogies	activity	production, consumption, storage, sharing, and sale of energy	
	purpose	promote direct involvement of citizen generate energy and social benefits rather than economic benefits	
Differences	members	any actor can participate	large enterprises are not allowed
	technology	technologically neutral	linked to renewable energy projects
	scope	not geographically constrained	proximity to renewable energy projects
	control	medium and large enterprises are excluded from the control	there are no limitations

The directives promoting the spread of RECs are:

- The Internal Electricity Market Directive (EU) 2019/944 (IEM) promotes the creation of a single and competitive electricity market. It allows consumers to sell self-produced energy and participate in the electricity market either individually or in an aggregated manner. It defines the CEC as an energy community which can assume the roles of end-user, producer, supplier, or distribution system operator.

- The Renewable Energy Directive (EU) 2018/2001 (RED II) promotes the use of renewable energy sources and, for the first time, defines the REC as a community with the right to produce, consume, share, store, and sell renewable energy.

The IEM aims to create a new electricity market based on competition, energy security, and sustainable development. Its major initiatives include increasing cross-border market connectivity, adopting new technologies, providing new services, and promoting new energy system configurations. IEM creates conditions for integrating national markets, promoting stronger interconnections among member states and cooperation among system operators at both the Union and regional levels. IEM recognizes the pivotal role of consumers to achieve the flexibility necessary for the transition of electrical system towards a new paradigm characterized by distributed and not dispatchable production from renewable energy sources. CEC represents a new type of entity that should be able to operate in the electricity market on equal terms without restrictions. Sharing of energy allows members to be supplied by production systems within the community without being in physical proximity to them. Grid charges, tariffs, and taxes related to electricity flows should be exempted in the case of shared energy. Sharing should be incentivized, while ensuring compliance with balancing and measurement.

The RED II establishes binding national targets for sharing of renewable energy in energy consumption and the transport sector. The Commission has set up a target of at least 27% of renewable energy consumed within the Union by 2030. All member states contribute based on their renewable energy potential and their support schemes. The EU supports member states through financial assistance with the aim of promoting a fair transition, even in high carbon intensity regions. The funding is for initiatives aimed at reducing the capital cost of renewable energy projects, launching projects and programs to integrate renewable sources into the energy system, increasing the flexibility of the energy system, maintaining grid stability, and managing grid congestions. Additionally, it focuses on developing the infrastructure of transmission and distribution networks, smart grids, storage systems, and interconnections, with the goal of achieving 15% electrical interconnectivity by 2030; Strengthening cooperation among member States and between member States and third countries. Each state can also decide how to support electricity from renewable sources by establishing support schemes that contribute to maximizing the integration of renewable electricity into the electricity market. Support schemes should be established openly and transparently and can include market-based incentives, price integration, or exemptions for small-scale installations and pilot projects. Distributed production systems can gain public acceptance and promote renewable energy projects at the local level.

EU encourages member States to establish a national framework for promoting self-production and renewable energy self-consumption. The national framework should establish regulatory conditions which allow consumers to:

- self-produce renewable energy, either individually or through aggregators;
- store and sell the surplus renewable production;

- install and manage energy storage systems;
- retain their rights and obligations as end customers;
- receive revenues possibly through support schemes, for the electricity they feed into the grid, based on the value of electricity market.

The production systems of consumers can be owned by a third part or managed by a third part concerning installation, operation, metering and maintenance. The opportunity for all consumers to participate in RECs must be guaranteed, while preserving their rights or obligations as end customers and avoiding discriminatory conditions or procedures. Private enterprises can also take part in community initiatives unless their participation constitutes their primary commercial activity. The RED II directive introduces RECs for the first time as legal entities with the right to produce, consume, store, and sell renewable energy and access all electricity markets. A great novelty includes the sharing of renewable energy produced by systems owned by the community itself. One of the main objectives of RED II is the development of a regulatory framework aimed at promoting RECs. The key aspects of RECs, as defined in the European legislative package, include:

- Use of renewable energy sources

- Open and voluntary participation: participation should be open to all potential members and based on non-discrimination criteria. Eligibility criteria should be objective and inspired by the principle of proportionality to include different types of members, ensuring maximum participation. Members should not only to be able to join spontaneously but also exit if it is no longer convenient. Members should not be excluded based on arbitrary or discriminatory decisions.

- Social and environmental sustainability: the main aim is to generate environmental and social benefits rather than economic profits.

- Direct involvement of consumers: control is taken by citizens, local authorities, or enterprises.

- Democratic decision-making: decisions are based on the principle of "One member, one vote".

In the analysis aimed at defining the role of RECs in the European transition, among the main factors which promote the spread of RECs, [22] have identified coherent policies, a clear legal framework regulating the operation and access to the energy market, financial instruments which reduce investment risk, and the involvement of local authorities. Among the main obstacles are the constraints imposed by national legal frameworks that limit the conditions under a community can be established, difficulties in accessing financing and the lack of political support. Furthermore, it is necessary to remove policy barriers; improve the timing of policy implementation incentivize cooperation between RECs and the distribution system operator to facilitate energy transfers within communities; provide support to public authorities and encourage their involvement; develop regulations to ensure fair and non-discriminatory treatment of consumers.

EU energy policies are reshaping the roles of consumers, citizens, and local authorities in the energy transition. The EU regards RECs as key actors in the transition toward low-carbon energy systems. In conclusion, RECs are a tool available to member States to promote new energy models. They are a new model for energy production, an innovative organizational approach, and an emerging business model. These transitional entities improve the management of local resources, foster the political influence of local authorities, promote energy democratization by involving citizens in decision-making processes, and develop synergies among local actors. Member States are required to consider RECs when designing their support schemes for renewable energy.

1.3 Transposing into national legislative packages

The complete transposition of the Clean Energy Package in national legislation is crucial for the development of RECs. Member States are required to include RECs in their national energy and climate plans and introduce effective measures for facilitating technical and financial support, as well as support in the entrance in the energy market. Bover et al. [23] have mapped the main experiences in regulatory experimentation and highlighted a lack of coordination among member

States in the transposition processes. The transposition processes vary in terms of actors involved, maximum capacity of production systems, physical boundaries, funding mechanisms, monitoring procedures and dissemination methods.

Among the different approaches, two types can be distinguished: demand-led sandboxes and policy-driven pilot regulations. The first is based on the requests of interested actors who want to experiment with new services, technologies, or business models. This approach allows testing innovations in controlled conditions without traditional regulatory restrictions. The evaluation focuses on the impacts of innovation and the knowledge gained through experimentation. The second approach is policy-driven, aiming to test new regulations through an experimental regulatory phase before definitive implementation. In this case, the evaluation focuses on compliance with the new regulations and the impact of proposed policies.

In the literature, many studies have examined the status of the transposition of European directives into national legislation, identifying good and bad practices[24][25][26]. The progress of the national transposition of the main EU States is presented in *Figure 5*. Among the best countries are Ireland, Italy, the Netherlands, Luxemburg and Austria. RECs have been introduced in Belgium by the Wallon government through the Decree of 30 April 2019; in Denmark with the Renewable Energy Act; in France with Article 6bis A of the Energy and Climate Law; in Germany with the Renewable Energy Act; in the Netherlands with the Dutch Experimentation Decree of 2015; and in Portugal with Decree-Law No. 162/2019. Other member States, in the process of transposition present critical elements. For instance, in Spain, there is no regulatory authority, and the legal entity of the community is not clearly defined. This situation can lead to confusion regarding the REC concept and a decrease of citizen involvement. A similar situation can be found in Greece, where the transposition allows for a wide interpretation of the REC concept, and the first communities were formed by private investors with limited citizen and local authorities' involvement. A case of incorrect transposition is in Romania, where the lack of clear procedures and stringent criteria makes the establishment of RECs challenging. Countries such as Cyprus, Croatia, Malta, Latvia, and Poland are yet to enact laws on RECs. Lastly, Bulgaria and the Czech Republic represent extreme cases where there is not even a government bill.

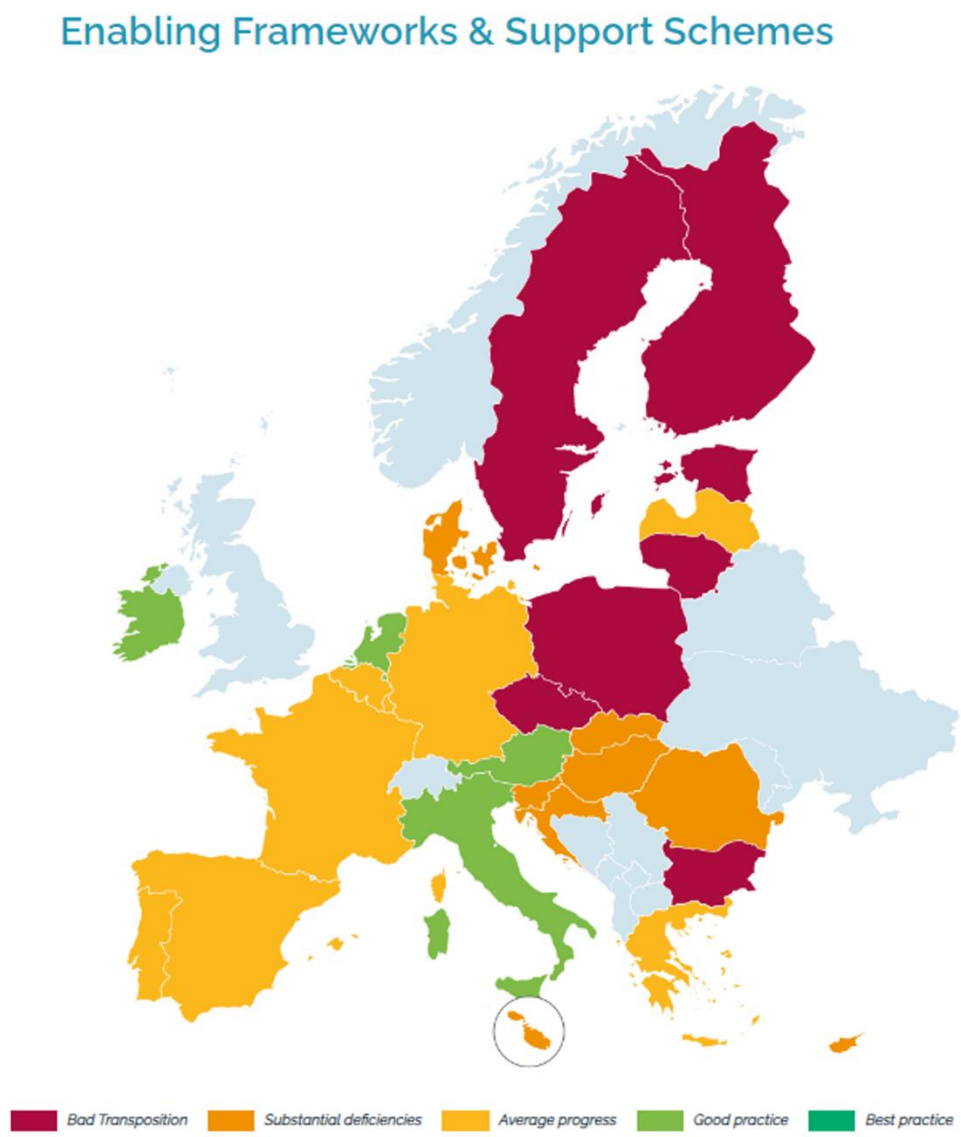


Figure 5. The progress of the national transposition of the main EU legal provisions on enabling frameworks and national support schemes for Renewable Energy Communities (RECs) [27].

From the analysis of the transposition status, some trends emerge regarding energy vectors and the reduction of network usage fees. Since the concept of RECs is not restricted to the electricity sector, the national transposition of the RED needs to be neutral towards the energy vector. However, most countries focus on electricity production and only partially hint at potential expansion to other forms of energy. A common element is the reduction of local electrical network management costs [28] . In Austria and Italy, reduced grid tariffs are foreseen for electricity sharing in RECs at MV and LV level. In Spain no grid fees are charged for the electricity exchanges within the REC. In France, opting for a specific self-consumption tariff is discretionary and may not result in cost savings in every scenario.

The main differences concern limits on the sizes of production systems, the organizational forms adopted, and the physical boundaries. Maximum capacity of production systems varies significantly, ranging from 200 kW in Italy to 3 MW in France. Regarding organizational forms, the EU does not impose restrictions on the legal structure, which can be either new or adapted from those already existing. Some States require the formation of a legal entity and specify a list of permitted legal forms to limit the choice of organizational models. In contrast, most States do not require the creation of any legal form or the signing of a contract among participating actors. Other States include RECs in existing initiatives, such as local or regional aggregations or cooperatives. Furthermore, due to the lack of stringent requirements in some parts of RED II, some aspects of RECs are left to the free interpretation of states. The local character of RECs is interpreted differently by states that adopt different spatial or electrical network connection criteria to limit the REC's boundary [29]. The most common criterion is the connection of members to the same low and medium voltage transformer substation (LV/MV). An overview of spatial boundaries adopted by member States is presented in *Table 3.*

Table 3. Overview of spatial boundaries for RECs and CSC schemes in selected EU Member States [29].

Country	Approach to physical boundaries
Austria	LV/MV
Belgium/Wallonia	LV/MV and distance
Belgium/Flanders	LV/MV and activity
Hungary	MV/HV
Slovenia	LV
Italy	LV /MV
Ireland	LV/MV
Croatia	Municipality, LV
Lithuania	Municipality
Poland	Municipality
Greece	Regional or system-related, depending on location.
France	Distance (up to 20 km) (only CSC)
Spain	LV, cadastral area, distance (500 m) (only CSC)
Portugal	System-related, individual decisions (RECs and CSC)

In Luxembourg, the open and voluntary participation criterion is partially violated by imposing a minimum participation period of one year. Lastly, the opportunity that RECs can offer in terms of energy poverty is not adequately emphasized. Hanke et al. [30] have investigated the impact of EU legislation on promoting the social role of RECs as key actors in involving various social entities, particularly vulnerable families. Currently, only Portugal, Spain, Italy, and Greece have recognized the role of RECs in addressing energy poverty in their national energy plans.

1.4 Focus on Italian Regulatory Framework

The National Integrated Plan for Energy and Climate (PNIEC) establishes the five actions that Italy is expected to carry out: decarbonization, efficiency, development of energy market security, research, innovation, and competitiveness. The plan aims to increase the use of energy from renewable sources by 30% and include RECs, investigating their role in the transition process and in reducing energy poverty. The process of transposition of the RED II directive has begun with the "Milleproroghe" Decree of 2020, Legislative Decree of December 30, 2019, N. 162. Article 42bis of this decree, for the first time, has introduced RECs. The timeline of RED II implementation is illustrated in *Figure 6*.

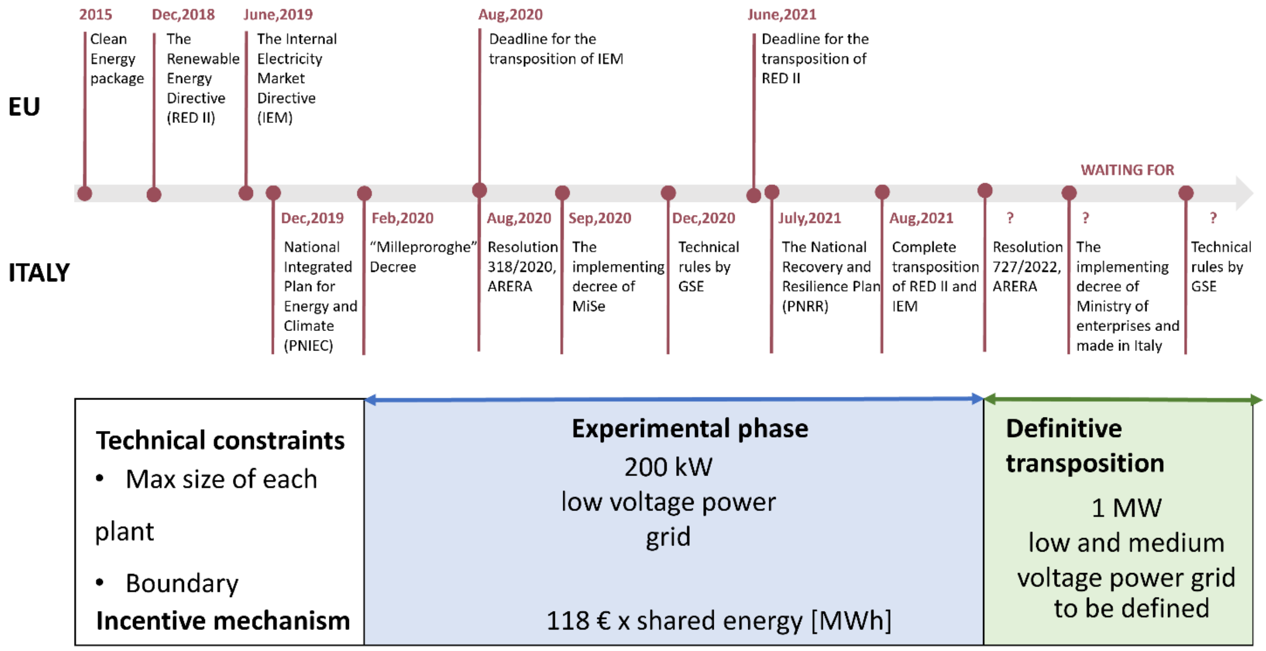


Figure 6. Timeline of RED II Implementation in Italy.

With this decree, Italy has launched an experimental phase with the aim of identifying the implications of the directive and facilitating the development of the final regulatory framework. The legislation focuses on groups of renewable energy self-consumers who act collectively and RECs. The differences lie in the physical boundary and the type of entity: self-consumer groups are located in the same building or condominium, while the boundary of RECs extends to neighbourhood or city. Furthermore, a REC is defined as a legal entity, requiring articles of association and a statute for its establishment. These acts certify its existence, regulate all aspects, and represent a contract among the members. In the experimental phase, the first RECs must respect the following technical constraints: each production system must be new, powered by renewable sources, have a capacity of less than 200 kW, and be connected to the same secondary substation. Members must be located in the low-voltage electrical network, under the same medium/low-voltage transformation station. These technical constraints not only limit the size of production systems but also the types of installations, the types of members, and the community's boundary, reducing it to the spatial area covered by the secondary substation. The entities introduced by the regulatory framework include:

- The Italian Regulatory Authority for Energy, Networks and Environment (ARERA)
- The energy services manager (GSE)
- The Ministry of Economic Development (MiSE)

ARERA defines the techno-economic regulatory model, technical instructions, and incentive mechanisms. With mise introduces a virtual regulatory model that allows RECs to use the existing national electrical grid for energy exchange and sharing. The virtual regulatory model is an alternative to a physical regulatory model that would otherwise require the construction of expensive private networks for the energy sharing. The virtual model offers several advantages: the status of national electricity network remains unchanged; the establishment of RECs is fast, and the implementation of expensive technical solutions is avoided.

GSE provides incentivization services for shared electrical energy. The main tasks of GSE include defining procedures for participation requests, evaluating the requests, carrying out contracts, establishing technical rules and methods for the calculation of shared energy, collecting data, calculating shared energy, providing incentives, managing configuration changes, and providing technical support.

MiSE, with the emanation of the implementing decree on September 16, 2020, establishes incentive tariffs and access procedures. With the transposition of the RED II, the sharing of electrical energy becomes possible for the first time in Italy. Shared electrical energy is defined as "the minimum, calculated on an hourly resolution, between the electrical energy fed into the grid by renewable energy production and the electrical energy withdrawn by connection points of RECs".

Shared energy is distinguished from physical self-consumption[31][26]. Self-consumption is defined as the amount of renewable production that is physically consumed by users connected to the production systems and is not fed into the grid. Shared energy is generated when three conditions occur simultaneously: the presence of surplus production, the surplus is fed into the grid, and the surplus is virtually consumed by REC members, either partially or entirely. The innovation of the REC is a change in the incentive paradigm, incentives are no longer proportional to the capacity of production systems but to shared energy. The incentive tariff is given by the sum of a variable component which depends on avoided losses in the electric network and a fixed component. The incentive is calculated by multiplying shared energy by the incentive tariff and is guaranteed for 20 years. The incentive can be cumulated with revenues from the sale of electricity. The incentive tariff for the year 2022 was 118 €/MWh of shared energy.

Despite the technical constraints that limit the size and the boundary of the community, the experimental phase allowed to identify issues in the REC assembly process, gaps in regulations, and to facilitate the development of the final regulatory framework. The early transposition guarantees actors such as governments, enterprises, and local institutions the necessary time to organize, plan, and implement changes, thus avoiding the urgency of compliance by the deadline. During the experimental phase, member States can also share their experiences and best practices in implementing the directives.

The Legislative Decree that definitively transposes the two directives RED II and IEM was emanated on December 15, 2021. The complete transposition extends the size of production systems from 200 kW to 1 MW, removes the connection limit from the secondary substation to the primary substation, and extends the type of participating entities to include third-sector enterprises, religious institutions, and all local administrations listed by ISTAT (the Italian institution for census). The new regulation extends the scope of RECs both in terms of participating entities and technical requirements. The expansion of participating entities is relevant as it reflects a growing trend in fostering public-private collaborations in the implementation of RECs. The REC represents a new form of public-private partnership based on the principle of horizontal subsidiarity and on Article 118 of the Italian Constitution, which mandates local authorities to promote the autonomous initiatives of citizens. RECs involve horizontal cooperation among citizens, enterprises, governments, and local actors to meet energy needs [32]. Although Italian legislation is currently awaiting the law, which is expected to provide comprehensive and definitive regulatory framework covering all renewable technologies, from photovoltaic to wind, from hydroelectric to biomass, it is already recognized that the future development of RECs is connected to initiatives by local authorities and small and medium enterprises and the energy production should be derived from local resources.

The National Recovery and Resilience Plan (PNRR) [33] has allocated €2.2 billion for RECs establishing in municipalities with fewer than 5,000 inhabitants. The funds are distributed as follows: €1.6 billion for RECs and €600 million for collective self-consumption. These funds are cumulated with incentives provided by MiSe and regulated by GSE. Additionally, national legislation has encouraged regional initiatives aimed at promoting RECs. Piedmont region was the first to adopt a law on the RECs: Regional Law n.12 of 3 August 2018 “Promotion of the institution of energy communities”. Piedmont region was followed by the Puglia region with the Regional Law 9 August 2019, n. 45 “Promotion of the institution of RECs”. While not all regions have enacted legislation at the current state, they are progressively equipping to align with national regulations and establish measures to promote RECs within their territories. One of the most effective measures is the provision of incentives to facilitate the establishment of RECs. The Lazio region the development of RECs falls within the framework of the energy policy guidelines of the 2021-2027 unified planning, the Regional Energy Plan and the Regional Plan for Ecological Transition . Among the most prominent initiatives: Lazio region has allocated 1 million euros to finance technical-economic feasibility studies of RECs. An economic contribution ranging from 6,000 to 13,000 euros is allocated for each REC. Similarly, Lombardy Region has allocated 20 million euros to finance the establishment of RECs. Regional measures implemented up to September 2023 are listed in *Table 4.*

Table 4. Regional measures implemented up to September 2023 in Italy.

Region	Regional measures
Abruzzo	Regional Law May 17, 2022, N. 8
Calabria	Regional Law November 10, 2020, N. 25
Campania	Regional Law December 29, 2020, N. 38
Emilia Romagna	Regional Law May 27, 2022, N. 5
Liguria	Regional Law July 6, 2020, N. 13
Marche	Regional Law June 11, 2021, N. 10
Piemonte	Regional Law August 3, 2018, N. 12 Regional Decree March 8, 2019, N. 18-8520
Puglia	Regional Law August 9, 2019, N. 45, Regional Decree Puglia August 7, 2020, N. 1346 Regional Decree July 9, 2020, N. 74
Veneto	Regional Law July 5, 2022, N. 16
Lombardia	Regional Law February 23, 2022, N. 2
Sicilia	Regional Law July 29, 2023, N.9,
Valle D'Aosta	Legislative Decree 74/XVI July 13, 2022
Sardegna	Deliberation N. 6/20 of February 25, 2022

1.5 The current spread of RECs in Europe

According to REScoop MECISE, 2019, there are more than 3,500 energy cooperatives in Europe and this number is even larger if other types of energy initiatives are also included. In *Figure 7* the number of community energy initiatives in 9 European countries is represented. Germany has the highest number, followed by Denmark and the Netherlands. European RECs show significant differences in terms of organizational models and energy resources, reflecting the energy challenge within the EU. In Germany, Spain, and France, most configurations produce electricity from solar source exploiting the photovoltaic technology. In the Netherlands and Denmark electricity production is dominated by wind turbines, with several biomass systems for heat generation. In Alpine countries like Austria, Switzerland, and northern Italy, hydroelectric systems play a key role in electric generation while biomass is used for heat generation. Biomass district heating is prevalent in Sweden and Finland and can also be found in Denmark, Germany, Poland, and Belgium.

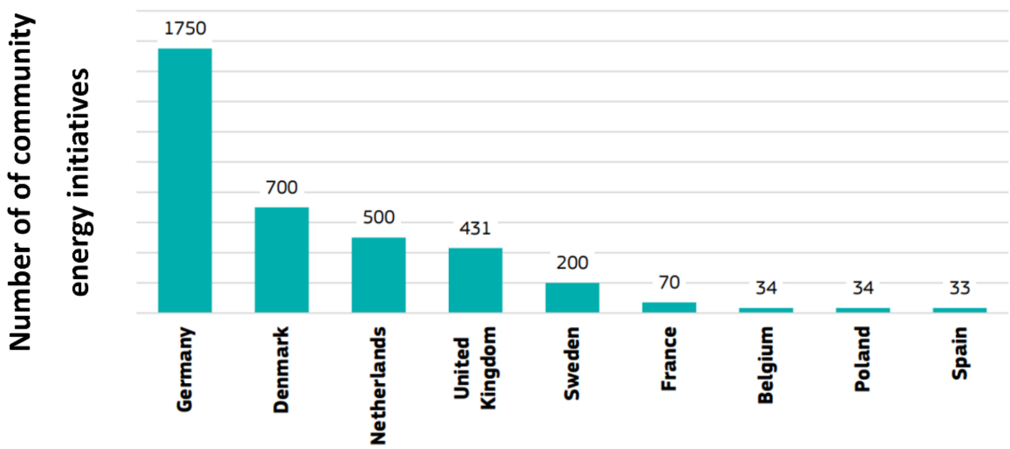


Figure 7. Approximate number of community energy initiatives from the nine countries of Europe [21].

Several initiatives aim to track RECs in Europe. The European commission's energy community repository has recently launched a map of RECs in Europe based on a list developed by the EU-funded COMETS project. Wierling et al. [34] has examined different data sources, from websites to official records, with the goal of compiling a European inventory of over 10,000 citizen-led initiatives and projects in 29 countries, focusing on the last 20 years. Koltunov et al. [35] have classified communities based on characteristics such as geographical context, dimension, legal form, scope and more. However, an international database is still lacking. Data is scattered among different government organizations, private companies, local authorities, and other sources. Due to the localized nature and the heterogeneity of communities, collecting data and creating an official database which can serve as a reference for member States, pose several challenges. The Identification of communities is often difficult, because communities can be very small in size, operate at the local level and include a vast range of technologies, energy resources, participating entities, and organizational forms. The heterogeneity complicates the process of identification and classification. An international database may support statistical analysis, coordination of initiatives among member States, trend identification, highlighting best practices, supporting policy decisions, and improving the transparency of projects.

1.6 Focus on RECs Diffusion in Italy

The early transposition of RED II through experimental regulations has encouraged the spread of the first RECs. Due to technical constraints, such as a maximum capacity of 200 kW per each production systems and limitations on connection to the medium-to-low voltage transformation substation, most RECs focus on photovoltaic systems with capacity ranging from 20 to 70 kWp, and their members are mainly residential users. The maximum power limit not only restricts the types of production systems and energy vectors but also limits the number of participants, the involvement of enterprises, and energy-intensive activities. The limit of connection to the secondary substation restricts the community's boundaries and territorial extension. This implies that the RECs established during the experimental phase offer only a limited perspective of the complexity of this energy system. According to Legambiente's Renewable Communities report [36] , as of 2022, there are 26 operational RECs in Italy. Geographical distribution across Italy of REC is shown in *Figure 8*. These RECs are mainly based on photovoltaic systems, with membership ranging from 3 to 70 and production system not exceeding 70 kWp. Among the generation technologies, there are photovoltaic systems with a total capacity of 2 MW, a 50 kW biogas power system, and a 58 kW hydroelectric system. Additionally, there are 500 kW wind turbines in the design phase. Electrochemical energy storage and charging stations are present in fewer than 5 cases. These RECs are evenly distributed across the territory and developed in diverse contexts, ranging from metropolitan areas of major cities like Rome and Milan to small islands like Ventotene, as well as Alpine and Apennine regions.

Figure 8. Geographical distribution across Italy of RECs, collective self-consumption groups, and emerging Initiatives according to the Renewable Communities 2022 Report [36].

These initiatives collectively involve hundreds of households, 55 municipalities, and 20 enterprises. The promoters in most cases are municipalities or local actors, but there are also groups of enterprises, some cooperatives, and companies operating in the energy sector. Members consist of individual citizens, mainly residential users, but also include commercial activities, sports centers, offices, and small and medium enterprises. The energy vector is mainly electricity. Funding for the establish of RECs is supplied by private, municipal, regional sources, or consortia of companies.

The analysis of these RECs highlights the pivotal role of local institutions operating within the region in the establishment process. Especially in this early stage when RECs still represent a new and unexplored reality, local actors play a crucial role in gaining social acceptance and the trust of citizens. Hence, incentivizing collaborations with public administration is crucial. The activation of special synergies with the local context is the key to the success of many RECs. The local context strongly influences the development of the REC, impacting not only energy resources and technologies but also fund acquisition, the selection of governance models, time of realisation and common objectives. The recognition of the social role of RECs is another key role. In many of analysed cases, RECs are considered as a tool to combat energy poverty and involve vulnerable families. Regulatory uncertainty in recent months concerning incentive mechanisms is one of the main obstacles to the spread of RECs. This uncertainty complicates the assessment of REC's economic impacts and dissuades potential investors. Another obstacle is the absence of specific expertise in RECs, as many local government employees are still unprepared. Therefore, training activities aimed at developing multi-sectoral technical and managerial skills are necessary. Political responses are crucial, especially for local administrations that oversee considerable financial resources and need objective evaluation criteria to determine the most efficient configurations from an energy, economic, environmental, and social perspectives. These responses are also crucial for investors and, finally, for citizens who need to understand the advantages and disadvantages of participating in a REC.

This analysis provides an overview of RECs in the Italian territory. However, it is important to emphasize that RECs are emerging realities with constantly fluctuating numbers. Furthermore, if the maximum power limit is extended to 1 MW and the boundary is extended to primary substation, RECs become more complex. The geographic scope expands, along with the size and number of production systems, energy vectors, and the technological mix diversifying, while also increasing both the number and the type of actors involved. All these factors result in growing complexity during the phases of feasibility analysis, implementation, and management. The establishment process becomes more intricate and may require the involvement of specialized operators to provide aggregation and REC establishment services. According to the analysis conducted by the Energy&Strategy Group at POLIMI, which has estimated the potential of RECs in Italy for the period 2021 to 2025, between 14,000 to 31,000 RECs will be established. These developments are expected to result in the installation of 2.2-4.6 GW of photovoltaic capacity, the generation of incentives valued between 300 and 600 million euros, and an increase in the photovoltaic market up to 5.1 million.

1.7 Exploring the complexity of the RECs

The REC is a complex energy system whose characteristics are influenced by several key factors, including the time scale, spatial scale, local context, stakeholders, technology, adopted business models, and the organizational models governing its activities.

- *Time Scale*: Currently, incentives for shared energy have a duration of 20 years. During these 20 years, the REC acts as a dynamic system, allowing changes in its configuration as members can join or exit at any time. As a result, the composition of the REC can vary over time, both in terms of the number and types of members. This flexibility and adaptability are key strengths of the REC. However, managing a dynamic REC can be complex, as it involves tracking changes in membership, managing transitions, and ensuring the proper documentation of contracts and agreements. It's also important to consider that the entry or exit of members can modify the energy flows within the REC. Shared energy may increase or decrease compared to the initial configuration, potentially necessitating updates to the production systems.

- *Spatial Scale*: This term refers to the geographical dimension where energy-related activities are implemented. The RED II directive emphasizes the local character to the REC and requires the proximity of its members, leaving the precise definition of boundaries to individual member States. In Italy, during the experimental phase, boundaries were restricted by the requirement that members must be connected to the same secondary substation. As a result, the REC developed during the experimental phase covered the scale of a street or portions of a neighbourhood and involved at most dozens of buildings. With the extension of the boundaries to include the primary substation, the spatial scale can vary significantly from groups of buildings to entire cities. The design of a REC involves a territorial analysis to estimate the potential from renewable sources, map the available surfaces for the installation of renewable technologies, identify any environmental and landscape constraints, assess the number and types of users, estimate energy demand, and select potential members. In addition, it is also crucial to determine the primary substation to which members are connected. Until a few years ago, this information was not publicly available and could only be obtained through a formal request to energy suppliers. To simplify the procedure, GSE is collaborating with energy suppliers to develop a platform mapping primary substations. Through this platform, by inserting the user's tracking number (POD), it's possible to determine the corresponding primary substation. The development of this platform allows to speed up the identification of potential REC members. The digitalization of information is necessary when the spatial scale increases and territorial analysis becomes more complex. Firstly, there is a larger volume of data to collect, analyse, and manage. Secondly, the probability of heterogeneous data increases. For instance, when considering energy bills, users may have different suppliers, leading to multiple procedures for accessing consumption data and various formats. Similar situations concern data related to renewable sources, space constraints and funding. These can be found from different sources, each with proper procedures and formats. GIS tools and the development of automated procedures are necessary to support the analysis when the spatial scale is expanded. Finally, as the number of users increases, issues related to privacy and security, number of support requests, also increase along with possibility of errors.

- *Local context*: the REC can be established in a wide range of contexts, ranging from small municipalities with fewer than 5,000 inhabitants to metropolitan cities with millions of residents, from mountainous areas to small islands, and from agricultural areas to industrial districts. The geographical context strongly influences the development of the RES due to factors as the availability of energy sources, climatic conditions, end-uses of energy, energy consumption patterns, type of existing technologies, type and number of available spaces to install renewable technologies. Furthermore, energy regulations, funding opportunities, involved stakeholders, and dynamics of member involvement also vary within these diverse contexts.

- *Technology*: Currently, a REC can generate, sell, share, and consume renewable energy. The adopted technologies can be classified into three categories: distributed generation systems powered by renewable sources, conversion systems, and storage systems. Within this classification, there are commercially configurations such as photovoltaic systems, solar collectors, wind turbines, hydroelectric systems, geothermal plants, biomass power plants, electrochemical batteries, heat pumps, and charging stations; and innovative configurations, still in the prototype phase, such as wave motion conversion systems, and particularly efficient setups like cogeneration systems fuelled by non-traditional sources which produce electricity and heat simultaneously. Considering all the technologies, the complexity of a REC can vary significantly. It can range from the simplest configuration, which includes photovoltaic installations to meet electricity demand, to much more intricate setups. These complex setups can involve bidirectional flows, multiple energy vectors, and the exploitation of more than one non-programmable source, such as solar and wind, along with at least one programmable source, such as biomass. Storage systems and controllable loads, such as electric vehicle charging systems, can be adopted to improve the flexibility. The complexity of the REC depends on the size of installations, the types of technologies and the energy vectors. In the future, REC activities may include energy services including the supply, transmission, and distribution of energy, increasing the complexity.

- *Stakeholders*: the actors involved depend on the context and scope of the REC. The interaction among these actors can vary significantly based on aims.

- *Business Models*: A REC involves not only technical aspects related to energy but also economic and financial considerations. REC business models often focus on sustainability, achieving energy independence, and optimizing the exploitation of local resources.

- *Organizational Models*: The organization of the REC should ensure the right to open and voluntary participation, directly involve members in decision-making processes, management, and resource utilization. In addition, the dynamic nature of the REC must be guaranteed, allowing changes over time and adaptation to emerging technologies. Key elements include openness in allocating economic resources, involvement of local actors, and compliance with existing regulations. External entities such as energy service companies (ESCO) can be necessary to manage the RECs when their size increases.

Given the wide range of factors, design process should be customized for each REC to identify an energy system that fits fully with resources and aims.

1.8 Stakeholders, business and organisational models

This paragraph explores actors involved in the REC at different stages of its lifecycle, the ways the community creates value through business models, and how the community is structured through organizational models. Di Somma et al. [37] have compiled a comprehensive list of actors and analysed the benefits that each actor can offer and receive from the REC, along with the advantages that the REC brings to the society. The main actors include:

- REC members (consumers and prosumers)
- Technology suppliers
- Energy suppliers
- ESCOs
- Transmission system operators (TSO)
- Distribution network operators (DNO)
- Policymakers
- Regulatory bodies
- Aggregators

When joining the RECs, members first gain access to locally produced clean energy and then can obtain discounts on their electricity bills. Local renewable energy supply increases energy independence, security, penetration of renewable sources, and reduces greenhouse gas emissions. The spread of RECs encourages the growth of distributed production systems and technologies focused on demand management and storage, creating new sales opportunities for technology suppliers. Energy suppliers benefit from a greater diversification of the generation mix, increasing business resilience. ESCOs can explore new opportunities by offering efficiency and management services. Transmission and distribution network operators can more effectively balance demand with production and minimize energy losses during transportation. For policymakers and regulatory authorities, RECs represent a tool to ensure the supply of clean and affordable energy for all users. Furthermore, given the complexity of the RECs, aggregators can optimize the management, encourage participation in energy markets, and potentially offer flexibility services to the network in the future. According to Italian regulations, members of the REC can include individual citizen, small and medium enterprises, local authorities, research institutions, religious organizations, third sector and environmental protection organizations, military entities and local administrations listed by

ISTAT as (Article 1, paragraph 3, of Law No. 196 of December 31, 2009). The admitted legal forms include associations, third-sector organizations, cooperatives, consortiums-partnerships, and non-profit organizations.

Through the analysis of 90 RECs, Kubli et al. [38] have identified 25 business models. In these models, the community's value can be found in distributed renewable energy generation, increased consumption of local energy production, improved grid stability, reduced energy consumptions. Economic value is generated by savings on energy supply costs, revenues from the sale of energy or other services, data sales, and in some cases, membership fee. Social value is generated by fostering a sense of community where goods, values, and aims are shared. Reis et al. [39] has found that business models implementing demand flexibility services, aggregation, energy efficiency, and electric mobility services are still limited. Several studies investigate new models for the distribution of revenues derived from incentives on shared energy among REC members. [40] [41] have suggested the Shapley value, a well-established solution in cooperative game theory known for its fairness in allocating costs and profits for shared infrastructures, for distributing benefits among community members. Casalicchio et al. [42] have analysed the adoption of the Allocation Metric, henceforth referred to as 'Contribution Distribution.' The reason for this choice is that in an energy system where members exhibit different resource demands and offer diverse services and production, fairness can be established based on the individual contribution of each member to the overall system. Norbu et al. [43] have provided a method inspired by cooperative game theory concepts to equitably redistribute incentives.

Sawin et al.[44] , among traditional organizational models in the field of RECs, have identified partnerships, cooperatives, trusts and community foundations, public and private limited liability companies, and nonprofit customer-owned enterprises. Although organizational models already exist within RECs, the introduction of the REC, as defined by RED II, has encouraged new models aimed at ensuring open and voluntary citizen participation, promoting local actor involvement and public-private collaboration. The new models are based on the horizontal cooperation. De Vidovich et al. [45] have identified three organizational models: the public lead model, pluralist model, and community energy builder model. These models are distinguished based on the actors involved, methods for involving citizens, relationships with third parties, including industry, and aims. In the first model, public and governmental actors such as local or regional entities play a key role. Member are involved through official campaigns, public events, and website announcements. Aims focus on creating local benefits for all members. Decisions follow a top-down model. In the second model, actors involved belong to different categories, each with different aims and interests within the REC. Member involvement process is broader and more diversified. Participation is often bottom-up and member are involved in decision-making process. The REC has a more open relationship with third parties, including industry, allowing for diversification of funding sources and resources. Aims are diversified and may favour specific members. The last model is based on specific actors that act as promoters and managers of the REC, establishing the methods for involving members, aims and relationships with third parties. The choice of the organizational model depends on several factors including aims, size, scale of action, local regulations. Furthermore, it is strongly influenced by the available financial resources and the experience of the promoter.

1.9 Thermal energy and multiple energy vectors

With the expansion of capacity from 200 kWp to 1 MW and the extension to the primary substation, RECs can integrate multiple renewable sources and energy vectors. The first step in the potential evolution of RECs is the integration of thermal production to meet heating and cooling needs. Currently, most established RECs include only renewable electricity generation technologies, while thermal energy systems used for heating, cooling, and domestic hot water production are less common. Considering that approximately 60%-75% of energy consumption of European households is related to heat production, there is a need for thermal energy communities [46]. The Thermal Energy Communities (TECs) refers to all communities involved in heat production integrating multiple renewable energy sources. The renewable sources exploited by TECs include solar, biomass, and geothermal energy. Waste heat from other processes also represents an opportunity for TECs in cases where there is a renewable source downstream of the process.

The development of TECs in Italy is currently blocked by the lack of government guidelines. Regulations only establish rules for sharing electricity. The virtual model proposed by ARERA, which is based on the use of the public network for energy exchange between generation and consumption units, avoiding the physical connection of members and maintaining the existing network structure, is compatible only with electricity. Recent initiatives are exploring the feasibility of virtual heat sharing among REC members and incentive mechanisms for shared thermal energy, but there are no indications regarding the establishment of thermal RECs. If the virtual model cannot be applied, heat sharing could involve the implementation of district heating. Another option is to provide an additional incentive for electric RECs that also integrate heat production. Denarie et al. [47] have estimated the potential of district heating in Italy which amounts to 38 TWh. Thermal energy could contribute to covering 12% of the heating demand. The implementation of district heating systems would result in the shutdown of 4 million boilers and avoid the emission of 5.7 million tons of CO_2. TECs may play a crucial role in achieving energy transition.

In Italy, biomass is fundamental for the development of TECs for several reasons. Firstly, the spread of biomass-powered plants depends on local resources and is promoted by local actors, which matches well with the local character of TECs. Secondly, biomass is a controllable source that can compensate for the intermittent nature of solar and wind sources, helping to achieve 100% coverage. Finally, involving biomass businesses rooted in the local community can create specific synergies and accelerate the establishment of TECs. Furthermore, the use of cogeneration systems, which generate simultaneously electricity and heat, can improve the efficiency of biomass utilization. The Ministerial Decree of August 4, 2011, establishes rules for incentivizing electricity produced through high-efficiency cogeneration. These incentives can be cumulated with the REC incentives when the cogeneration system is powered by renewable sources.

Several European initiatives aim to promote TECs. For instance, the ConnectHeat project, launched in October 2020, aims to establish a regulatory framework for promoting energy communities focused on heating and cooling. This initiative, involving seven EU countries including Belgium, Bulgaria, Croatia, Germany, Italy, Portugal, and Spain, has allocated a budget of 1.5 million euros to fund seven pilot projects, one in each participating country.

1.10 Development of RECs in Industrial Districts

Currently, Italian regulations allow small and medium enterprises to establish a REC. The RECs established by enterprises during the experimental phase are mainly based on photovoltaic systems installed on the roofs of buildings or warehouses. As technical constraints are removed, industrial

RECs may become more intricate. Huang et al. [48] have described the developments of RECs. Future RECs systems are designed in accordance with the principles of industry 4.0. These systems are based on the exchange of information through digitalization, the use of intelligent systems, consumer involvement, and the integration of different activities. Furthermore, future RECs integrate multiple energy vectors, employ meters and sensors for data collection, utilize artificial intelligence for energy flow analysis, and manage production systems through centralized controllers. A dense network of sensors provides geolocated data on energy demand and production, ensuring careful production management and improving efficiency in energy generation, transmission, and distribution. Computers are connected to the Internet using IoT technology to create a network of machines. Data is interpreted in real-time, ensuring optimization of resource utilization and generating savings without compromising user needs. Now-casting systems are used for diagnostic control and anomaly detection. Data-driven decisions improve production management, integration with demand, planning, and control. However, this scenario is still far off, contingent upon the digitalization of the energy sector.

1.11 RECs' Potential in Off-Grid Islands

The Clean Energy Package acknowledges the role of islands as experimental hubs for testing innovative energy projects. On May 18, 2017, the European Commission launched the "Clean Energy for EU Islands" initiative, aiming to accelerate the transition of over 2,700 European islands. In addition, the "The Clean energy for EU islands secretariat" was established to support to island governments in clean energy transitioning. In this paragraph, we explore the potential of RECs for small islands not connected to the continental electric grid, with a focus on Italy.

The Italian Island heritage includes over 800 islands, covering a total area of more than 50,000 km2, including 19 smaller islands not connected to the continental electric grid. Smaller islands, covering 0.3% of the national territory and inhabited by 0.3% of Italy's population, have common energy-related features. They are distinguished by their extraordinary environmental heritage, which constrains the type and capacity of energy production technologies. Due to the tourist flows the population increases by up to 15 times during the summer periods. Seasonal population fluctuations result in high variability in energy and water demand. Despite the great potential of renewable energy sources, electrical power generation is still supplied by obsolete production systems fuelled by fossil fuels. Production systems are often oversized to meet the peak demands of summer. Fuel and water supply are provided by the mainland via shipping tankers, involving intensive energy activities and emissions of tons of CO_2 per year. Isolation and limited storage capacity pose energy security challenges. Major energy issues of Italian small islands are summarized in *Figure 9*.

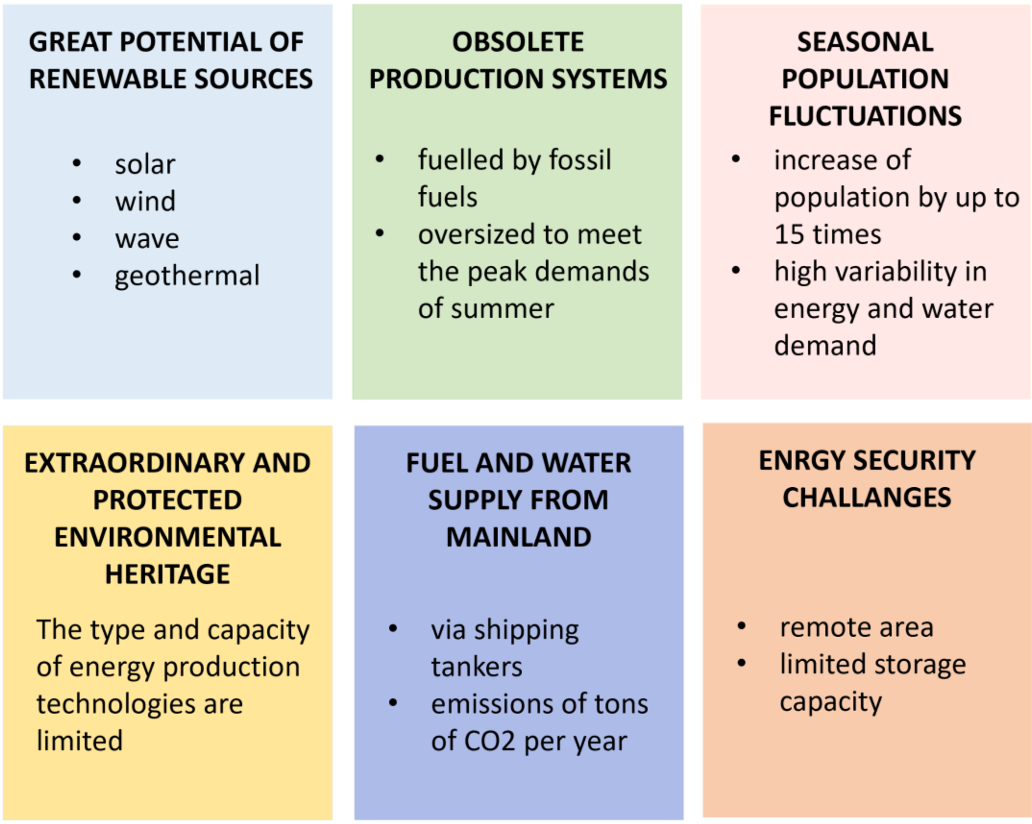


Figure 9. Major energy issues of Italian small islands.

According to the Sustainable Islands Report 2023 [49], the average sustainability index of the Italian islands is equals to 40%. Photovoltaic systems are the leading renewable technology, while wind turbines are only present on Pantelleria and Ventotene. The development of wind power is hindered by tight landscape constraints, prolonged authorization procedures, and a lack of communication among interested authorities. Pantelleria, with 281.89 m2 of solar collectors, 6475 kW of photovoltaic systems, and 32 kW of wind turbines, has the highest penetration of renewable sources. Only 10 out of 19 islands desalination employ desalination systems for producing clean water directly on the island, and in just one out of ten cases, the desalination system is partly powered by renewable sources.

The RECs can accelerate the transition of the islands by promoting local resources, renewable technologies, and citizen involvement. Especially in isolated areas, RECs can play an active role in shaping local energy policies. Through citizen involvement, RECs can influence policy decisions that support regulatory changes in favour of renewable energy. With the support of Sapienza University of Rome, Ventotene is the first island to establish a REC based on photovoltaic systems. San Pietro in Sardinia is one of the three pilot islands participating in the React project which was launched in 2019 as part of the Horizon 2020 program with the aim of establishing a REC. The island of Elba has also started the establishment of a REC. Considering that the PNRR has allocated 200 million euros for the development of 100% renewable energy systems on small islands, REC initiatives may rapidly increase.

1.12 Socioeconomic, Environmental, and Grid Impacts

RECs play a pivotal role in local economies, by supporting energy democracy, energy security, reducing energy poverty and greenhouse gas emissions [21][22]. First, RECs raise social cohesion, autonomy, and public awareness about climate-related issues, encouraging education and citizen mobilization. Second, REC combat energy poverty, not only by generating savings on energy bills but also by involving vulnerable families and reinvesting returns in local sustainability projects. Co-investments stimulate the local economy by creating jobs, developing skills, and preventing the outflow of financial resources from the local area [50]. Third, RECs increase democratic control over energy investments by involving citizens in decision-making processes [30]. Then, by increasing the penetration of renewable productions systems, they reduce carbon emissions and encourage energy independence and security [51]. Finally, RECs contribute to the development of new technologies as platforms for supporting interaction among stakeholders, sensors, and meters for data digitization and monitoring [52].

Gjorgievski et al. [53] have conducted a comprehensive review aimed at identifying methods and indicators for assessing the main impacts of RECs. The economic indicators include savings on energy bills, investments, operation and total cost savings, levelized cost of energy (LCOE), internal rate of return (IRR), payback period; life cycle cost, net-present value (NPV). Environmental indicators include greenhouse gas emissions and life-cycle emissions. Technical indicators include self-consumption ratio, self-sufficiency ratio, loss of load probability, load match index, electricity exports, primary energy. Finally, for assessing social impacts, there are indicators such as social acceptance, human development index (HDI), health issues, universal education, gender equality, and the creation of jobs. Although the impacts of RECs on the electrical grid have been the subject of many studies, they are not fully quantified [17]. The only positive impact recognized by national regulations is the reduction of network losses. In fact, additional incentives are provided when network losses are avoided. From a technical perspective, the goal of the REC is to maximize self-consumption by locating production systems close to consumers. This model, in contrast to centralized generation, which involves transmitting energy over long distances, allows to limit power exchanges to shorter network segments. However, the reduction of network losses is not the only positive impact. Iazzolino et al. [24] have hypothesized that maximizing self-consumption optimizes the use of the transformation substation, leading to reduced management and maintenance costs. Furthermore, given that distribution networks are designed to meet demand from all connection points, a well-designed REC may increase the penetration of renewable power without requiring upgrades to existing infrastructure. Finally, it's still unclear if self-consumption can reduce dispatching costs. Di Silvestre et al. [26] have identified similarities between RECs and virtually aggregated mixed units (UVAMs). RECs may provide demand management services in the future, ensuring network stability and voltage quality. In this study, they have explored how RECs contribute to increasing the penetration of renewable sources without changing power flows into the grid.

1.13 Key elements of success and barriers preventing RECs spread

Previous research has highlighted the pivotal role of public opinion in the adoption of renewable technologies. For instance, Heras-Saizarbitoria et al. [54] described the role of public debate in the evolution of the photovoltaic industry in Spain from 2004 to 2010. Greenberg [55] demonstrated the close connection among public choices, trust in new technologies and risk perceptions. They also explored the impact of social media on public trust levels. Soeiro et al. [56] have analysed motivations driving citizens to join a REC. In contrast to other studies that emphasize low energetic costs as the major factor, Soeiro found that environmental sustainability and climatic crisis play significant roles in fostering social participation. Citizens perceive RECs as a tool to achieve energy transition and launch environmental initiatives, recognizing their value not only from an economic perspective but also in terms of their social impact. Trust in new technologies, cultural norms, and concerns about climate change all contribute to creating conditions in which people feel motivated to collaborate for sustainable energy initiatives. Trust plays a crucial role in REC participating. When individuals have trust in the organization, they are more likely to actively engage in its activities. Trust can be established through past experiences, the organization's reputation or through the conviction that the organization is competent and that its intentions align with the community's interests. In contrast, a lack of trust represents one of the main barriers preventing RECs spread. The lack of trust can be caused by superficial knowledge of RECs, the spread of false information that overestimates the economic benefits, fostering unrealistic expectations. It can also result from the limited expertise among the involved stakeholders, a lack of transparency in defining objectives and economic benefit, and reduced member involvement in the management of RECs.

Boulanger et al. [52] have provided an overview of most successful existing RECs in Europe. Key elements of success include the members' attitude, the development of innovative technologies as platforms that facilitate interaction among stakeholders, and customized projects that consider the needs of members. Innovative technologies are often developed within European projects and remain in prototype phase. Instead of customizing projects to the local context and the needs of involved members, standardized or general approaches are commonly adopted. The absence of a customized design can lead to reduced engagement among citizens because their requirements may not be adequately considered, resources may be used inefficiently, and the expected benefits may only be partially realized. Hence, a non-customized design increases the risk of REC failures. Gancheva et al. [22] have evidenced that adhering to with RED II guidelines constitutes a best practice. Among the key elements of success are a clear political commitment to energy transition at all levels of government, coherent policies, financing to mitigate investment risks, and the development of specific synergies with local authorities. These synergies can facilitate citizen engagement processes, access to funding, and improve public acceptance. Starting with projects of lower financial commitment and exploring different financing options are optimal approaches.

Prolonged authorization procedures, resulting in delays, additional costs, investor uncertainty, and, in extreme cases, project abandonment, are among the main barriers that prevent the spread of RECs. Other obstacles include frequent changes in regulations and incentive mechanisms, opposition to some types of renewable energy such as wind turbines, and disparities in the implementation among member States. These disparities may tie the economic feasibility of RECs to their specific geographic location. Iazzolino et al. [24] have identified that the main barriers preventing the diffusion of RECs derived from a combination of technological, socioeconomic, environmental, and institutional factors. Among the technological factors are the intermittent nature of renewable sources, the high cost of energy storage systems, and reduced demand flexibility. Reduced demand flexibility refers to the limited controllable loads available to ensure flexibility in managing energy consumptions. Socioeconomic factors include consumer passivity, which refers to the tendency of consumers to remain indifferent to the initiatives and lack of financial support. Environmental factors include the limited availability of spaces for renewable technologies and landscape protection. Institutional factors include the absence of coherent policies, incentives, and support schemes, direct involvement of local actor and limited expertise in RECs within local institutions. Furthermore, internal factors include coordination challenges among different stakeholders.

Finally, Cambini et al. [57] have identified two success factors: data access and coordination among network users (e.g TSOs and DSOs). Access to data not only facilitates communication and coordination among network users but also the development of new business models aimed at optimizing the entire energy system. Hower, access to data is constrained by the adoption of smart meters.

1.14 Future pathways and policy recommendations

Currently most RECs are involved in renewable energy generation projects but the involvement of RECs in other projects is expected to grow. RECs could play a crucial role in addressing various sectors such as energy services, electric mobility, energy security, energy poverty and smart grid.

1. REC activities may not only concern energy generation or consumption but also participation in energy market auctions. RECs may provide ancillary services to regulate energy exchanges between production units and the grid, ensuring the maintenance of electrical parameters such as frequency and voltage within limits.

2. In the sector of electric mobility, RECs could offer charging stations and manage car-sharing services.

3. In the sector of energy security, RECs may mitigate the negative impacts of distributed generation systems on the electrical grid through integrated design, increased demand flexibility, and integration with energy storage systems.

4. In the fight against energy poverty RECs can involve the most vulnerable families and allocate revenue generated from incentives to fund social projects.

5. RECs may contribute to the spread of smart technologies for local grid monitoring and management, improving and control.

Additional political support is essential to fully unlock the potential of RECs. At the European central level, it is crucial to ensure consistency and integrity among the transposition processes of various member States and the definition of REC. Certain concepts such as "physical proximity" and "open and voluntary participation" are currently not well-defined in existing policies or regulations, they are subject to free interpretations. Hence, there is a need for clarifications. Additionally, it is crucial to set up new targets to enhance the spread of RECs. At the level of member states, it is essential to apply the principles of the directives appropriately, without introducing strict definitions or objectives that could exclude some types of members.

Lowitzsch et al. [19] have identified the aspects that require special attention in the transposition of RED II. First, the transposition of the new regulations should incorporate the principles of social justice and energy democracy. Second, it should encourage the complementarity of multiple renewable sources, introduce requirements for the heterogeneity of involved actors, and promote flexibility and demand control. Third, it should prioritize the development of rules that ensure the priority of RECs in dispatching. Finally, it should incentivize smart technologies that improve member connections and bidirectional flows.

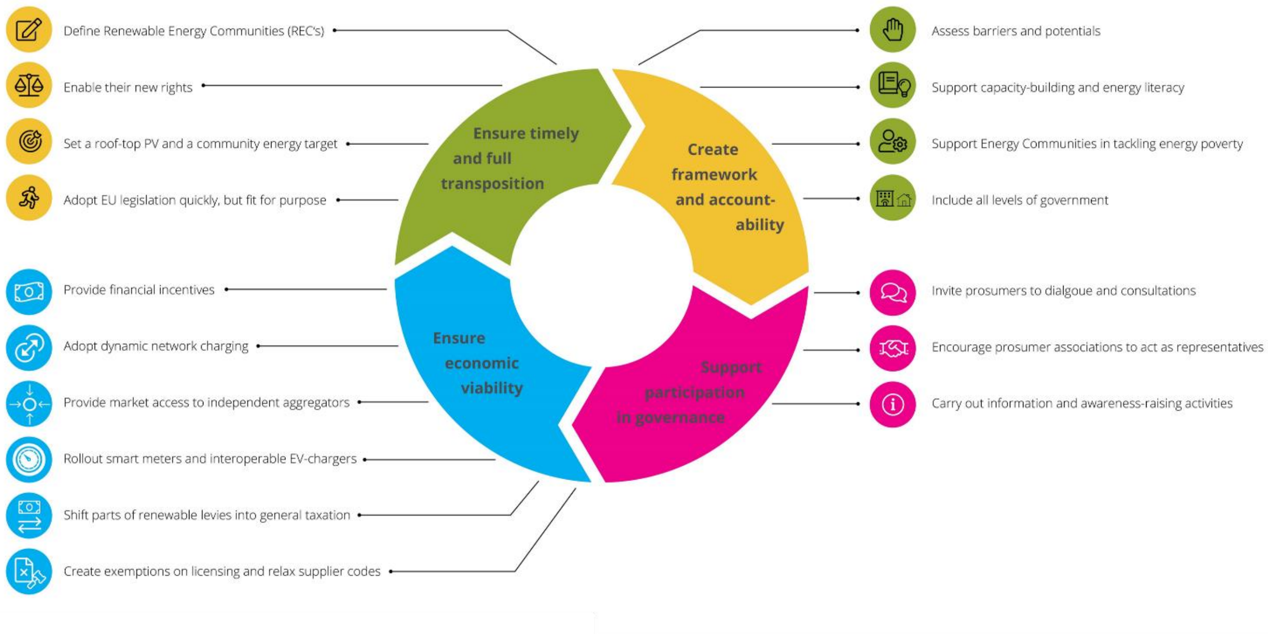


Figure 10. Policy recommendations for strengthening prosumers and energy communities. Infographic by PROSEU project [58].

Additionally, it's essential to interact with regional regulatory plans. De Vidovich et al. [45] have proposed two additional key actions: systematizing consumer involvement in entrepreneurial initiatives and ensuring a sustainable investment model for REC projects. At the national level, it is also necessary to update dispatch regulation to enable active participation of RECs. Simplifying the authorization processes of renewable technologies is crucial to encourage the spread of RECs. Free access to technical information, promoting data exchange, and establishing training and skill-updating programs are necessary to develop REC expertise. Furthermore, guidelines for designing RECs are needed without restricting the development of customized projects. Finally, specific funding sources should be established in addition to the existing incentives. Policy recommendations are summarized in *Figure 10*.

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2. Unlocking open modelling of RECs

The advent of new models of sustainable development not only revolutionizes energy production methods but also transforms design approaches. To unlock the potential of RECs, new modelling tools are required. Traditional energy systems are based on a limited mix of energy sources and conventional technologies operating independently. The design of traditional systems typically follows conventional approaches with limited openness and model-sharing. Developers retain ownership of these models, which are accessible to only a select few. Today, there is a shift in the design criteria for energy systems. The complexity of design and the number of stakeholders involved increase significantly as renewable sources, diverse technologies, energy vectors, energy market liberalization, and direct consumer involvement all come into play. As a result, the development of easy-to-share digital models with high spatial and temporal resolution becomes necessary.

Commercial energy system modelling software, including tools like HOMER, RETScreen, TRNSYS, EnergyPlus, energyPRO, SimulationX-GreenCity, and EnergyPLAN [1] face challenges in simulating of complex energy systems like RECs. The main challenges include the integration of novel calculation methods to simulate prototype technologies, implementing customized management and control logic, simulating new incentive mechanisms, and sharing models and results in their original form, with individuals lacking licenses, given that this software is not open source. Updating of modelling tools or even developing new ones is necessary to encourage new sustainable development models. The first requirement is that the tools are open source.

Several studies have highlighted the importance of open energy modelling [2][3][4]. Open-source models provide access free access avoiding costs of licenses, ensure transparency in methodologies and underlying assumptions, support reproducibility and result verification, promote collaborations among researchers, governmental bodies, academic institutions, and other stakeholders, preventing duplicate works. The establishment of an open community not only simplifies the dissemination of models for diverse applications but also encourages revisions and enhancements through contributions from other authors. Three other important requirements for new modelling tools are flexibility, adaptability, and scalability. Chang et al. [5], through the analysis of 54 energy system modelling tools, have identified current trends in energy system modelling, including:

- Open source

- Improved temporal resolution, shifting from yearly intervals to hourly or even finer intervals. Analysing real-time production-demand coupling is particularly crucial in systems reliant on weather-dependent renewable sources.

- Improved spatial resolution. Tools are advancing towards two sectors: point representations, with detailed descriptions of individual components; and aggregate representations, grouping technical specifications and variables to extend the analysis over large geographic areas, including regions, nations, or even groups of nations.

- Extension of the time horizon. Most of the analysed tools allow simulations with an observation period of at least one year of operation, with the goal of identifying seasonality, recurring events, and trends.

- Sector coupling: Tools include a wide range of sectors such as transport, heating and cooling, industry, with the goal of supporting integrated design.

- Model coupling: Tools ensure integration with other instruments via APIs and the use of standardized input and output data formats.

- Incorporation of energy storage systems: Tools include energy storage solutions such as batteries and thermal storage systems.

- Incorporation of demand-side management: Tools explore how controllable loads can maximize the production-demand match and improve system flexibility.

- Incorporation of energy policies: Tools support the assessment of the impact of energy policies, including incentives for renewable energies, carbon taxes, and emission reduction targets.

- Use: The most innovative tools are currently used in academic world.

In the specific context of RECs there is a growing number of open-source initiatives. Kazmi et al. [6] have provided an overview of open-source datasets, models, and tools used for the optimized design and management of RECs. These initiatives promote the dissemination of RECs by supporting the design process. These tools allow for the development of a digital model of RECs, aimed at assessing its energy, economic, and environmental performance. The digital model supports the optimization of RECs through automated analysis of various configurations and scenarios. Different configurations can be based on one or more key factors characterizing the REC, including technologies, spatial scale and involved stakeholders. Different scenarios can be defined to assess the impact of energy policies, business models, organizational models, energy costs, incentive mechanisms, and technology costs.

2.1 Modelling approach

The approach entails the development of a digital twin of the REC to simulate techno-economic and environmental performance. This model is then utilized for conducting multi-objective optimizations and comparative analyses (*Figure 11*). Creating the digital model involves a territorial analysis to collect the required data. The main aim of modelling a REC is to reconstruct the energy flows that occur within the community over a specified observation period. Typically, this observation period spans at least one year of operation with a temporal resolution of at least one hour. This requirement is driven by the current incentive mechanisms of RECs, which are based on hourly calculations of shared energy. Consequently, the digital twin needs to estimate the main energy variables for each hour of the year:

- Energy production
- Self-consumption
- Shared energy
- Energy fed into the grid
- Energy withdrawn from the grid

The calculation of energy metabolism allows analyse how energy is produced, distributed, consumed, and managed within the REC and to estimate energy flows to and from the grid. This not only facilitates energy supply planning and resource management but is also pivotal for estimating the economic variables:

- Savings on the bill, which are proportional to prosumer self-consumption.
- Revenues from selling to the grid, which are proportional to the energy fed into the grid.
- Incentives, which are proportional to shared energy.
- Costs for purchasing from the grid, which are proportional to the energy withdrawn from the grid.

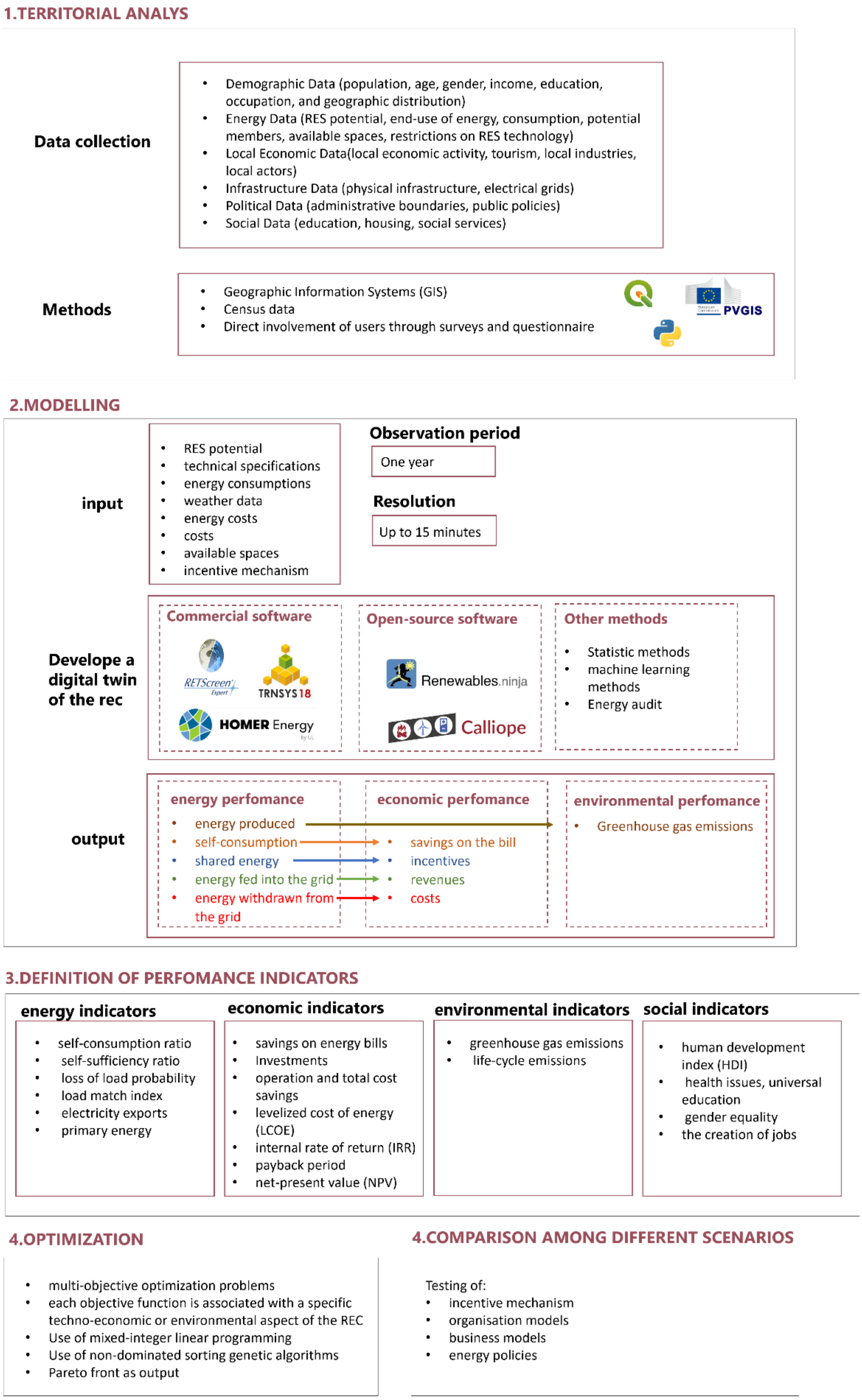

Figure 11. Key steps in modelling of a Renewable Energy Community (REC).

The cash flow of the REC can be calculated by adding the revenues and costs associated with energy flows to the investment costs incurred for the purchase of production systems and maintenance. The estimation of energy flows assumes that the examined year is representative of the entire lifespan of the investments. The estimation of energy flows requires the reconstruction of production and demand curves.

The reconstruction of production curves is based on the simulation of distributed generation systems. In many analyses, simulation is carried out using commercial software that include extensive libraries containing models of the main technologies. Among the main software tools are TRNSYS [7][8][9],HOMER [10][11], and RETScreen[12]. Among the main open-source tools are Calliope [13] and Renewable.ninja [14]. The reconstruction of demand curves is based on various methods [15]. The most accurate method is direct measurement, which involves the use of meters to record energy consumption in real-time or at regular intervals. Unfortunately, acquiring real data is not always possible, and even when available, the installed meters may not provide data with hourly resolution. Statistical models can be used in the absence of real data. These models can be based on historical consumption data and related variables such as temperature, population, or activities. Another approach for reconstructing demand curves is computational simulation, based on energy simulation software. Demand curves are reconstructed by investigating on their relationship with variables such as season, time of day, weather conditions, and human behaviour. Among the most innovative methods are machine learning methods that can estimate demand curves through training on large datasets. The last method is energy audit.

Input data depends on the selected methods but generally includes information about the availability and distribution of renewable sources, technical specifications of production systems, end uses of energy, consumptions, type of actor involved, energy costs, fixed and variable costs of the technologies. Other significant data may relate to regulations and technical constraints, including environmental restrictions that limit the areas where renewable technologies can be installed. Data collection is closely connected to territorial analysis.

When a digital twin of the REC is available, the design process can involve simulating various scenarios or formulating an optimization problem. Setting up the optimization problem entails defining the independent variables, which frequently include the capacity of production systems, storage systems and the number of REC members; the definition of objective functions such as maximizing energy and economic performance, and sometimes minimizing environmental impact.

These are multi-objective optimization problems where each objective function is associated with a specific techno-economic aspect of the REC (*Figure 12*). Energy objectives are often represented by self-consumption or shared energy. Economic objectives are often represented by a cost function that includes investment, operation, and maintenance costs. Finally, environmental objectives are often represented by a function estimating greenhouse gas emissions.

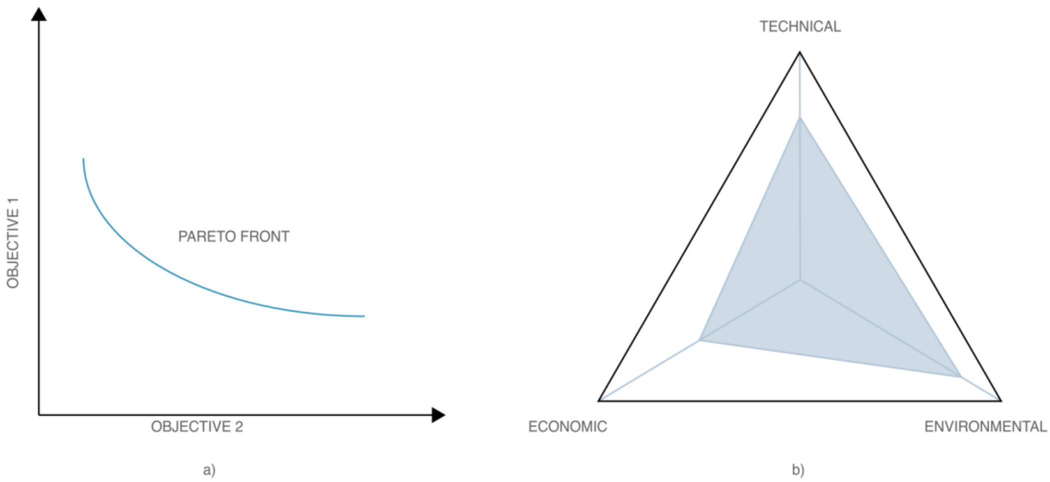

Figure 12. Graphical representation of a) two-dimensional trade-off analysis and b) three-dimensional trade-off analysis [16].

Gjorgievski et al. [16] have identified mixed-integer linear programming (MILP) as the most used optimization method, while the non-dominated sorting genetic algorithm II (NSGA-II) [17] is considered the most useful algorithm for setting multi-objective problems, as in the case of RECs. The goal of NSGA-II is to find a set of high-quality solutions represented by non-dominated fronts. It starts with a population of randomly generated solutions. Each solution in the population is assessed according to the multi-objective optimization criteria specified in the problem. Each solution possesses an objective vector that represents its value for each objective. Solutions are categorized into different ranks or "fronts." The solutions in the first front are not dominated by any other solution, while solutions in subsequent fronts are dominated by those in prior fronts. Solutions within the same front are ordered based on their "crowding distance," which quantifies how close a solution is to other solutions. Solutions with greater crowding distance are retained. Parent solutions are chosen to form a new generation of solutions based on the fronts and crowding distance. High-quality solutions from less dominated fronts with high crowding distance are preferred. Operators for crossover and mutation are applied to parent solutions to generate a new population. These steps are iterated for a specified number of generations or until a stopping condition is met. Procedure to implement NSGA -II is shown in *Figure 13*.

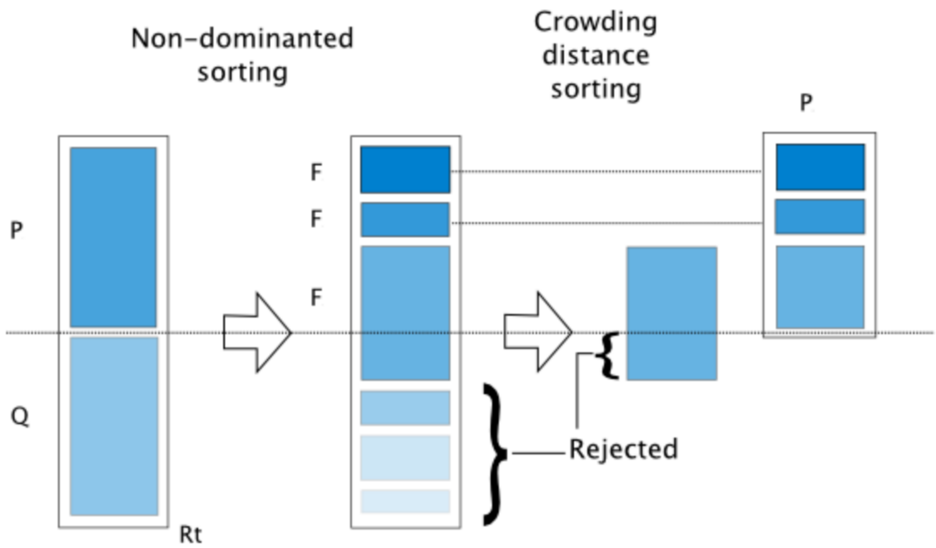

Figure 13. NSGA-II procedure [17].

2. 2 Perfomance indicators

Results are evaluated by defining indices which allow for the synthesis of information and comparison among different configurations. In the assessment of RECs, indicators can be classified into:

- Energy Indicators: to quantify the efficiency of energy resource utilization. The main indicators focus on the integration of renewable sources, coverage from renewable sources and the self-consumption of renewable energy [18][19][20].

- Economic Indicators: to quantify the financial aspects of RECs and assess the economic sustainability of a solution. They main indicators focus on the comparison between the cost of energy produced from renewable source to that of traditional sources, the analysis of the total life cycle costs, return on investment (ROI) for renewable technologies [18][20][21].

- Environmental Indicators: to quantify the environmental impact and calculate greenhouse gas emissions [22][23].

- Social Indicators: to quantify the impact of RECs in the local context. The main indicators focus on local employment opportunities created by RECs, residents' accessibility to renewable energies, the impact on energy poverty and energy security, and other social factors that reflect the role of RECs in the local context [24].

2.3 Software choice

Selecting software for supporting the design of RECs represents a crucial decision. The Software not only supports the design but also automates the analysis and data management. In the process of software selection, factors to consider include budget, compatibility with existing systems, and ease of integration. In this project, we decided to develop new software due to limitations in existing solutions for several motivations:

- To create customized models by analysing not only prototyping-stage technologies, such as wave energy conversion devices, but also specific control logics with the aim to optimize the integration of flexible systems with weather dependent systems

- To Incorporate energy policies which are constantly evolving. Their changes can significantly impact the cost-effectiveness of systems. It is crucial to have a flexible tool that can adapt to these changes.

- To analyse energy systems with a minimum resolution of one hour, as the current incentive mechanism governing RECs is based on hourly shared energy calculation.

- To have an open-source tool available for sharing, both for educational and research purposes. Sharing results of scientific analysis with external partner who do not possess licenses represents a critical issue and slows down the feedback process.

- To ensure model coupling ensuring integration with other instruments via APIs and the use of standardized input and output data formats.

- To incorporate demand-side management by exploring how controllable loads can optimiza the match between production and demand match and improving system flexibility.

- To expand the toolkit for energy analysis of the entire research group, which is highly specialized in energy system modelling and innovative energy solutions.

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3. pyRES

3.1 Rationale behind pyRES development

pyRES is an open-source tool developed in Python for the dynamic simulation of complex energy systems with a high penetration of renewable sources, featuring a time resolution of up to 15 minutes. Energy metabolism and key variables, such as energy production and demand, are calculated at 15-minute intervals throughout the entire analysis period. The tool is specifically developed to support the design of distributed production systems, optimization of existing systems, parametric analyses, and comparative assessments through the development of a digital model. The main functions can be categorized into energy, economic, and environmental performance calculations, energy demand estimation and optimization. Generation technologies include photovoltaic solar panels, wind turbines, internal combustion engines, cogeneration systems, wave motion energy converters. Fuels include petrol, diesel, natural gas, hydrogen, biogas, biomass, syngas with the possibility of customization. Energy storage options include conventional batteries. pyRES supports system sizing by analysing layouts, conducting comparative assessments, setting optimization problems, testing management strategies and legal frameworks, and evaluating organizational and business models. The main advantages compared to existing tools include flexibility, modularity and python programming language. pyRES is completely open source, with no access or usage limits, and it can be shared on official platforms (For collaborative code development and version control, widely recognized platforms such as GitHub [1] are commonly employed). pyRES is used for the design and analysis of RECs. In the case of RECs, shared energy is computed on an hourly basis; hence, hourly resolution is sufficient.

Each REC constitutes a complex energy system which includes at least one renewable energy production system. Within RECs consumers simultaneously assume the roles of energy producers and system owners. The inclusion of energy storage technologies is optional. The analysis of a REC involves a multidisciplinary approach aimed at identifying the optimal combination of production systems and REC members to arrive at the best compromise between energy and economic performance. RECs serve as a comprehensive case study to evaluate computing capability of pyRES. Simultaneously, unlocking the potential of RECs requires the development of new modelling tools. pyRES is completely open-source, with no access or usage limits, and will be made available to all users on official code sharing website. It can be used for educational purposes, research, or to support techno-economic assessments in the process of designing new RECs. pyRES can also be extended, as users can provide improvements and develop new modules.

3.2 Modelling RECs in pyRES

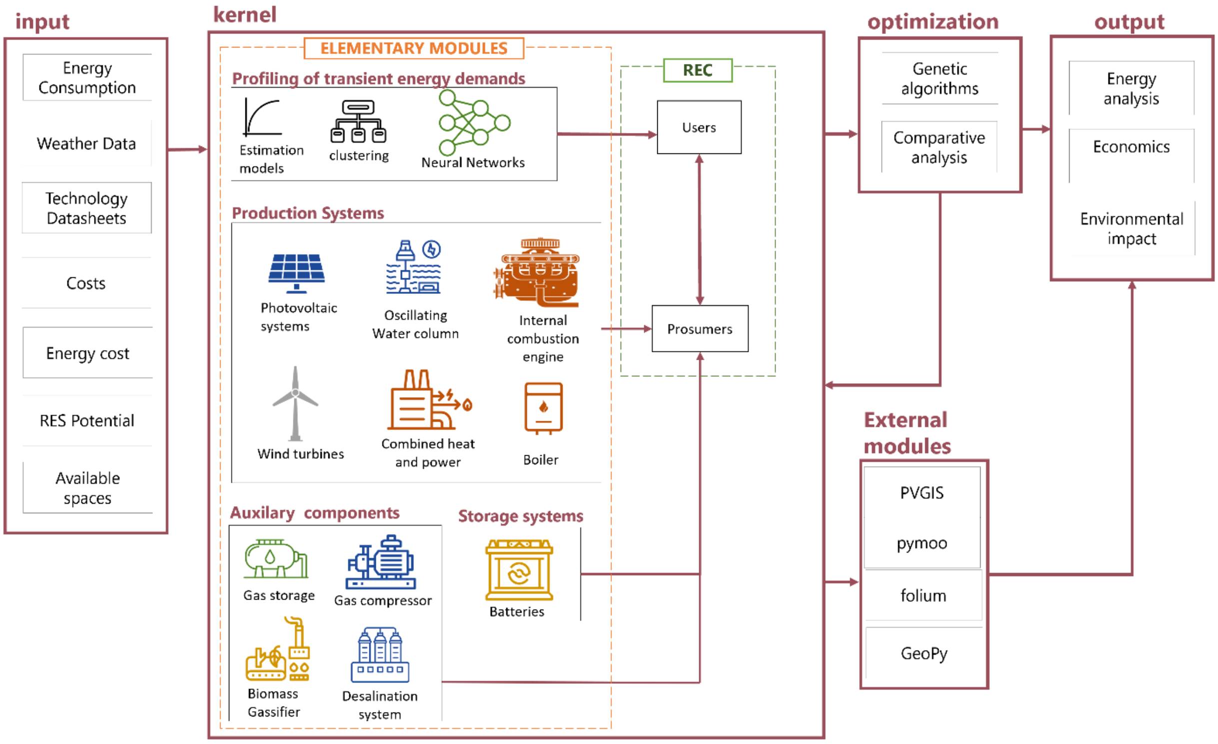

Figure 14. Schematic representation of pyRES: Key Components.

pyRES is specifically developed to support the design process of RECs through by creating a digital twin of the REC, where each component of the real system is simulated through a module. A schematic representation of pyRES is illustrated in *Figure 14*. The digital twin supports the optimization of the size of renewable energy production systems, the identification of the optimal mix of production systems and consumers to achieve the best balance between energy and economic performance, and the estimation of quarter-hourly demand curves in the absence of real consumption data. The development of the digital twin involves several phases: firstly, a territorial analysis is carried out to collect data on energy consumption, the availability of renewable sources, suitable spaces for installing production systems, the potential number and types of consumers and prosumers, any environmental and regulatory constraints. Secondly, an energy analysis is carried out to reconstruct quarterly demand curves using real consumption data, or through an energy diagnosis when real consumption data are not available. Thirdly, for each prosumer, the type of renewable production systems is selected, and production curves are estimated. Finally, a multi-objective optimization problem is formulated for the sizing of systems and the selection of the best combinations of REC members. The goal is to identify consumers who contribute the most to generate incentives.

The analysis in pyRES is divided into 4 blocks:

- *Input*: consists of the technical specifications of technologies, fixed and variable costs, users' energy consumption, meteorological data and energy costs. Input data is cleaned to remove incorrect, corrupted, incorrectly formatted, duplicate, or incomplete data. Quarter hourly demand curves are then constructed using users' electrical consumption.

- *Modelling and simulation*: the digital twin of the REC is created by assembling elementary modules, which include production systems, storage systems, auxiliary components, and modules for reconstructing demand curves based on energy consumption. These elementary modules are then assembled to build REC members. Each consumer is simulated by a demand curve, while each prosumer, defined as a user physically connected to a renewable energy production system, is simulated by combining a demand curve with a production curve. The REC is established through the integration of both consumers and prosumers.

- *Formulation of the optimization problem*: The desired impacts of the REC are translated into the objective functions of an optimization problem. Economic objectives are represented by a cost function that includes investments, operating costs, and maintenance over the system's lifetime. Energy objectives are represented by the maximization of self-consumption and shared energy.

- *Output*: consists of a dynamic analysis of energy performance with a temporal resolution of up to 15 minutes within a predefined period, often set to one year, along with an assessment of the economic and environmental impacts. Results offer detailed insights into the REC's performance over time, including energy production from renewable sources, self-consumption, energy exported and imported from the grid by each prosumer, shared energy among members, economic advantages associated with different layouts and management choices, as well as the reduction of greenhouse gas emissions.

3.3 Overview of features

The main functions of pyRES can be classified into:

1. *Calculation functions*: energy systems are dynamically calculated with the aim of identifying the energy flows that occur during a specific period, with a temporal resolution of up to 15 minutes. Economic performance is calculated based on energy flows, considering inputs such as energy costs, business models, and incentive mechanisms. Additionally, the analysis of energy flows allows to estimate greenhouse gas emissions and environmental impacts. In summary, the output consists of energy, economic, and environmental performance.

2. *Optimization functions*: Adopting a multidisciplinary approach the expected impacts of the REC are translated into objective functions of a multi-objective optimization problem, where each objective function is associated with a specific techno-economic-environmental aspect of the system.
   Independent variables of the optimization problem include production system capacity, storage system capacity and the number of REC members. Objective functions often involve

maximizing energy and economic performance and sometimes minimizing environmental impact. Energy objectives often include the maximization of self-consumption or shared energy, while economic objectives are typically represented by a cost function that includes investment, operation, and maintenance costs. The goal of optimization problem is to explore all feasible configurations within defined ranges of independent variables and select those that maximize the specified objectives. The output consists of optimal configurations.

3. *Estimation Functions*: In scenarios where real data on energy consumption is missing, these functions estimate demand curves on different time scales, including monthly, daily, or hourly up to one-eight of an hour. The choice of estimation methods depends on the availability and nature of the data:
   I. Machine Learning Models
   II. Models based on annual consumption: annual consumption are utilized to construct an hourly demand curve, making reasonable assumptions about how energy consumption is distributed throughout the months of the year and specifying a daily usage pattern.

The main strengths are:

1. *Flexibility*: pyRES is designed to simulate a wide range of energy systems, from simpler configurations with a single production-consumer pair, like residential buildings with photovoltaic panels, to more complex systems with multiple renewable sources, production systems, consumers, multiple energy vectors, storage technologies, specific incentive mechanisms, business models, customized management and control logics.

2. *Modularity*: each function is performed by a dedicated module. This framework offers several advantages, the most significant one is the autonomy of each module. Each module can be independently developed, used as a standalone component, tested individually, modified, or removed without impacting the functionality of other modules. Additionally, new modules can be added at any time to expand the available functionalities. The open modular structure, complemented by open-source code, allows users to customize the available functions.

3. *Python programming language*: Python can be used and distributed without any copyright restrictions. It is portable and compatible with computers and smartphones, making the tool accessible to a wide range of users. This ensures the easy sharing and replication of simulation results. Furthermore, users can actively contribute to its improvement, report errors, or expand its functionalities. Finally, python community is highly active and offers a wide range of modules and libraries that can be easily integrated to extend the pyRES' functionality.

3.4 Development phases

The development of pyRES took place within the research group of the Department of Mechanical and Aerospace Engineering (DIMA), specialized in energy systems modelling and renewable energy generation. pyRES is built upon the principles of object-oriented programming, making extensive use of classes. A common class structure was established since the early phase to allow the future assembly. The development of the pyRES occurs in the following phases *Figure 15*.

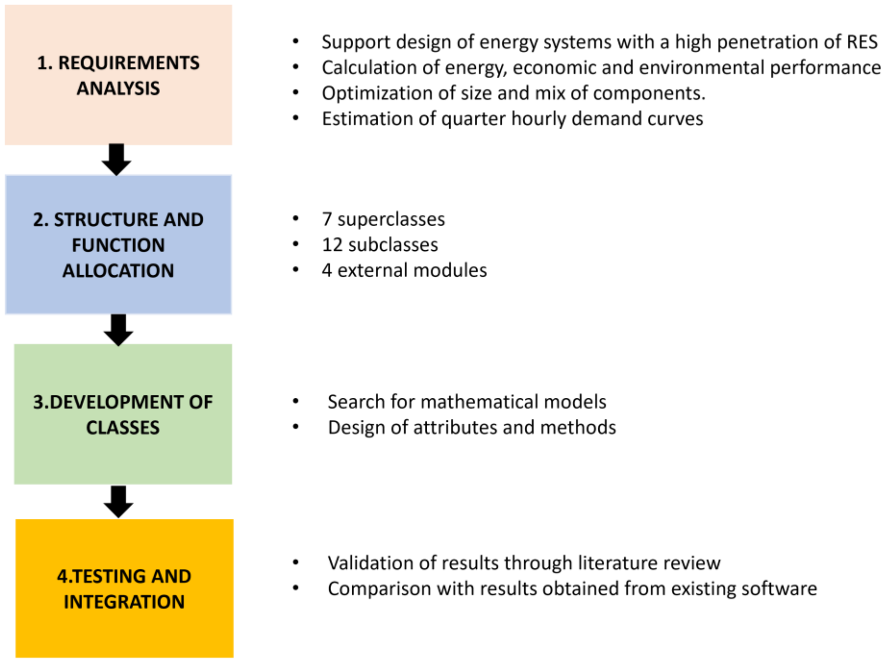

Figure 15. Main phases of the pyRES development.

First, a list of requirements was compiled to identify expected functions, the tool's structure and the distribution of functions were established. Second, the main classes, including generation technologies, energy storage systems, and auxiliary components were identified, along with methods for estimating energy demand and optimization algorithms. Third, classes were developed, tested and validated. Each class was developed independently, ensuring that they met the requirements necessary for their assembly. Each class is based on a mathematical model which describes the real component which the class is intended to simulate. Following the black-box logic, each class takes input data, processes it based on the code that governs its behaviour, and calculates outputs. Results were tested using experimental data or by making comparisons with existing software. Finally, classes were integrated into a unified environment, and the complete tool was tested.

3.5 The Kernel: core components and main models

pyRES is built upon the principles of object-oriented programming, making extensive use of classes. In object-oriented programming, classes are the building blocks that encapsulate both attributes and methods and serve as blueprints for creating objects, which are instances of these classes. Each component of the real energy system is associated with an object, which is characterized by attributes and methods characterizing his behaviour.

- *Attributes*: are the characteristics or variables that describe the state or properties of the object. For instance, in the case of a class representing a photovoltaic system, attributes might include power, the number of modules in series, the number of modules in parallel, cost per kW and so on.

- *Methods*: are functions that an object can perform. They define the behaviour of the object and allow to carry out specific actions. For instance, a class for a photovoltaic system might have methods like "compute power".

- *Object*: is created using a class and is defined as an "instance of the class". It is an object that inherits the attributes and methods defined by the class. For instance, by defining a "PhotovoltaicSystem" class, it's possible to create different instances of specific photovoltaic systems, each with its own power or different layouts defined by number of panels in series and in parallel.

The structure of classes is particularly suited to complex energy systems that include a wide range of components. In pyRES, a hierarchical structure among classes is established using "inheritance" to create new classes based on existing classes. The existing class is referred to as the "superclass" and the newly created class is "subclass". The subclass inherits attributes and methods from the superclass, and it can also introduce new attributes and methods or override the inherited ones to adapt or specialize the behaviour. The main idea behind inheritance is to promote code reusability. For instance, developing a "ProductionSystem" class is possible to create subclasses like "PhotovoltaicSystems" or "Wind Turbines". The "PhotovoltaicSystems" subclass (*Figure 16*) inherits attributes and methods like "power" and "compute power" and can also introduce specific attribute like “number of panels in series” or override methods to behave differently. This subclass is used to generate different types of Photovoltaic systems defined as “instance of class”.

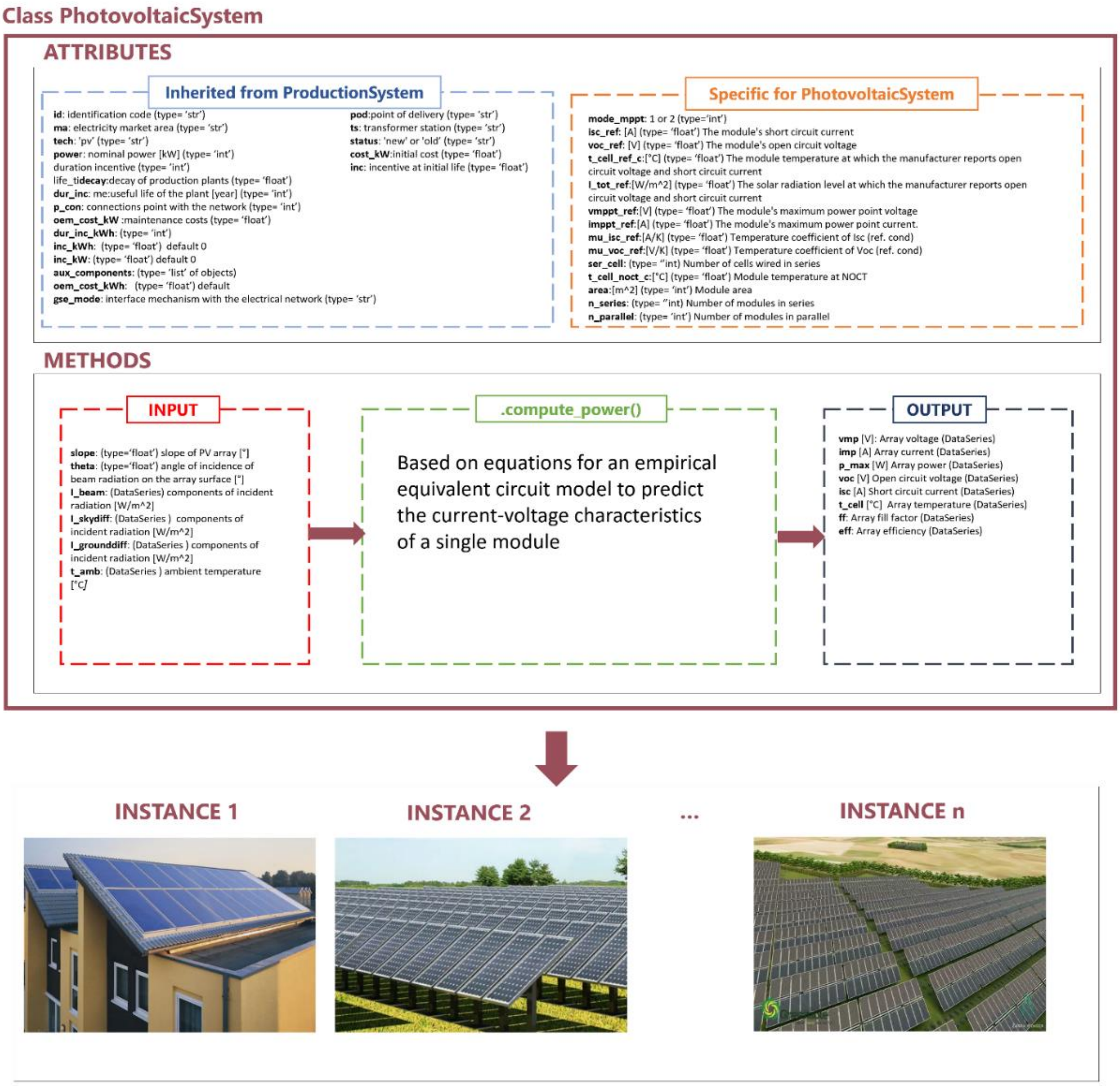

Figure 16. Schematic representation of “PhotovoltaicSystem” subclass: attributes, methods and instances.

In pyRES, seven superclasses and 12 subclasses are defined (*Figure 17*):

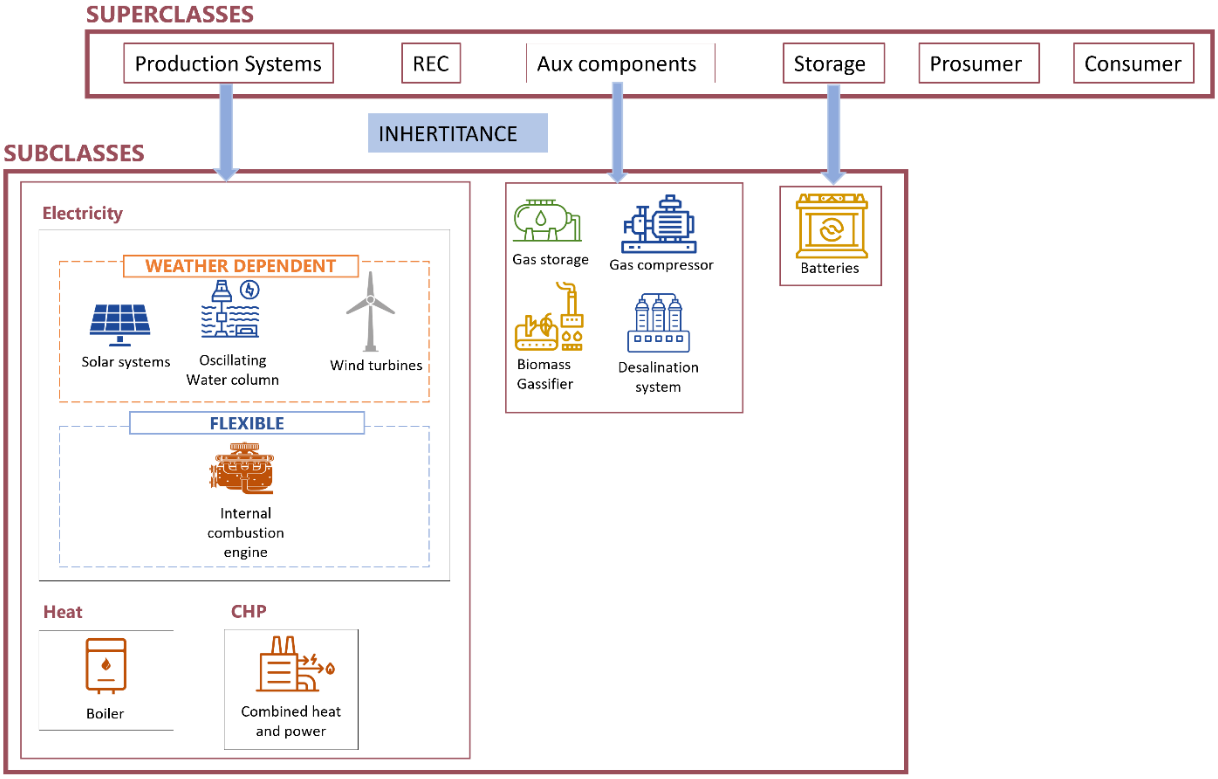

Figure 17. Class Inheritance structure in pyRES.

- *ProductionSystems*: groups all the common attributes characterizing a production system, including technical specifications such as power, energy vectors, technology, along with economic parameters such as investment costs, maintenance costs, and incentives. This superclass allows to generate subclasses for simulating different types of production systems such as wind turbine, photovoltaic systems, combined heat and power, internal combustion engine, oscillating water column. Each subclass integrates specific technical attributes of its category, such as power curves and characteristic curves. Currently, there are only two available energy vectors, categorizing systems into heat generation, electricity generation and cogeneration. An additional classification distinguishes flexible systems from weather-dependent systems. The output is an object designed to simulate an energy production curve and estimate the costs and revenues associated with production.

- *AuxiliaryComponents*: groups all the common attributes characterizing auxiliary components, including economic attributes for estimating purchase and replacement costs. This superclass allows to generate subclasses for simulating various categories of auxiliary components such as biomass gasifiers, gas compressors, gas storage units, heat recovery systems, and desalinators. Each subclass integrates specific technical attributes of its category, such as characteristic curves and capacity. The output is an object designed to simulate the behaviour of the specific auxiliary component, calculate the energy consumption associated with the component's operation and assess the costs related to purchase and potential replacement.

- *StorageSystems*: groups all the common attributes characterizing storage systems including technical specifications like storage capacity, energy vectors, technology, along with economic parameters such as investment costs, maintenance costs and incentives. This superclass allows to generate subclasses for simulating different storage systems. Currently, only electrochemical storage is available. The output is an object designed to simulate the behaviour of an energy storage system, calculating the energy exchanges that occur between storage and production units and costs resulting from the purchase and replacement.

- *Profiling of transient energy demand:* The incentive mechanism on RECs shared energy requires to analyze the hourly energy metabolism of the REC and thus to reconstruct the hour-per-hour internal energy fluxes and grid interactions. This entails the necessity of modeling the electrical loads when quarter-hour demand is not available from data acquired from the smart meters that currently map about 1/3 of the italian PODs. In this case integral monthly consumption of energy are usually available from previous invoices and a methodology was developed to map these values and reconstruct the quarter-hour unsteady load. This methodology exploits Variational Auto-Encoders to map the consumption habits of the POD users and the invoices and reconstruct the unsteady loads.

- *Consumer*: groups all the common attributes characterizing a consumer including energy vectors and energy consumption patterns. The output is an object designed to simulate a demand curve.

- *Prosumer*: groups all the common attributes characterizing a prosumer. In the pyRES modelling, a prosumer is defined as a consumer physically connected to a production system. The prosumer is simulated through the integration of one or more production curves and one or more demand curves. The output is object designed to simulate a prosumer, estimating energy flows (production, self-consumption, exchanges with the grid), economic performance (savings on bills, revenue from energy sales, incentives, purchase and maintenance costs, cash flow, and economic parameters such as NPV and PBP), and environmental impacts (reduction of greenhouse gas emissions).

- *REC*: group all the common attributes characterizing a REC. The REC is simulated through the integration of prosumers and consumers. The output is an object designed to simulate a REC, estimating energy flows (production, prosumer's self-consumption, exchanges with the grid, and shared energy) and economic performance (incentives, operating costs, cash flow, economic parameters such as NPV, and revenue for each individual member).

pyRES allows the integration with the following **external modules**:

- *PVGIS*: is an open-source web application that provides data on solar radiation and photovoltaic system energy production, for locations across Europe, Asia and America. pyRES interfaces with PVGIS through an API. Solar radiation components referred to a typical meteorological year (TMY) can be obtained in CSV format, given as input location coordinates, solar system tilt, and orientation. Two databases are available including PVGIS-SARAH2:2005-2020 and PVGIS-ERA5: 2005-2020.

- *pymoo*: a Python library used for solving multi-objective optimization problems. It provides a set of optimization algorithms to develop and solve multi-objective optimization problems. pyRES employs pymoo, with a focus on NSGA-II. The formulation of multi-objective optimization problems is based on the following steps:

i. *Setting the Independent Variables*: for instance, independent variables may include the power of production systems, the capacity of storage systems or the number of REC members.

ii. *Definition of Range of Variables*: depends on the specific constraint, for instance, limited spaces for installing production systems, a limited budget or a confined geographical area.

iii. *Selection of Objective Functions*: Usually, two objective functions are selected, one to address the energy-related aspects and another to address economic factors. For instance, objectives of the problem may include maximizing the NPV of the investment, minimizing the initial investment, maximizing revenue per each member, maximizing self-consumption or maximizing shared energy.

iv. *Problem Formulation*: the problem is formally defined, specifying the relationships and constraints among the independent variables and the selected objective functions through the creation of a digital twin of the REC using pyRES classes.

- *folium and Geopy*: are python libraries used for creating interactive maps. Input data is in JSON format.

3.5.1 Production systems

Included in this category are all subclasses that simulate the behaviour of electricity and heat production systems and provide a production curve as output.

Photovoltaic system (PV)

In pyRES a photovoltaic panel is based on the four-parameter (ILref, I0ref, gamma, Rs) equivalent circuit model developed largely by Townsend and expanded by Duffie and Beckman [2][3][4]. The model is based on an empirical equivalent circuit model to predict the current-voltage characteristics of a single module. The model extrapolates the performance provided by the manufacturer data sheet using a single module equivalent circuit to predict the performance of a multi-module array. In the four-parameter model, the electrical behaviour of the photovoltaic cell is represented by the equivalent circuit shown in *Figure 18* , where a DC current source i_L is placed in parallel with a diode, both in series with a resistor.

- Diode represents the p-n semiconductor junction of the solar panel, and i_D is the current flowing through it.
- R_s represents losses due to leakage between the two electrodes and within the semiconductor.

This schematic representation aims to determine the relationship between the supplied current i and the voltage V across the cell, defines as characteristic curve (1).

$$i = f(V) \tag{1}$$

The calculation of the power supplied by the cell under specific conditions is based on this characteristic curve.

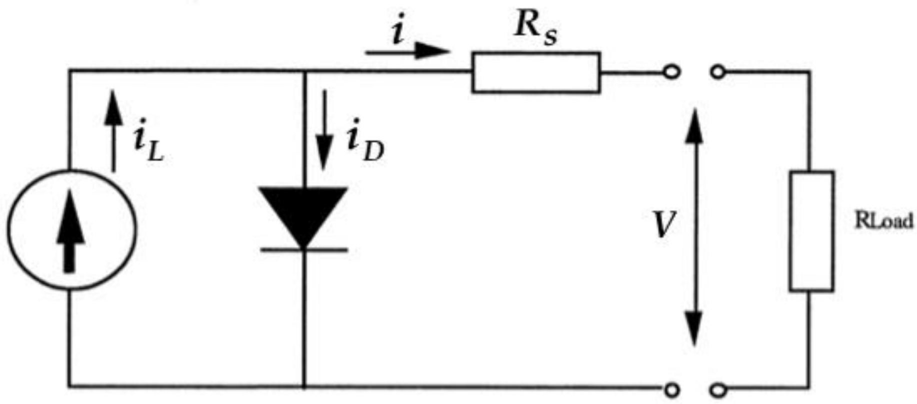

Figure 18. Equivalent circuit of a photovoltaic panel in the four-parameter model [5].

The four parameters necessary to describe the circuit are:

1. i_L photocurrent: the current generated by the incident radiation on the cell
2. i_D, diode current
3. R_S series resistance
4. γ ideality factor for measuring the imperfection of the cell

The determination of these parameters relies on solving a system of four independent equations:

1) Kirchhoff's law for the electrical circuit:

$$i = i_L - i_D \tag{2}$$

2) Definiton of photocurrent:

$$i_L = \left(\frac{I_{total}}{I_{tot_{ref}}}\right) * \left(i_{Lref} + \mu_{ISCref} * \left(T_{cell} - T_{cell_{ref}}\right)\right) \tag{3}$$

where:

- I_{total} total radiation [W/m^2]
- $I_{tot_{ref}}$ reference radiation (1000 W/m^2)
- i_{Lref} photocurrent [A] at reference conditions (1000 W/m^2, 25°C)
- μ_{ISCref} short-Circuit Current (Isc) Temperature Coefficient
- T_{cell} operating temperature [K]
- $T_{cell_{ref}}$ reference temperature (25°C)

3) The voltage-current characteristic curve for the diode, described by the Shockley equation:

$$i_D = i_O\left(e^{[q_{bz}(V+iR_S)/\gamma T_{cell}]} - 1\right) \tag{4}$$

where:

- q_{bz} defines as q / k
- q charge of an electron (1.602 × 10^{-19} C)
- k Boltzmann constant (1.381 × 10^{-23} J/K)

4) Definition of reverse saturation current i_O:

$$i_O = D * T_{cell}^3 * e^{(-q_{bz}\,\varepsilon_G/a\,T_{cell})} \tag{5}$$

where:

- D diode diffusion factor

- ε_G band gap (1.12 eV for Si, 1.35 eV for GaAs)
- a diode ideality factor

The system of equations is nonlinear. In order to solve this nonlinear system the Townsend method involves:

- Iterative calculation of R_S, using the bisection method and comparing the coefficient of temperature for open circuit voltage μ_{Voc} (provided by the manufacturer) with the analytical expression.
- The utilization of three points on the current-voltage characteristic curve (1), which must be supplied by the manufacturer: $(V_{OC_{ref}}; 0)$, $(0; i_{SC_{ref}})$, $(V_{mppt_{ref}}; i_{mppt_{ref}})$. These points represent the points on the curve for open-circuit voltage, short-circuit current, and maximum power point, respectively *Figure 19*.

  where:

  - $V_{OC_{ref}}$ open-circuit voltage
  - $i_{SC_{ref}}$ short-circuit current
  - $V_{mppt_{ref}}; i_{mppt_{ref}}$ voltage and current at maximum power

This method reduces the number of parameters to three, and by using of three points on the characteristic curve, the following additional relationships are determined:

1) $$i_{SC_{ref}} = i_{L_{ref}} - i_{O_{ref}}(e^{\frac{\nu * i_{SC_{ref}} * R_S}{\gamma}} - 1) \tag{6}$$

2) $$0 = i_{L_{ref}} - i_{O_{ref}}(e^{\frac{\nu * V_{OC_{ref}}}{\gamma}} - 1) \tag{7}$$

3) $$i_{mppt_{ref}} = i_{L_{ref}} - i_{O_{ref}}(e^{\frac{\nu\,(V_{mppt_{ref}} + i_{mppt_{ref}} * R_S)}{\gamma}} - 1) \tag{8}$$

where $\nu = \frac{q_{bz}}{T_{cell_{ref}}}$.

(9) and (10) are based on the following simplifications:

- $i_{L_{ref}} \approx i_{SC_{ref}}$

- -1 in (9) can be neglected.

$$\gamma = q_{bz} * \frac{V_{mppt_{ref}} - V_{OC_{ref}} + i_{mppt_{ref}} * R_s}{T_{cell_{ref}} * ln\left(1 - \frac{i_{mppt_{ref}}}{i_{SC_{ref}}}\right)} \tag{9}$$

$$i_{O_{ref}} = i_{SC_{ref}} * e^{-\frac{q_{bz} * V_{OC_{ref}}}{\gamma * T_{cell_{ref}}}} \tag{10}$$

Finally, the characteristic curve i-V (*Figure 19*) is:

$$i = i_L - i_O\left(e^{[q_{bz}(V+i\,R_S)/\gamma T_{cell}]} - 1\right) \tag{11}$$

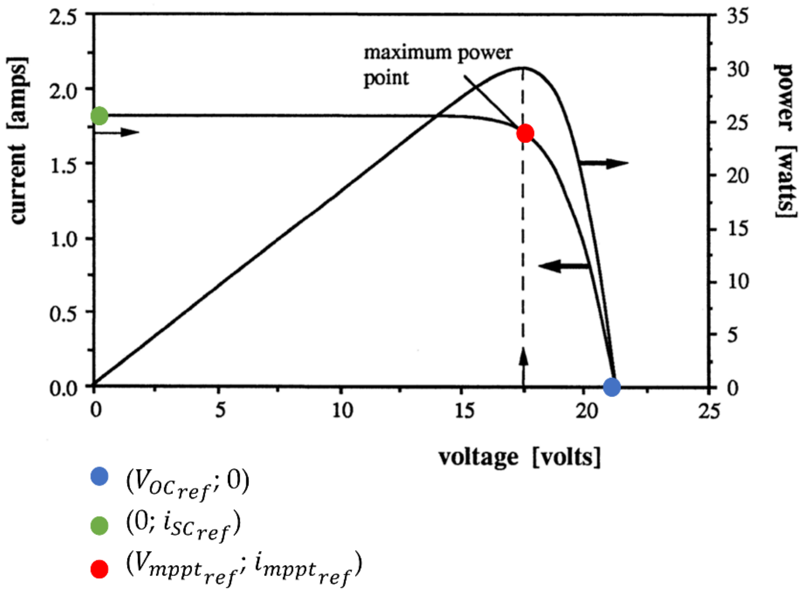

Figure 19. Voltage-current and voltage-power characteristics of a photovoltaic cell [5].

All the previously calculated quantities apply to an individual photovoltaic panel. To accurately describe the characteristic curve for the entire array, it is essential to update the obtained values by multiplying by the number of modules in series and in parallel, $nSeries$ and $nParallel$, respectively.

$$i_{L_{ref}} = nParallel * i_{L_{ref}} \tag{12}$$

$$\gamma = nSeries * \gamma \tag{13}$$

$$R_s = \frac{nSeries}{nParallel} * R_s \tag{14}$$

$$i_{o_{ref}} = nParallel * i_{o_{ref}} \tag{15}$$

$$V_{OC_{ref}} = nSeries * V_{OC_{ref}} \tag{16}$$

The black-box representation of the model is illustrated in *Figure 20* where the inputs that do not change during the simulation are indicated as parameters.

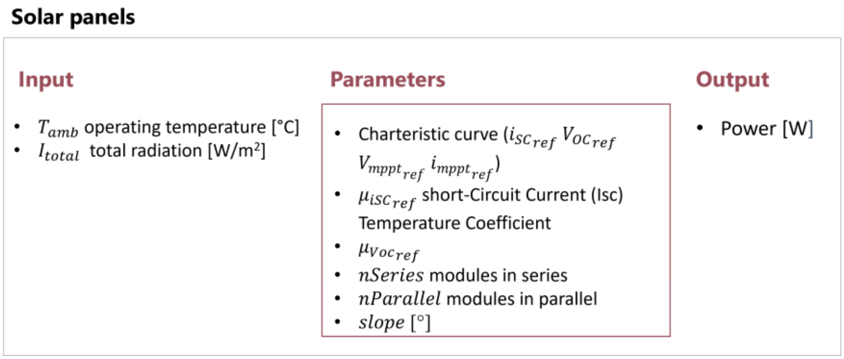

Figure 20. Black box representation of a solar panel in pyRES.

Results (*Figure 21*) were validated against those calculated by TRNSYS Type 103 [6]. The quarter-hour difference in computed power output for the whole year is always in the range of [− 0.96:1.012] mW.

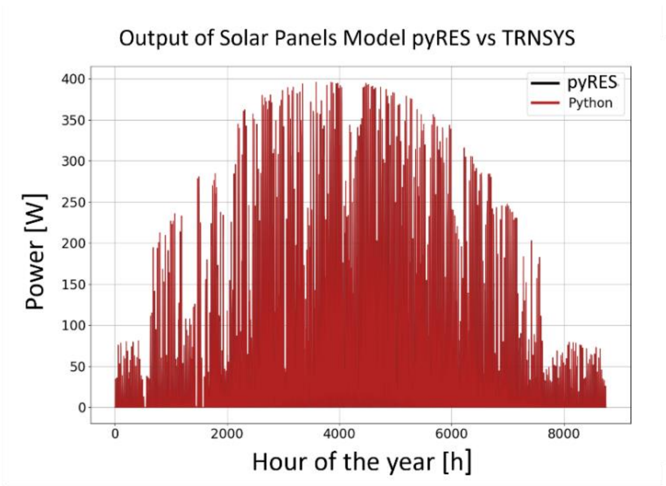

Figure 21. Comparison between pyRES and TRSNSYS models of a Solar panel.

Wind turbine (WT)

In pyRES, the modelling of a wind turbine is based on the theoretical work of Von Karman [9][10]. The model is based on five equations:

1. The Power-Wind Speed characteristic curve of the wind turbine:

$$P = f(v) \tag{17}$$

2. The law governing the temperature variation with altitude:

$$T(h) = T(h_0) - b \cdot h \tag{18}$$

b is the characteristic vertical thermal gradient of the location

3. The variation of the wind speed with the altitude:

$$v(h) = v(h_0)\left(\frac{h}{h_0}\right)^{\alpha} \tag{19}$$

The shear exponent α, depends on the reference site

4. The Ideal Gas Law to describe the behaviour of air:

$$p = \rho RT \tag{20}$$

R is the universal gas constant

5. The law of adiabatic transformation:

$$p(h)\big(T(h)\big)^{\frac{k}{1-k}} = cost \tag{21}$$

k is the adiabatic expansion coefficient

The wind turbine model calculates the power generated by the turbine starting from the wind speed, taking into account variations in wind speed and air density at different altitudes. The power-wind speed characteristic curve (17), also known as the power curve, is experimentally determined by the manufacturer. It provides the power output of the turbine for each wind speed under test conditions corresponding to a temperature of 15 °C, atmospheric pressure, a density of 1.225 kg/m3, and a specific altitude (*Figure 22*).

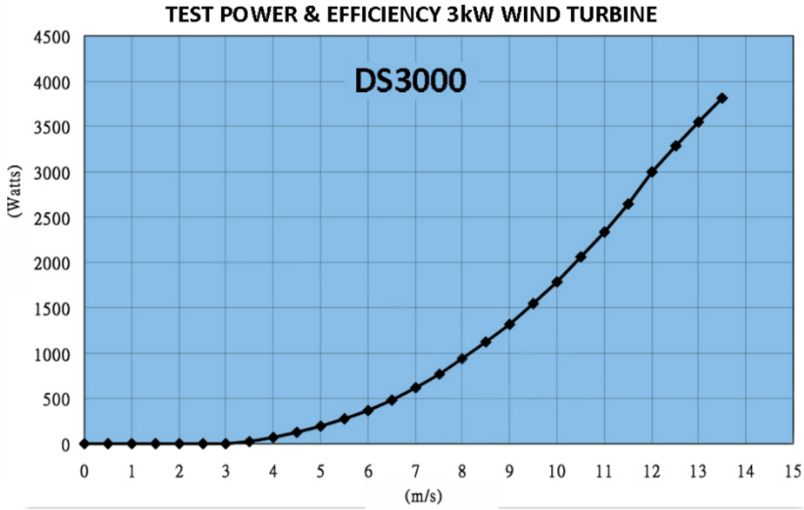

Figure 22. Example of a Wind Turbine power curve provided by manufacturer. Source: [7].

The power curve, characterizing the turbine's performance under test conditions, is used to derive the corrected power curve that describes the turbine's behaviour in real conditions. The corrected power curve considers variations in air density compared to experimental tests and the increase in wind speed with the height above ground level at the site where the wind turbine is located. Changes in air density with altitude are calculated based on temperature variations, assuming air behaves as an ideal gas and considering adiabatic transformation. Starting from (18), knowing the air temperature at a reference altitude h_0 and the coefficient *b*, it is possible to calculate the temperature *T* at any given altitude *h*. Under the assumption of adiabatic transformation (21), the variations in pressure $p(h)/p(h_0)$ and temperature $T(h_0)/T(h)$ satisfy the following relationship:

$$p(h) \cdot \big(T(h)\big)^{\frac{k}{1-k}} = p(h_0) \cdot \big(T(h_0)\big)^{\frac{k}{1-k}} \tag{22}$$

The air density $\rho(h)$ at a given elevation *h* is calculated according to the ideal gas law (20), by considering the temperature *T(h)* and pressure *P(h).* The wind speed v at altitude *h* is calculated using equation (19). If wind speed data is available at an altitude different from that of the rotor, the corrected speed v^* is calculated by multiplying the wind speed by the ratio of the height at which the rotor is located to the height at which wind speed data is available (23).

$$v^* = v\left(\frac{rotor\_ht}{sensor\_ht}\right)^{Sher\_Exp} \tag{23}$$

All heights are calculated with respect to the elevation of the installation site. Starting from the corrected speed and the power curve, the power output of the turbine under test conditions is obtained (24).

$$P = f(v^*) \tag{24}$$

Finally, the corrected power curve (25) is calculated, taking into account variations in air density $\rho(h)$ compared to the experimental tests ρ_0.

$$P^* = P\left(\frac{\rho(h)}{\rho_0}\right) \tag{25}$$

The model adapts the manufacturer's power curve to match the specific range of wind speeds at which energy generation occurs. Additionally, the model accounts for variations in air density and the increase in wind speed with the height above the ground where the wind turbine is installed. The wind turbine model in pyRES takes as input the power curve, provided as a set of wind speed-power pairs, the height of the turbine rotor *rotor_ht*, the height of the sensors detecting wind speed *sensor_ht*, the wind speed measured at *sensor_ht*, and the ambient temperature *T* and barometric pressure p of the site where the turbine is located. It interpolates the wind speed-power pairs to construct the curve (17) applies the equations outlined above to derive the corrected power curve (25), and outputs the power generated by the turbine under real operating conditions. The black-box representation of the model is illustrated in *Figure 23* where the inputs that do not change during the simulation are indicated as parameters.

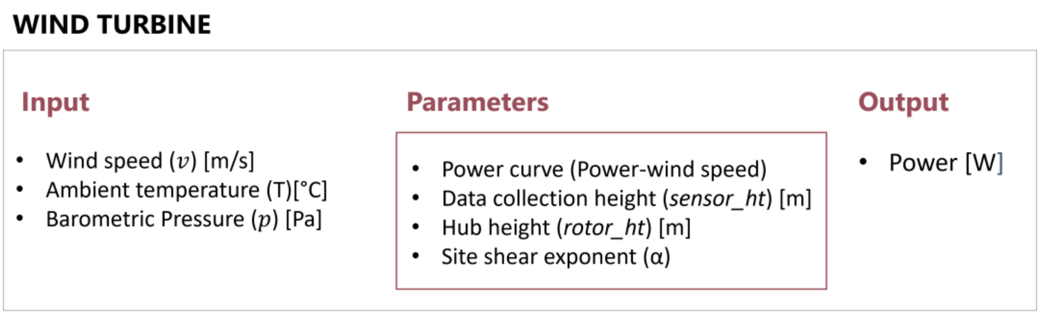

Figure 23. Black box representation of a wind turbine in pyRES.

Results were validated against those calculated by TRNSYS Type 90 [6] (*Figure 24*). The difference in computed power output for the whole year is always in the range of [− 0.89:1.078] mW.

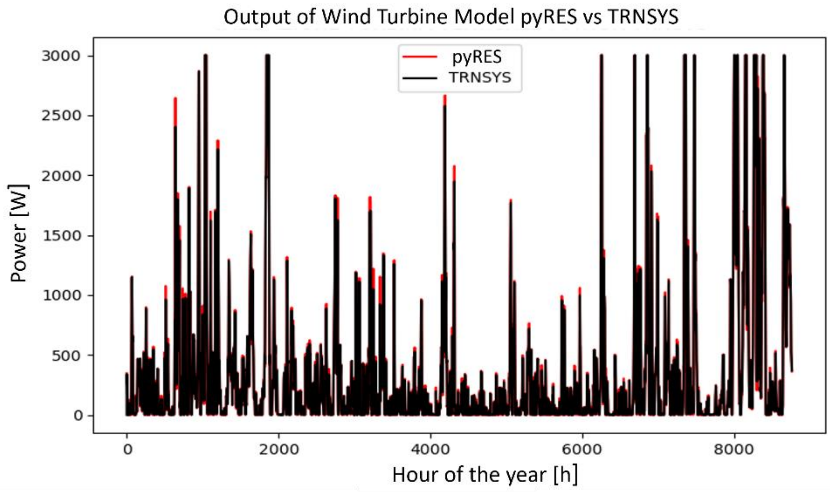

Figure 24. Comparison between pyRES and TRSNSYS models of a wind turbine.

Oscillating water columns (OWC)

In pyRES the modelling of an OWV is based on the formulation of Corsini et al. [11]. Main components and energy transformations of an OWC are represented in *Figure 25*. This model simulates the energy conversion process and calculates the power production. The wave motion is converted to an oscillating airflow in a duct equipped with a turbine, specifically the Wells turbine. The Wells turbine is a self-rectifying air turbine, capable of maintaining the same direction of rotation as the airflow changes direction thanks to its symmetrical blades The turbulent flow is governed by nonequilibrium behaviour. The main components are the chamber and the Wells turbine. In the primary stage, the chamber converts incident wave motion into the pneumatic power of the air column. In the secondary stage, pneumatic power is converted into mechanical energy by setting the Wells turbine in motion, subsequently generating electric power through an electric generator connected to the turbine. Pressure variations are calculated by evaluating wave characteristics, including the wave period *Tm*, wave height *Hs*, and the wavenumber *k*. These variations are calculated through a mass balance between the airflow and water flow rates across the chamber. The output of the Wells turbine is computed based on an experimental power curve that establishes the relationship between power and pressure variations, providing the energy produced at various pressure levels.

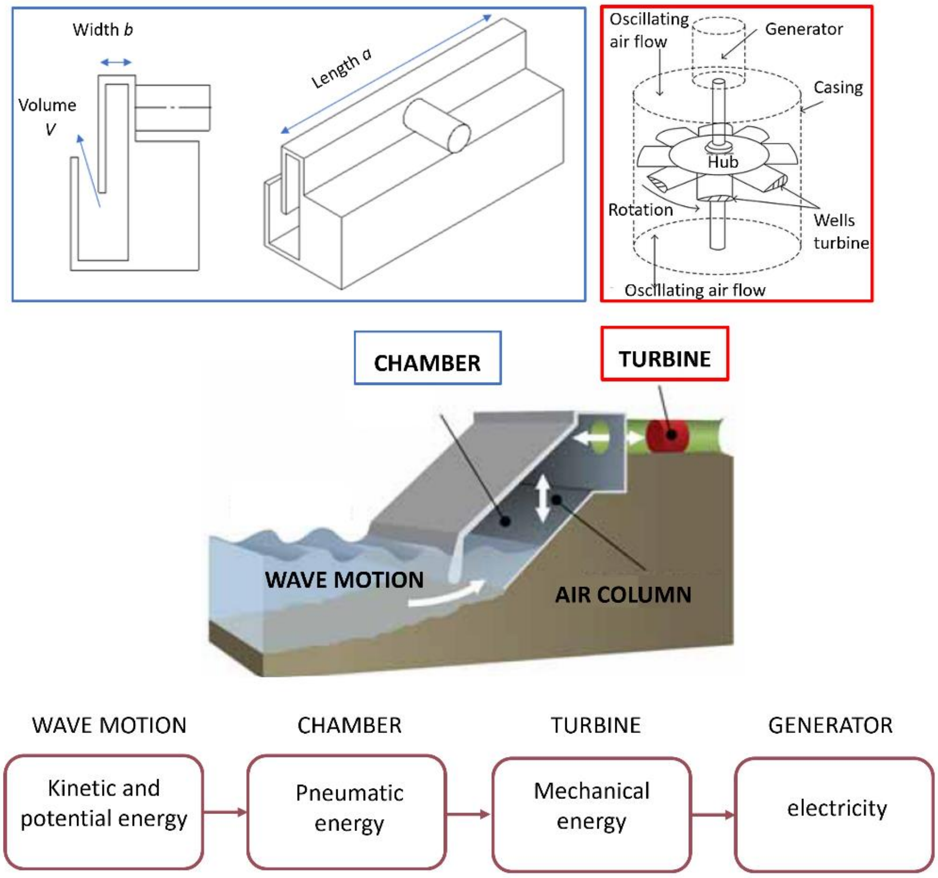

Figure 25. Main components and energy transformations of an Oscillating water column (OWC).

The history of pressure variation inside the chamber is reconstructed from the hydrodynamics of the wave. The chamber model is valid under the following assumptions:

- Chamber: simple geometry with a rectangular plan;
- Ideal gas behaviour for air;
- Adiabatic and reversible process within the chamber;
- Exchanges and losses due to viscosity related to the bidirectional passage of air in the turbine are neglected.

The chamber model is based on the following equations:

1. The wave equations:

$$\xi = A * \sin(\omega * t + k * x) = \frac{H_s}{2\sqrt{2}} * \sin\left(\frac{2\pi}{T_m} * t + k * x\right) \tag{26}$$

2. The equation of conservation of the air mass inside the chamber:

$$w + w_v = -\frac{dm}{dt} = -\check{V} * \frac{d\rho}{dt} + \rho_a * \left(q_i(t) + q_r(t)\right) \tag{27}$$

Where:

- Hs significant wave height
- Tm mean wave period
- ξ wave height
- $A = \frac{H_s}{2\sqrt{2}}$ wave amplitude
- $\omega = \frac{2\pi}{T_m}$ angular frequency
- t time
- x space
- k wave number
- w, w_v mass flow rate in the turbine and in the bypass valve
- m air mass in the chamber ($m(t) = r(t) \cdot V(t)$)
- $\check{V}$ air volume in the chamber
- ρ_a air density
- $q_i(t), q_r(t)$ accounting for the water flow entering and leaving the chamber in accordance with the adopted linear wave theory.

$$q_i = \frac{2 * A * b * \omega}{k} \sin(ka) \cos(\omega t) \tag{28}$$

$$q_r = \int_{-\infty}^{t} g_r(t-\tau)p(\tau)\, d\tau \tag{29}$$

Where:

- a chamber lenght
- b chamber width

By combining (26) and (27) with (28) and (29), it is possible to determine the law governing the variations of maximum pressure in the chamber (30) as a function of the chamber geometry and the properties of air and the wave:

$$p_{max}(t) = \frac{\frac{2 * A * b * \omega * \sin(a * k)}{k}}{\sqrt{\left(\frac{2 * \mu * b * \omega * \sin^2(ak)}{g * \rho_w * k} + \frac{k}{\rho_a}\right)^2 + \left(\frac{\omega * V_0}{\gamma * p_a}\right)^2}} \cdot \frac{0.05a + 0.45}{0.079T_m + 0.4223} \tag{30}$$

Where:

- V_0 chamber volume
- viscosity

$$\mu = \frac{1}{\left(1 + \frac{\frac{\omega^2 * h}{g}}{\sinh(k * h)^2}\right)} \tag{31}$$

- h depth of the seabed in front of the chamber
- g gravitational acceleration
- ρ_w water density
- γ ratio of specific heats of air

The law of pressure evolution is used as input in the Wells turbine model to calculate the power generated by the turbine. The Wells turbine model is based on the definition of two dimensionless variables (32) and (33) and the relationship (34) between the dimensionless power coefficient Π and the dimensionless pressure coefficient Ψ:

$$\Psi = \frac{p_{max}}{\rho_a * n^2 * d^2} \quad (32)$$

$$\Pi = \frac{P}{\rho_a * n^3 * d^5} \quad (33)$$

$$\Pi = f(\Psi) = \alpha_1 * \Psi^2 + b_1 * \Psi + c_1 \quad (34)$$

Where:

- n revolutions per minute
- d turbine diameter $[m]$
- α_1, b_1, c_1 derived experimentally, dependent on the geometry of the system
- $A = \frac{H_s}{2\sqrt{2}}$ wave amplitude
- $\omega = \frac{2\pi}{T_m}$ angular frequency

The equation (34) constitutes the characteristic curve of the Wells turbine *Figure 26*.

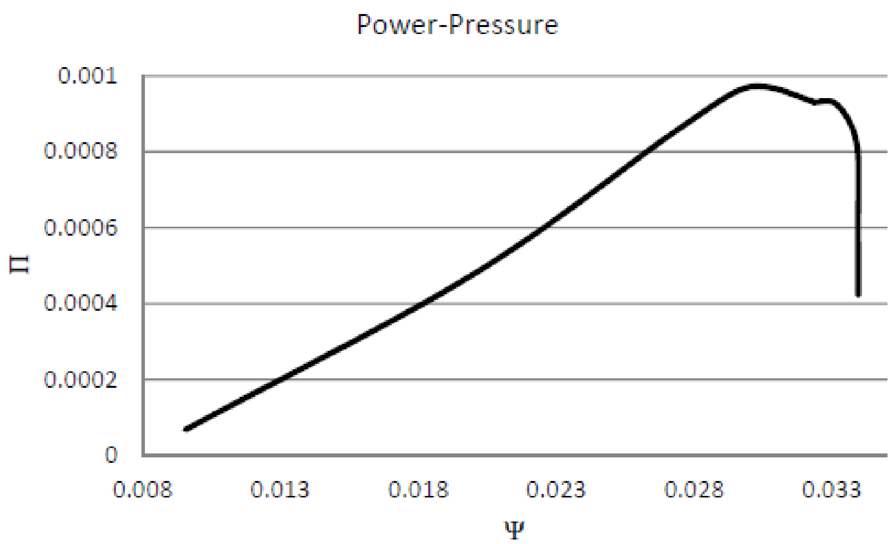

Figure 26. Example of a Wells turbine power curve. Source:[8].

1. Given the maximum pressure p_{max} , air density ρ_a , revolutions per minute N, and turbine diameter D, the dimensionless pressure coefficient Ψ is calculated by using the equation (32).
2. Given Ψ, Π is calculated by using the Wells turbine power curve (34).
3. Given the dimensionless power coefficient Π, air density ρ_a, revolutions per minute n, and turbine diameter d, the power P is calculated by using the equation (35)

$$P = \Pi * \rho_a * n^3 * d^5 \tag{35}$$

The black-box representation of the model is illustrated in *Figure 27* where the inputs that do not change during the simulation are indicated as parameters.

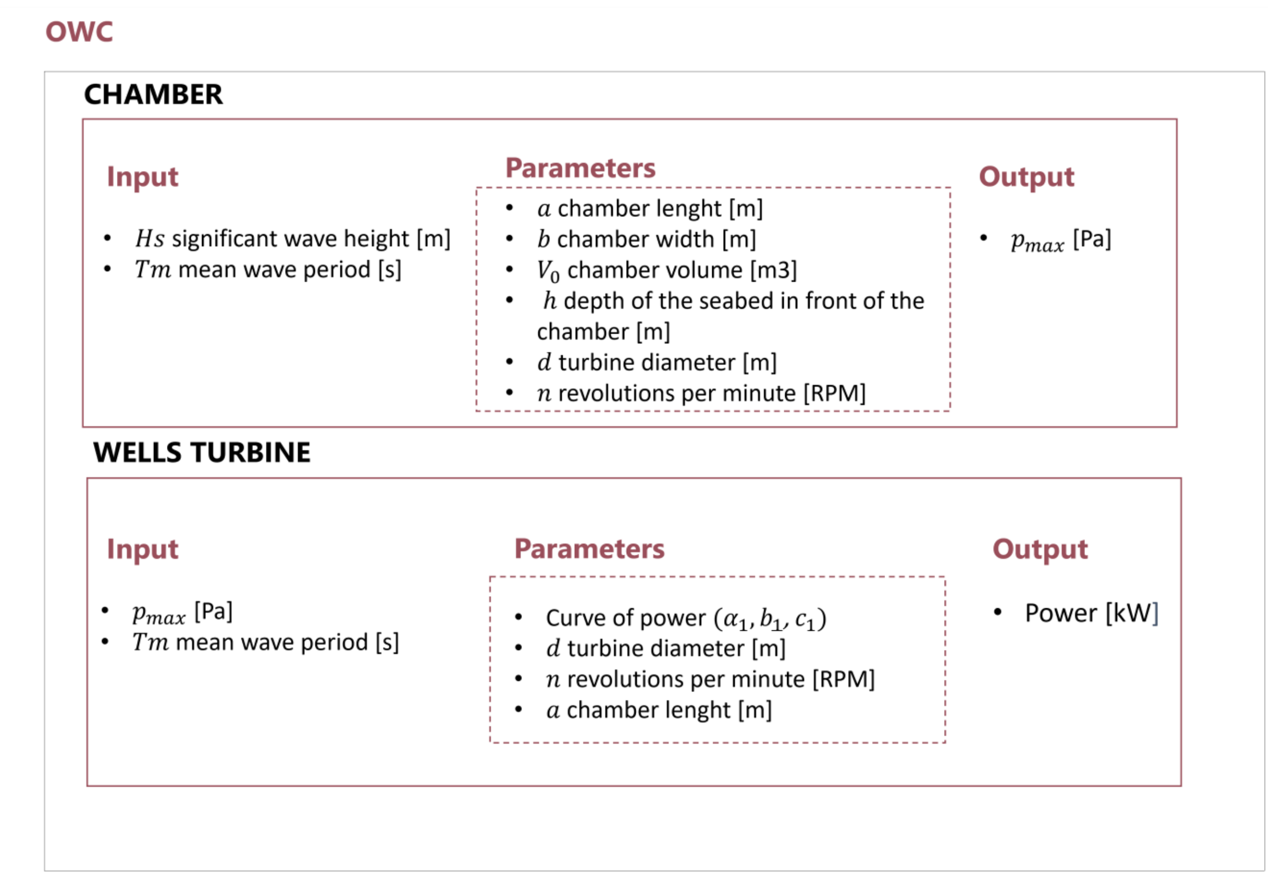

Figure 27. Black box representation of Oscillating Water columns in pyRES.

Results (*Figure 28* and *Figure 29*) were validated against those calculated by TRNSYS [6]. The quarter-hour difference in computed power output for the whole year is always in the range of [−2.05:1.456] mW.

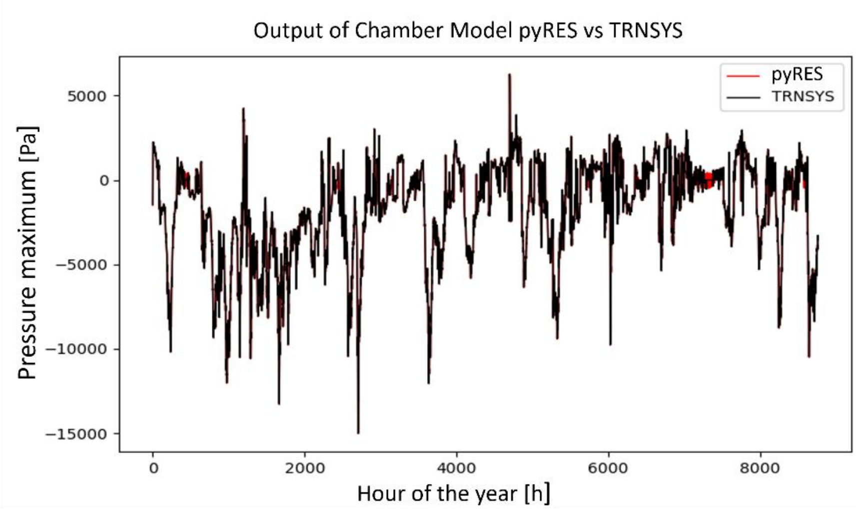

Figure 28. Comparison between pyRES and TRSNSYS models of a Chamber.

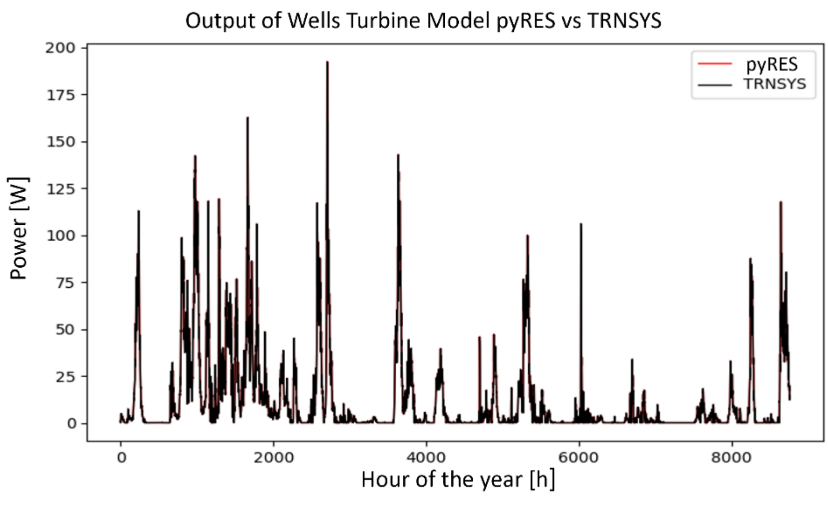

Figure 29. Comparison between pyRES and TRSNSYS models of a Wells Turbine.

Internal combustion engine (ICE) and combined heat and power (CHP)

in pyRES the modelling of an ICE and a CHP is based on the TRNSYS Type 120 and Type 102 [6][12][13][14]. The model is based on fuel consumption-power curve obtained from the technical data sheet. For each value of the power production P within the operating range of the engine (P_{min} , P_{max}), this curve provides the fuel consumption (The power P is divided by the rated power P_{rated} of the engine).

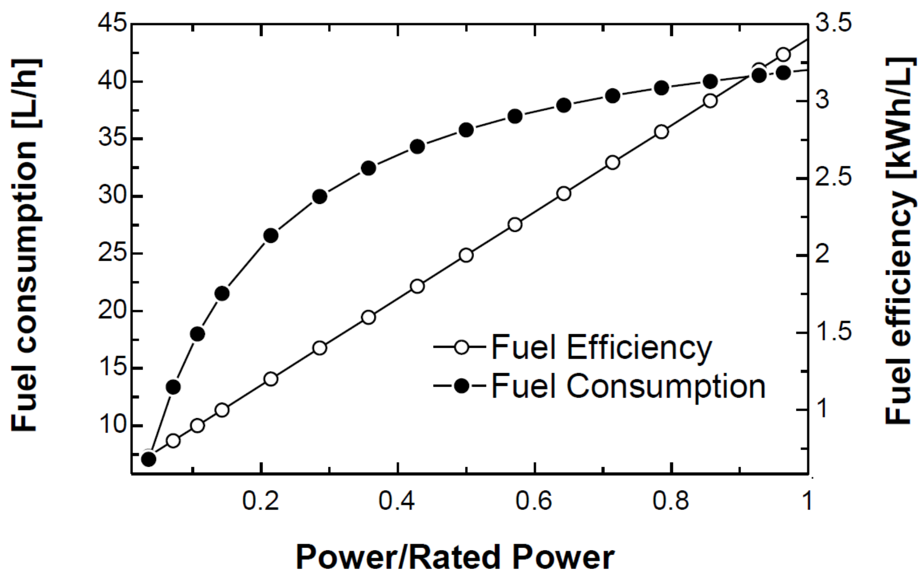

Figure 30. Example of Fuel efficiency and fuel consumption-power curves for an ICE [6].

The ICE model reconstructs the power curve represented in *Figure 30* by interpolating a set of power-consumption pairs available on the technical data sheet and providing the relationship (36). Given the power P delivered by the engine during the period t, the model calculates the fuel efficiency η_{fuel}, the electrical efficiency η_{el}, and the dissipated thermal power H according to equations (37), (38), and (39).

$$cons_{fuel} = f(P/P_{rated}) \tag{36}$$

$$\eta_{fuel} = \frac{P * t}{fuel_{cons}} \tag{37}$$

$$\eta_{el} = \frac{P * t}{\rho_{fuel} * lhv * fuel_{cons}} \tag{38}$$

$$H = P * \left(\frac{1 - \eta_{el}}{\eta_{el}}\right) \tag{39}$$

Where:

- ρ_{fuel} fuel density
- lhv lower heating value of fuel

The same model is used to simulate the behaviour of a CHP. In CHP operating mode, the dissipated thermal power H coincides with the recovered thermal power. The model can simulate more than one generator set at the same time and is integrated with a controller to match the electrical or thermal load D. CHP can operate in two modes, one mode follows the electrical demand, and the second mode follows the thermal demand. The controller is based on the logic represented in *Figure 31* . Given a set of engines (N_{min}, N_{max}) with minimum, maximum, and rated power $P_{min}, P_{max}, P_{rated},$ respectively, the controller calculates the number N of engines to activate simultaneously and the power P_{set} that each engine must deliver to meet the load. Given the P_{set}, using the ICE/CHP model, the thermal power H and fuel consumption $cons_{fuel}$ are calculated. The controller set the power P and the optimal number of active engines N. The power curve is specific for each fuel. Library of fuels include petrol, diesel, natural gas, hydrogen, biogas, biomass, syngas with the possibility of customization.

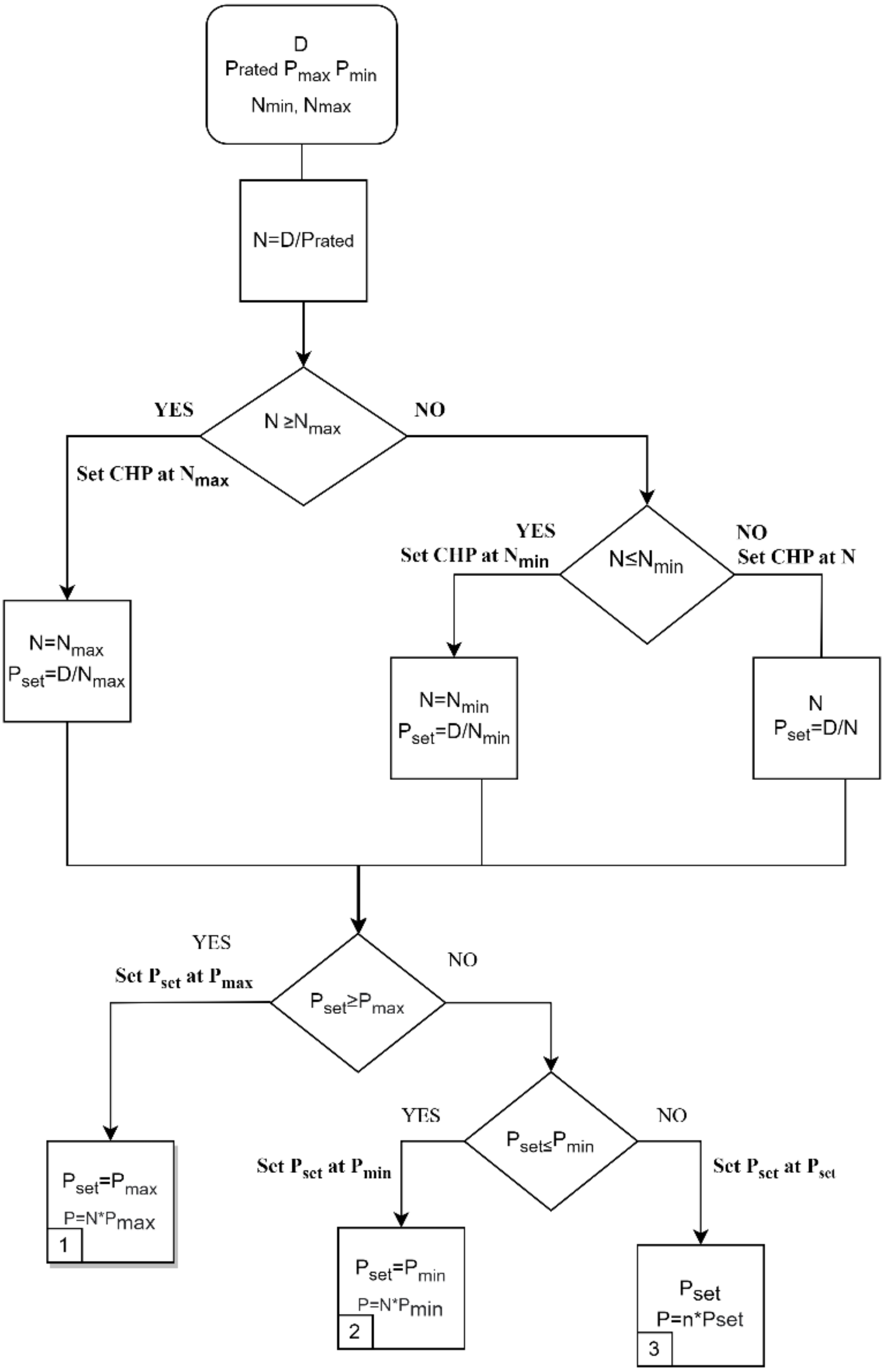

Figure 31. Default control logic of an ICE/CHP in pyRES.

The black-box representation of the model is illustrated in *Figure 32* where the inputs that do not change during the simulation are indicated as parameters.

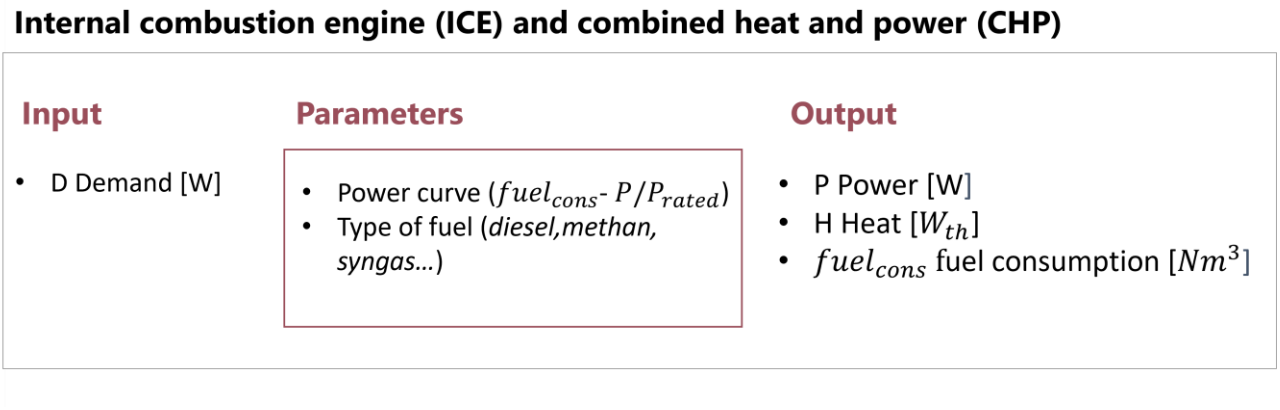

Figure 32. Black box representation of an ICE/CHP in pyRES.

Results were validated against those calculated by TRNSYS Type 120 and Type 102 [6]. The quarter-hour difference in computed power output for the whole year is always in the range of [−0.578:1.876] W.

3.5.2 Auxiliary components

Components that perform secondary operations related to energy production are generated by the superclass AuxiliaryComponents. These components are modelled with the aim of quantifying their energy consumption.

Gas Compressor

The modelling of a gas compressor in pyRES is based on TRNSYS Type 167 [6]. The model simulates the thermodynamic processes associate with compression stages according to ideal gas law (R, ρ_0). [15][16]. The compressor module calculates the power required (P) for compressing of $\breve{n}$ mole of gas from the initial pressure p_1 at final pressure p_2 (40) to estimate the electricity consumption associated with the compression process. The compression process is multi-stage and is approximated by a polytropic transformation of coefficient γ. Results were validated against those calculated by TRNSYS Type 167 [6]. The quarter-hour difference in computed power output for the whole year is always in the range of [– 0.890:2.786] W.

$$P = \frac{n_{parallel} * \check{n}}{3600} * \frac{(\gamma * R * T_1)}{(\gamma - 1) * \left(1 - \frac{p_1}{p_2}\right)^{\frac{(\gamma-1)}{\gamma}}} \tag{40}$$

Where:

- R the universal gas constant
- ρ_0 density of gas at standard conditions (1 atm, 0 °C)
- T_1 initial temperature of gas
- p_1 initial pressure of gas
- p_2 final pressure of gas
- $n_{parallel}$ number of compressors in parallel
- 3600 seconds in one hour

The black-box representation of the model is illustrated in *Figure 33* where the inputs that do not change during the simulation are indicated as parameters.

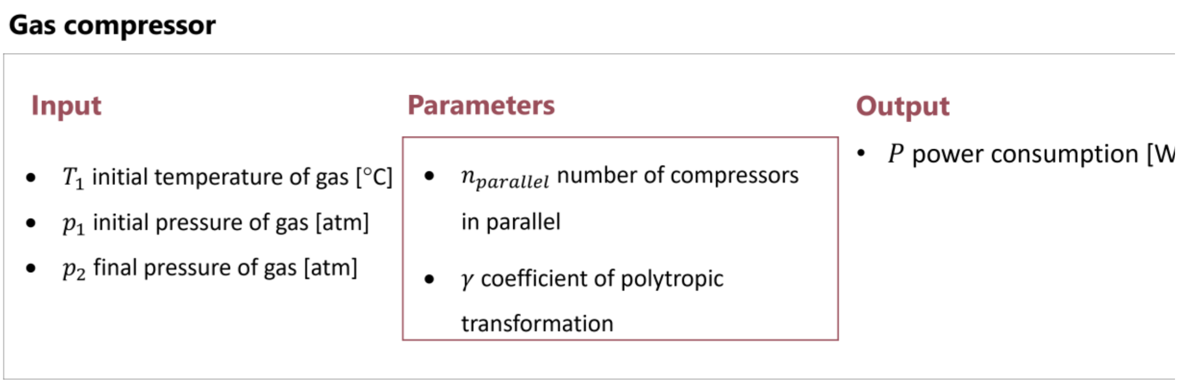

Figure 33. Black box representation of Gas compressor in pyRES.

Gas storage

The modelling of a gas storage in pyRES is based on TRNSYS Type 164 [6]. The model simulates the thermodynamic processes associate with the storage stage according to the ideal gas law (R, ρ_0) [17][18][19]. The gas tank module is based on the inlet ($V_{input} * \rho_0$) and outlet ($V_{output} * \rho_0$) mass balance (41). The module estimates the pressure level within the tank (p_2) according to equations (41)(42)(43).

$$\breve{V} * \rho_2 = \breve{V}_{input} * \rho_{input} + \breve{V} * \rho_1 - \breve{V}_{output} * \rho_2 \quad (41)$$

$$\breve{n}_2 = \frac{\breve{V} * \rho_2}{PM} \quad (42)$$

$$p_2 = \frac{\breve{n}_2 * R * T}{\breve{V}} \quad (43)$$

Where:

- $\breve{V}$ tank volume
- T tank temperature
- $\breve{V}_{input}$ Inlet gas flow rate
- $\breve{V}_{output}$ Outlet gas flow rate
- ρ_{input} initial density of inlet gas flow rate
- ρ_1 initial density of gas in the storage
- ρ_2 final density of gas in the storage
- $\breve{n}_2$ number of moles of gas in the tank
- PM molecular weight of gas

The black-box representation of the model is illustrated in *Figure 34* where the inputs that do not change during the simulation are indicated as parameters. Results were validated against those calculated by TRNSYS Type 164 [6]. The quarter-hour difference in computed output for the whole year is always in the range of [– 0.640:0.675].

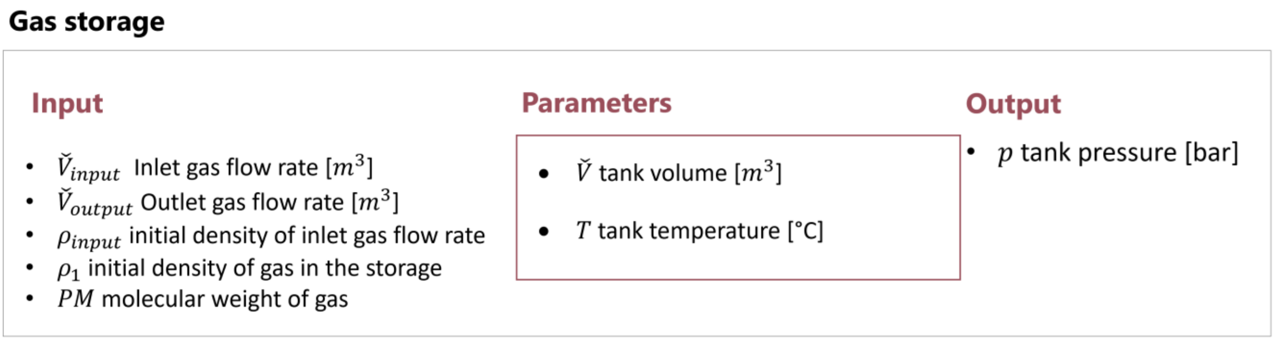

Figure 34. Black box representation of Gas storage in pyRES.

Biomass Gasifier

The biomass gasifier in pyRES is designed to estimate the electricity consumption and syngas production per kilogram of biomass. To simplify the description of the thermo-chemical process involved in converting biomass into syngas, the module relies on manufacturer specifications (ε, c) rather than on the thermal-chemical equations. The modelling of a biomass in pyRES is based on following equations:

$$\dot{m}_{syngas} = \varepsilon * \dot{m}_{biomass} * \frac{lhv_{biomass}}{lhv_{syngas}} \tag{44}$$

$$cons_{el} = \mathrm{c} * \dot{m}_{biomass} \tag{45}$$

Where:

- ε cold gas efficiency
- c specific consumption: electrical consumption per kilogram of processed biomass
- $\dot{m}_{syngas}$ steady-state production rate of syngas flow
- $\dot{m}_{biomass}$ steady- state biomass flow rate
- $lhv_{biomass}$ lower heating value of biomass
- lhv_{syngas} lower heating value of syngas
- $cons_{el}$ electrical consumption

Assuming that input biomass and output syngas properties at a specific working point (steady-state) are provided by the manufacturer, the module calculates the syngas production. This model offers advantages such as simple equations, short computation times and eliminates the need for experimental activities. However, this module is only valid under the assumption that the gasifier consistently operates at the same specific working point. The model does not account for variations in the thermos-chemical performance based on the specific characteristics of the input biomass or the environmental conditions. The black-box representation of the model is illustrated in *Figure 35* where the inputs that do not change during the simulation are indicated as parameters.

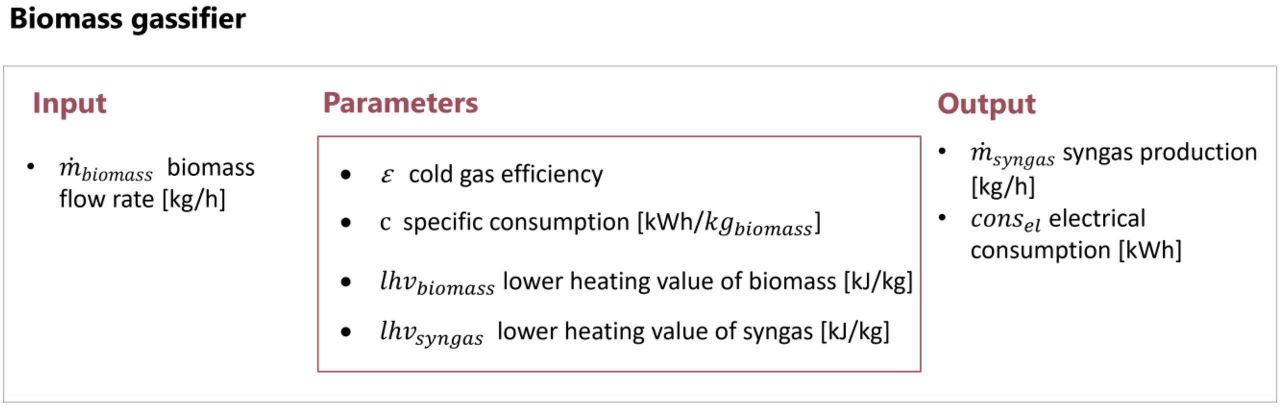

Figure 35. Black box representation of Biomass Gassifier in pyRES.

Results were validated using experimental data obtained from literature sources[20][21]. The quarter-hour difference in computed output for the whole year is always in the range of [− 2:5].

3.5.3 Storage systems

Currently, the storage systems in pyRES exclusively comprise conventional batteries.

Batteries

In contrast to electrochemical models which are based on descriptive equations for chemical-physical processes or on circuit laws for equivalent circuit models, the modelling of an electrochemical battery in pyRES relies on a system of two equations (46).The first equation governs the conservation of energy stored in the battery during transient conditions, whereas the second equation establishes the relationship between the battery voltage and state of charge considering as a parameter the operating temperature. The independent variables are the charge current i and the operating temperature T, while the dependent variables are the voltage v and the final state of charge q. At each time step, first, the state of charge q is calculated based on the charge current i, second the voltage v is calculated based on the temperature.

$$\begin{cases} q = q_i + \dfrac{i * t}{q_{max}} \\ v = v(T, q) \end{cases} \tag{46}$$

Where:

- q state of charge
- q_i initial state of charge
- q_{max} total capacity
- i current
- t time of current i
- T Ambient temperature
- $v(T, q)$ voltage-capacity relationship for the temperature T

The aim is to simulate the battery considering temperature variations to predict the state of charge and the amount of energy stored and supplied by the battery. The Curves characterizing battery's behaviour during the discharge and charge processes at specific temperatures are provided as input. For example, in *Figure36*, battery's behaviour is characterized for temperatures -20, -10,0,10 and 25 °C. The voltage- state of charge relationship is exclusively known for these specified temperatures. Using these curves and assuming a linear behaviour, the model extrapolates the relationship between state of charge and voltage for each temperature within the range T_{min} and $T_{max.}$ This range represents the minimum and the maximum temperature at which battery's behaviour is characterized according to the datasheet, in this case, (-20°C,25°C). The relationship between voltage and state of charge for all temperatures within a specific range is built by interpolating the two closest available curves according to equation (47). In *Figure36* the curve for a temperature of 15 °C is obtained by interpolating curves for temperature of 10 and 25 °C, the curve for a temperature of 5 °C is obtained interpolating curves for temperature of 0 and 10 °C and so forth.

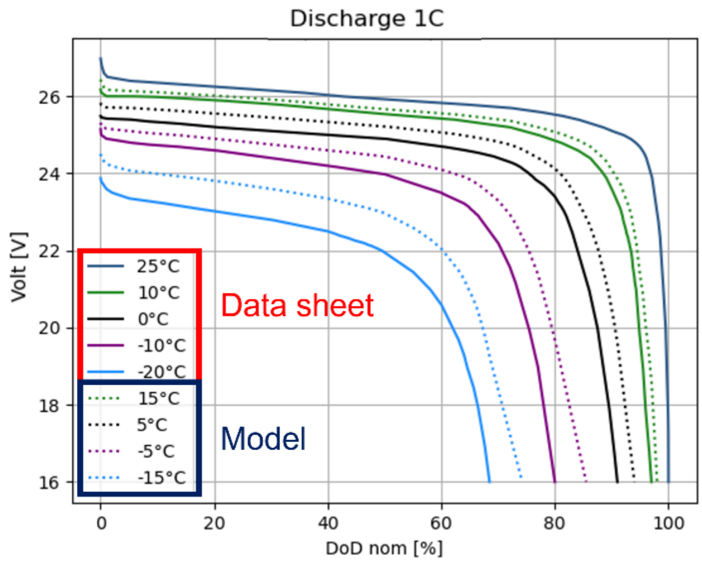

Figure36. Example of interpolation Of Lithium Battery Discharge Curves using Datasheet.

$$V = \frac{(q - q_1) * v_2 + (q_2 - q) * v_1}{q_2 - q_1} \tag{47}$$

Where:

- q, V voltage and state of charge at the temperature T between T_1 and T_2
- q_1, V_1 voltage and state of charge at reference temperature of T_1
- q_2, V_2 voltage and state of charge at reference temperature of T_2

Once the relationship voltage -state of charge considering as a parameter the operating temperature has been determined, the model is able to calculate the state of charge and the corresponding voltage level for each inlet and outlet current as represented in *Figure 37* for a lithium battery with a capacity of 100 Ah. The battery underwent cycles of charging and discharging with variable current ranging from -30 to 40 A.

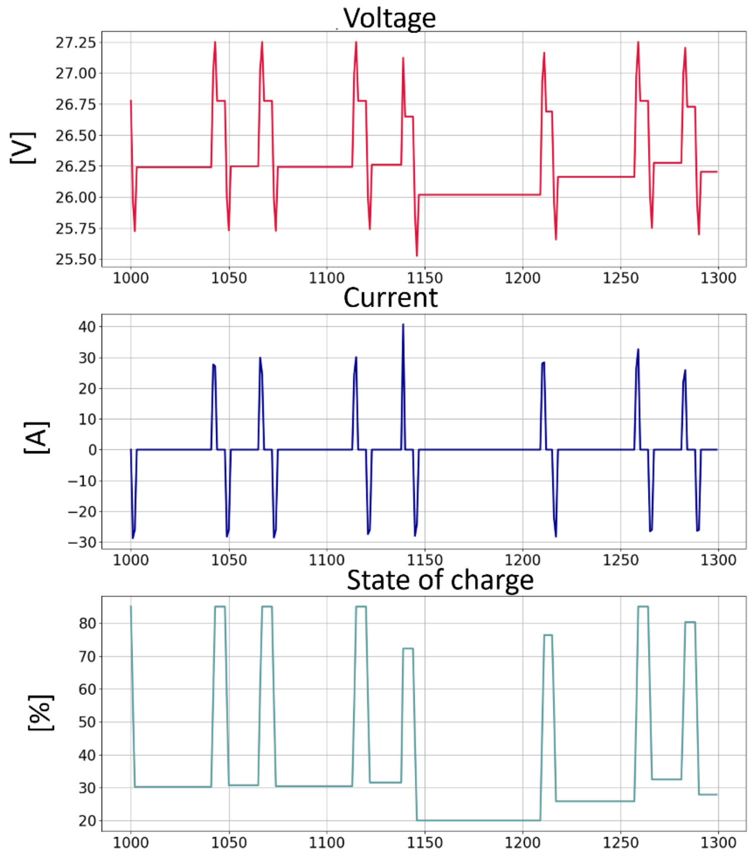

Figure 37. Variations in voltage, current and state of charge for a Lithium battery with a capacity of 100 Ah.

The battery is integrated with a controller to regulate maximum input and output currents and ensure that the state of charge always remains within the minimum and maximum values specified on the datasheet. One of the main advantages of this model is that it only requires input parameters that are available from the data sheet. This makes it possible to simulate the battery's performance without conducting experimental tests. Whereas it does not simulate the Peukert effect, aging, or memory effect, the model is suitable for rough calculations and initial analysis when detailed electrochemical reactions cannot be simulated [22]. The black-box representation of the model is illustrated in *Figure 38* where the inputs that do not change during the simulation are indicated as parameters.

Batteries

Input	Parameters	Output
• i current of charging (+) /discharge (-) [A] • T Ambient temperature [°C]	• q_i initial state of charge [%] • q_{max} total capacity [Ah] • I_{max} maximum current [A] • $v(T,q)$ voltage-capacity relationship for five temperature T_1, T_2, T_3, T_4, T_5	• V voltage [volt] • q State of charge [%]

Figure 38. Black box representation of Batteries in pyRES.

3.5.4 REC members

Consumer

The consumer class allows the management of a demand curve to simulate the behaviour of an energy-consuming user, supporting the simulation loads. A schematic representation of a consumer in pyRES is illustrated in *Figure 39*.

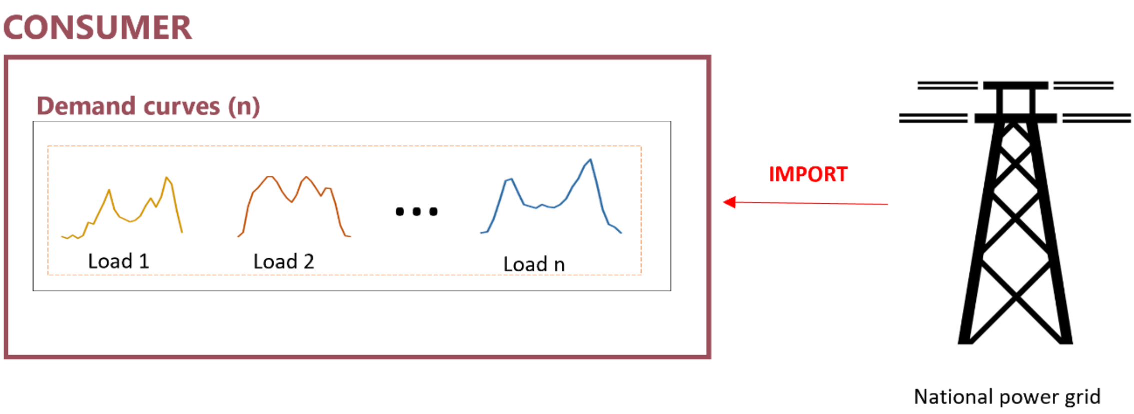

Figure 39. Consumer modelling in pyRES.

Prosumer

The prosumer class groups instances generated by other classes to combine one or more production systems, one or more consumers, and a storage system. A schematic representation of a prosumer in pyRES is illustrated in *Figure 40*.

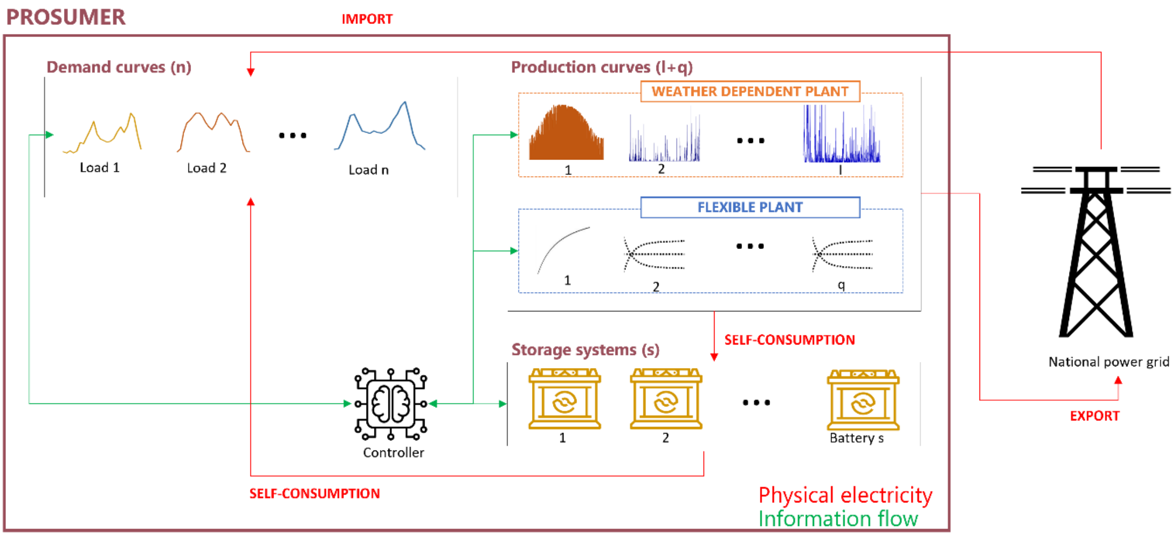

Figure 40. Prosumer modelling in pyRES.

Prosumer class can simulate a wide range of configurations, spanning from simple scenarios with a single consumer connected to one production system, to more complex scenarios with multiple consumers having flexible loads connected to multiple production systems and different storage systems. This versatility is achieved by incorporating by default control logic in the Prosumer class to manage the integration of flexible systems and weather-dependent systems. Control logic is designed to maximize the self-consumption SC (*Figure 41*). The controller optimizes the operation of flexible plants in coordination with weather-dependent systems. The control Flexible plants are maintained at a minimum operational level or, when feasible, switched off when demand is met by renewable sources. Conversely, they are activated and, if needed, operated at maximum capacity when renewable production falls short of meeting demand. Control variables include prosumer demand D, renewable production P_{ren}, production from flexible plants P_{flex}, maximum production of flexible plants P_{max}, $minimum$ production of flexible plants $P_{min.}$ Controller adapts production of flexible plants and calculates self-consumption SC, export to the grid $Export$ and import from the grid $Import$. The output is object designed to simulate a prosumer, estimating energy flows (production, self-consumption, exchanges with the grid), economic performance (savings on bills, revenue from energy sales, incentives, purchase and maintenance costs, cash flow, and economic parameters such as NPV and PBP), and environmental impacts (reduction of greenhouse gas emissions).

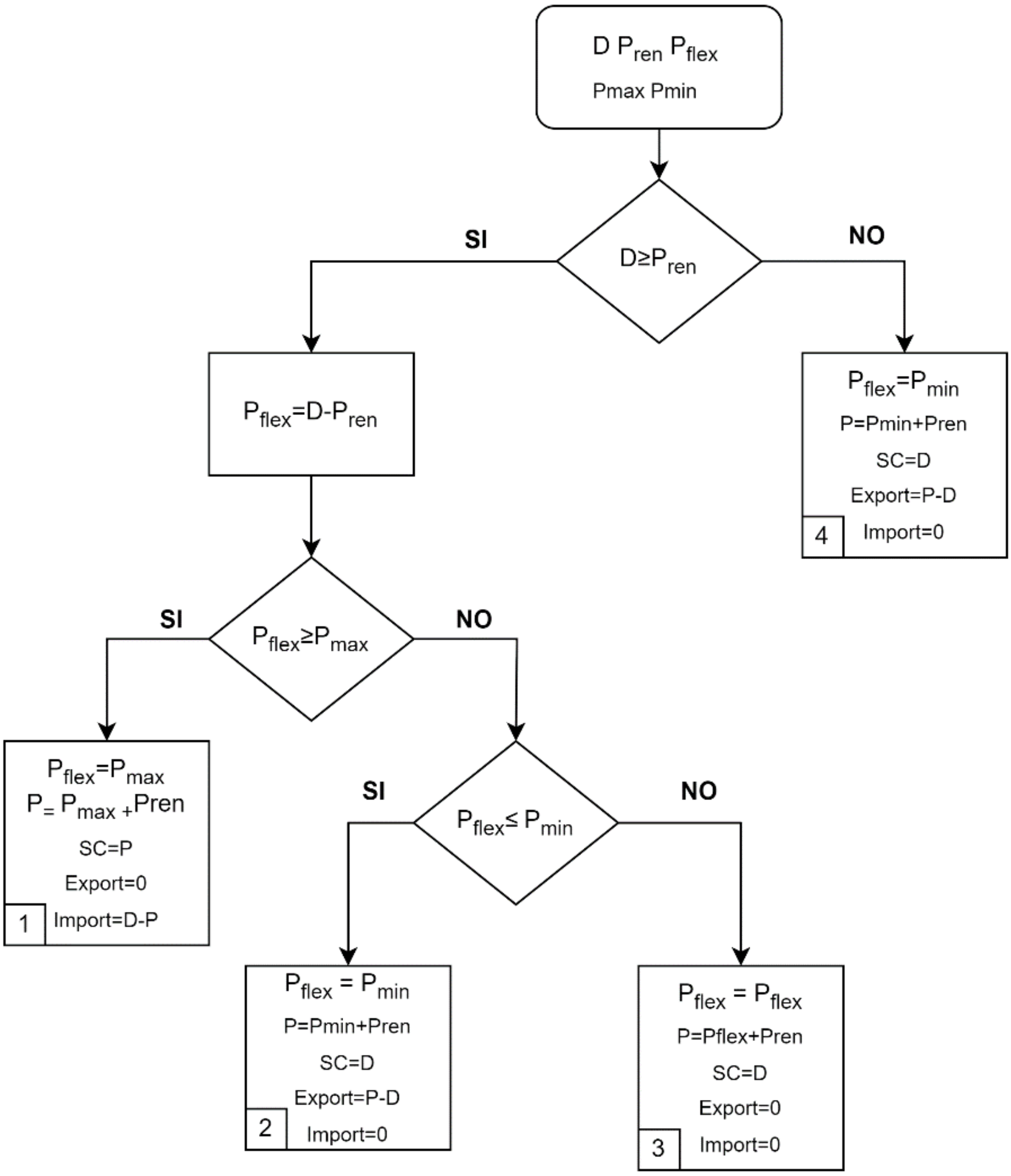

Figure 41. Default control logic of a prosumer in pyRES.

REC

A REC is simulated through the integration of prosumers and consumers combining instances from *Prosumer* and *Consumer* classes. A schematic representation of a REC in pyRES is illustrated in *Figure 42*. Energy flows, which include production, prosumer's self-consumption, exchanges with the grid and shared energy, are evaluated based on an energetic balance.

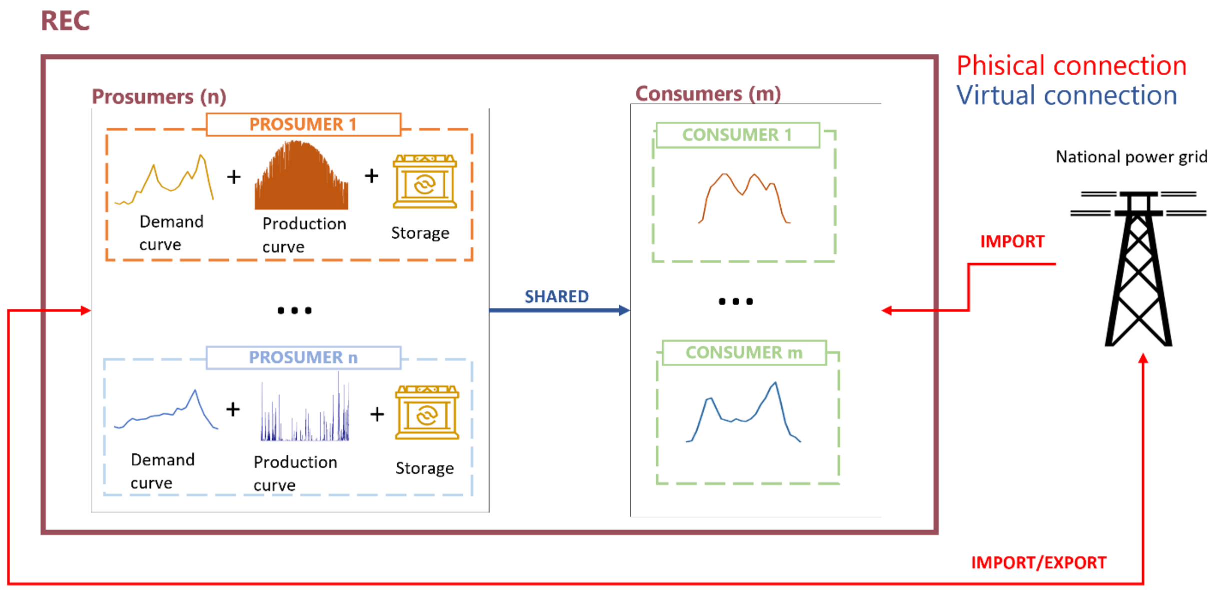

Figure 42. REC modelling in pyRES.

Given a community with a number of consumers, prosumers, and renewable plants of the REC, equals n_{con} , n_{pro} , n_{plant} respectively, for each time step t of a reference period T, and for each prosumer j, the selfconsumption is equal to the minimum value between the renewable productionP_j^t and the demand (D_j^t) . Additionally, for each prosumer the exported power $Export_j^t$ and imported power $Import_j^t$ from the network are calculated. The shared power SH_{REC}^t is calculated as the minimum value between the sum of the renewable production from REC plants P_m^t and the total export from all prosumers, and the sum of consumer demand and the total import from all prosumers. These definitions are represented by the following compact formulation:

$$SC_j^t = \min\left(P_j^t; D_j^t\right) \qquad \forall\, j \in \left(1, n_{pro}\right), \forall\, t \in (1, T) \tag{48}$$

$$Export_j^t = P_j^t - SC_j^t \qquad \forall\, j \in \left(1, n_{pro}\right), \forall\, t \in (1, T) \tag{49}$$

$$Import_j^t = D_j^t - SC_j^t \quad \forall\, \text{j} \in \left(1, n_{pro}\right), \forall\, \text{t} \in (1, T) \tag{50}$$

$$SH_{REC}^t = \min \left(\sum_j^{n_{pro}} Export_j^t + \sum_m^{n_{plant}} P_m^t \,;\, \sum_k^{n_{con}} D_k^t + \sum_j^{n_{pro}} Import_j^t\right) \forall\, \text{t} \in (1, T) \tag{51}$$

Where:

- n_{pro} number of prosumers
- n_{con} number of consumers
- n_{plant} number of renewable plants
- SC prosumer self-consumption
- P renewable production
- D demand
- $Export$ power exported to the grid
- $Import$ power imported from the grid
- SH shared power

The default controller (*Figure 43*) calculates the shared power SH and power exchanged between REC members and the national grid ($Import\ and\ Export$). Input variables include the total demand of prosumers and consumers D, and surplus of prosumers S_{pro}.

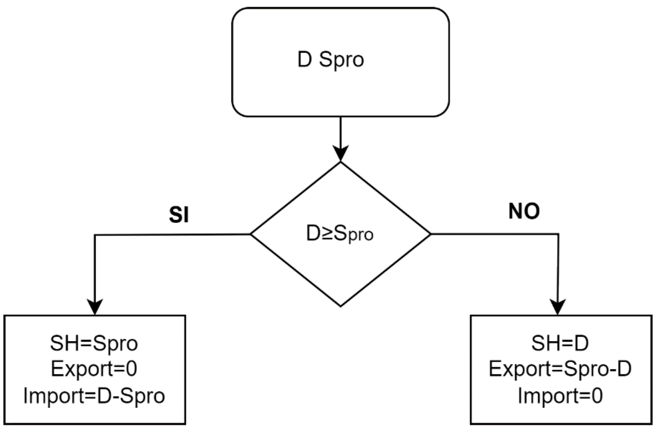

Figure 43. Default control logic of a REC in pyRES.

Based on self-consumption of each prosumer and the shared power, savings on the energy bill and incentives are calculated according to GSE rules. Additionally, the REC cash flow is calculated considering investments and operating costs. Finally, economic parameters such as NPV, and revenue for each individual member are calculated based on the business and organizational models. The output of pyRES is a dynamic analysis of energy performance with a temporal resolution of up to 15 minutes, and the economic analysis of the digital twin. Results of the analysis provide precise details about how the REC perform over time and what economic benefits are associated with different design and operation choices.

3.5.5 Profiling of transient energy demand

Included in this category a class that estimate the quarter-hourly curve of the energy demand of users for whom real consumption data are not available. This class provide a demand curve as output. The purpose of the model is to reconstruct a quarter-hourly demand curve when real consumption data is not available. The demand curve is reconstructed starting from a minimum amount of information requested in the form of a questionnaire, which includes:

1. Contracted power [kW]
2. Estimate of Annual Consumption [kWh]
3. Building area [m2]
4. Number of residents
5. Weeks of usage
6. Type of usage (habitual -non habitual)
7. Seasons or period of usage
8. Type of stove: gas or electric
9. Cooling and heating with air conditioners (not present or present)
10. Total power of air conditioners (BTU/h)
11. Monthly consumption data in the three hourly bands [kWh] (available from energy bills)

As represented in *Figure 44* the model is based on an information compression algorithm (Auto-Encoder) and on the association between the compressed latent space and the questionnaire data through neural networks: the Multi-Layer Perceptron (MLP).

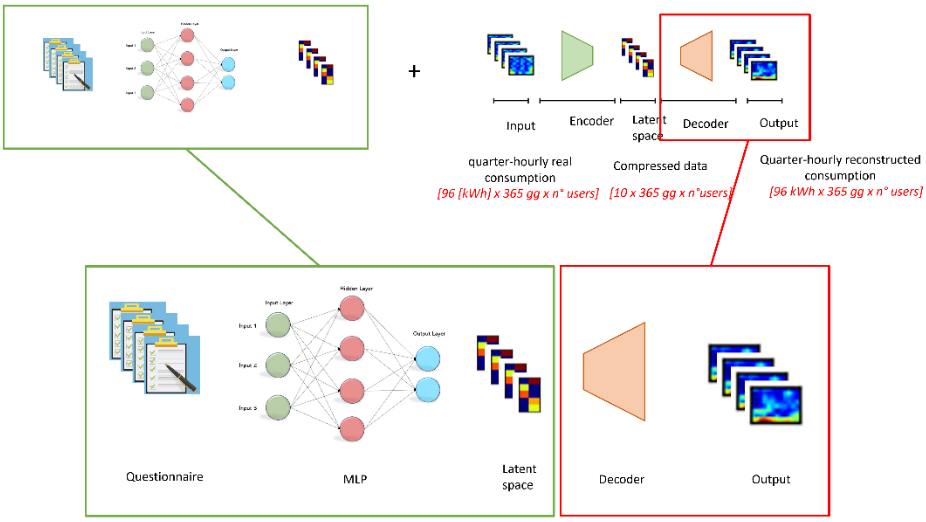

Figure 44. Algorithm structure for profiling of transient energy demand in pyRES.

An Auto-Encoder (AE) is a machine-learning model developed for the compression of input data through a neural network that produces a reduced dataset in a compressed latent space. The model also involves the presence of a second neural network that acts as a decoder, capable of reconstructing the initial data from the compressed data in the latent space. A daily consumption curve consists of 96 values: one consumption data for each quarter-hour of the day. The logic of the algorithm is to represent this curve with only 10 values, thus compressing the data while limiting information loss. To enhance the accuracy of the compression process, the data is divided into four periods of the year, or seasons, and to make the most of the similarity among data belonging to the same month, the data is associated through boxplots and clustering (*Figure 45*).

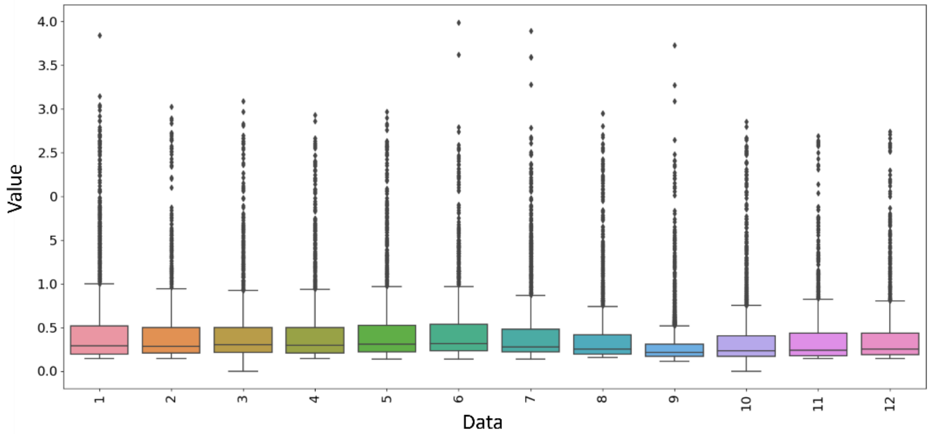

Figure 45. Boxplot for the association of months with seasons.

The year is then divided into four seasons and an AE is trained for each identified season. The initial demand cruves are then normalized. Each value is normalized with respect to a reference power, equal to 6.5 kW. This reference is usually the maximum value for a single-phase system with a residential usage. Thanks to this methodology, it is no longer necessary to establish a connection with all 96 quarter-hourly power values associated with consumption, but only with the 10 compressed indices. These indices are later decompressed to obtain the demand curve. The problem of assigning values is significantly simplified. The ten indices, represent the degrees of freedom of demand curve. The connection between the compressed space and the questionnaire is not direct. To correctly associate the survey results with the latent space, specific neural networks, the Multi-Layer Perceptron (MLP), are employed. Four MLPs are trained to establish the connection between the 10 questionnaire responses and the 10 values in the compressed space of the autoencoder. For their training, a sample of 10 representative curves for each user is selected, and a Euclidean clustering algorithm is applied. At the end of the reconstruction of the new 96 quarter-hourly data, profiles corresponding to each season are obtained (*Figure 46*). In the post-processing phase, the demand curve for each hourly bands is corrected to adapt it to real consumption. Finally, starting from the monthly profiles, the annual consumption profiles are reconstructed.

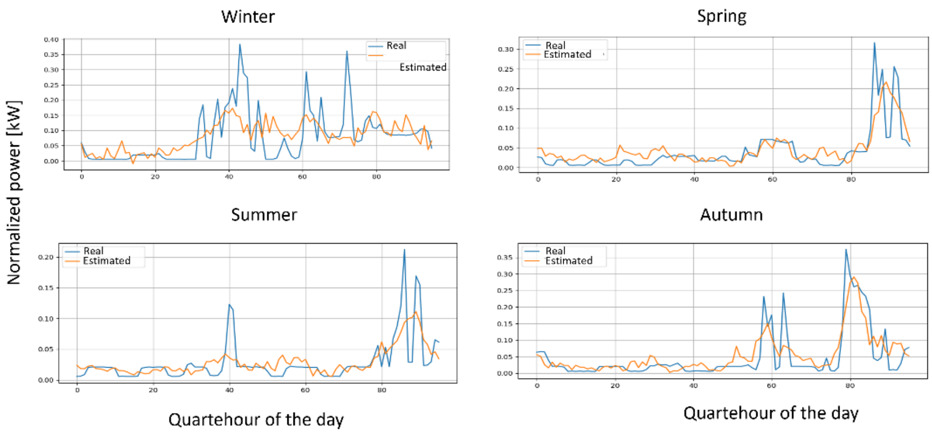

Figure 46. Direct comparison between the results and the real demand curves for the four seasons.

The training of the compression system applied to winter month profiles shows deficiencies in reconstructing load curves. Some incorrect data are identified, later discarded, presumably due to measurement errors or anomalies in the meter. As a result, the corresponding dataset narrowed, which may have affected the quality of profile predictions in this season, an issue not observed in other periods of the year.

3.6 Control logic

The control logics in pyRES can be classified into:

- *Default control logics*: They are already integrated into the pyRES classes and are specific to the object, as previously illustrated in the case of the Internal Combustion Engine (*Figure 31*), battery, prosumer (*Figure 41*) , and REC (*Figure 43*).

- *Customized control logics*: are system-specific and can be designed by the user as functions of an existing class or as additional classes. The following chapters illustrate three analyses conducted in pyRES, in each case, a customized control logic is designed based on the context and technologies involved. In Chapter 4, describing the implementation of a REC in an island context, the control logic aims to optimize the integration between the REC and a desalination unit, ensuring efficient desalination operation, avoiding repeated and close cycles of start-up and shutdown, and maximizing the absorption of energy produced by the solar systems. Control variables include water demand and production, as well as the water level in the storage coupled with the desalination unit. In Chapter 5, discussing the feasibility of installing batteries for a prosumer, the control logic aims to maximize the prosumer's self-consumption. Control variables include photovoltaic production, demand, and battery charge level. In Chapter 6, describing the integration between solar panels and biomasses, the control logic aims to optimize the integration between flexible production systems and weather-dependent systems, ensuring efficient cogenerator operation and maximizing the absorption of energy produced by the solar systems.

3.7 Internal implementation

The process of building a digital model in pyREC is divided into 5 phases: data import, prepocessing and interface, create model, optimization, run and save results. pyRES enable data stored in CSV and JSON files to be prepared for the analysis, and the results of optimisation to be analysed and/or saved. The internal workflow is shown below (*Figure 47*).

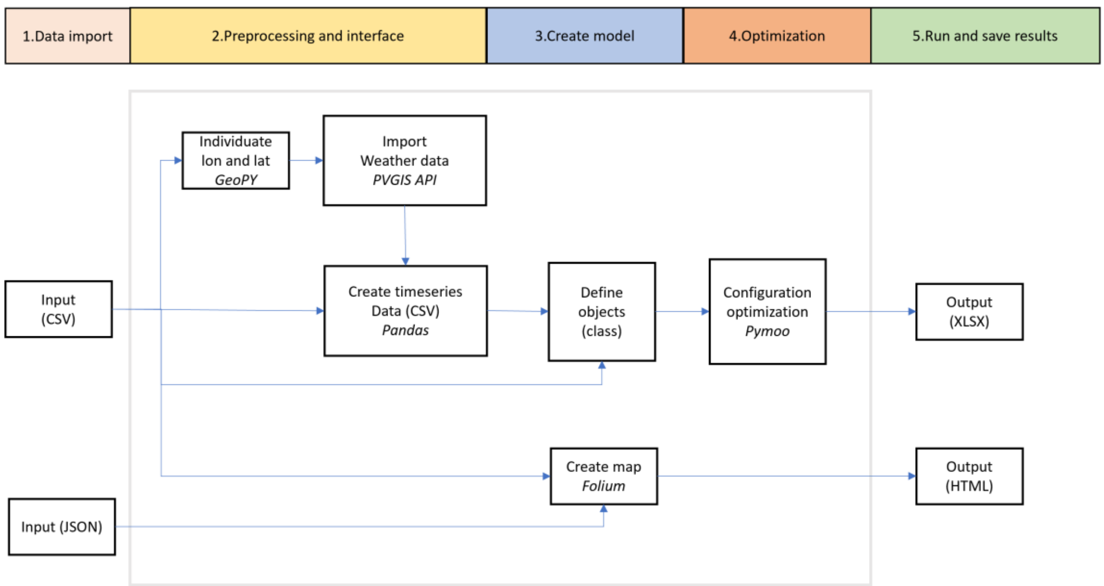

Figure 47. Internal workflow of pyRES and data structures.

pyRES processes input data in either CSV or JSON formats. Demand curves are in CSV format while geodata are in JSON format. The interface with python package pandas is used to elaborate data in CSV format while JSON data is processed by the Folium and GeoPy package and provided as output in HTML format. Weather Data are automatically downloaded by using PVGIS API. The creation of a digital twin involves the selection of classes that define the key attributes and characteristics of the physical object or system being replicated. Input Data is restructured by pyRES classes into DataFrame which is a data structure. Restructured data are saved, plotted, or send to the backend. The pymoo package is currently used in the backend to set an optimization problem. All parameters, sets, constraints, and decision variables are defined as pymoo objects. Results are extracted from pyomo into an XLSX dataset, ready to be analysed or saved. pyRES allows to formulate an optimization problem. Independent variables frequently include the capacity of production systems, storage systems and the number of REC members. Objective functions frequently include maximizing energy and economic performance, and sometimes minimizing environmental impact. These are multi-objective optimization problems where each objective function is associated with a specific techno-economic aspect of the REC. Energy objectives are often represented by self-consumption or shared energy. Economic objectives are often represented by a cost function that includes investment, operation, and maintenance costs. Finally, environmental objectives are often represented by a function estimating greenhouse gas emissions.

3.8 Potential and future development

Development of pyRES represents an effort to expand tools for energy analysis within RECs and, in a broader context, distributed generation systems. pyRES is completely open-source, providing unrestricted access and usage, and it will be available through official Python code-sharing platforms. Its applications encompass educational and research objectives, as well as providing support for techno-economic assessments during the design phase of new RECs. pyRES supports the design of RECs by calculating their performance and automating the analysis and management of the substantial volume of data related to real user consumption. Thanks to its flexible structure, pyRES has extension and development potential, as it can be gradually improved and enriched with new modules. Potential developments include:

1. Expanding functionalities by adding forecasting capabilities through the development of modules for energy demand, weather conditions, and energy price forecasting.
2. Extending the library by developing modules for the simulation of geothermal and hydroelectric systems.
3. Accelerating the control logic design process through the development of machine learning modules

3.9 Study case examples

Three case studies implemented in pyRES, following the methodology outlined above, are presented in the following chapters:

- In the first study the REC model is studied in a minor island disconnected from the national grid, with strongly seasonal energy load and water demand. This is a typical Mediterranean scenario where energy demand is covered by Diesel gensets and water supply is provided with tankers. The implementation of RES is investigated, exploiting the current REC model of incentives. Two sub-optimal REC configurations were defined using time-dependent simulations on pyRES. Results show the economical unfeasibility of REC when there is a poor mix of users. In contrast, REC can achieve economic profitability including industrial demand of a desalination unit (DES). The increase of self-consumption guaranteed from the DES allows to increase the NPV of the community and results in major cuts in CO_2 emissions (60% of those related to water supply and 10% of those from Diesel gensets) and a reduction of fuel costs of 22%. This method can be applied to investigate the performance of a REC in a local environment and help stakeholders in planning the expansions of RECs on the territory.

- In the second work the REC model is studied in a small town. The challenge is to stress the issues of assembling a profitable REC in this scenario, discussing the proper selection of prosumers and consumers, solar panels and battery storage. Following the guidelines for RECs, a prosumer was found with a sufficiently high load and availability for a PV plant. The PV plant was sized according to the load of the prosumer finding the optimal combination of

VAN and self-consumption. Then a REC was assembled around this prosumer finding optimal combinations of consumers to further increase VAN and self-consumption, and thus the economical return through decrease of expenses and increase of incentives. Energy metabolism of the REC and stand-alone prosumer were then also analysed in presence of battery energy storage (BES), highlighting the impact on self-consumption, CO_2 emissions, CAPEX and OPEX of both scenarios. Major conclusions include the negative impact of BES on the economy of the REC and the benefits of the REC on energy costs for the consumers. The presence of BES leads to a 55% increase in initial costs, coupled with a corresponding approximately 25% decrease in NPV. The REC generates a cash flow of approximately of 50 000 €. Finally, a sensibility analysis on these results was carried on discussing the effects of the fluctuations on the energy costs.

- In the third work the REC model includes a mix of production characterized by the integration of photovoltaic and biomass plants for cogeneration, several residential and commercial users and is in a city of Lazio Region in Italy. First, a territorial analysis is carried out to identify the energy demand and the availability spaces to install distributed generation plants. Second, the mix of consumers, the size of solar systems and combined power and heat fuelled by biomass is selected following a multi-objective optimization strategy. Modelling of biomass was developed for this work and validated against available experimental data and TRNSYS results. Energy, economic and environmental performance indices highlighting the impact on shared energy, CO_2 emissions, capital and operating expenditure have been defined for the comparison between different configuration analysed. Results show that with a biomass cogenerator prosumers have minor economic interest in being part of a REC as the incentives are proportional to shared energy. Increasing their share of the REC revenue, on the contrary, reduces the appeal to normal users, resulting in a difficult balance.

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4. Challenges of renewable energy communities on small Mediterranean islands: A case study on Ponza island

4.1 REC as a transition model for the smaller islands

This work focus is on the technical aspects involving the optimal selection of users and prosumers and their integration into a local community [1] and the challenges of the implementation of RES on a minor island scenario[2]. To this aim, a geographically- and power- isolated case study was selected: a minor island not connected to the national power grid that also required clean water supply from the mainland. Ponza is in fact a small island that offers particularly challenging constraints and requires creative aspects that can help building a profitable REC. In what follows particular importance is in fact given to the implementation of a REC on Ponza together with a desalination plant. This operation increases the energy load of the island but allows to store excess of PV production in form of fresh water stored in a tank and in so doing to better mix with the highly seasonal load of the island. Even if the introduction of desalination systems in RECs is scarcely discussed, their integration with RES is quite-well documented. In fact, in Kasaejan et al. [3] the authors provided a review of latest findings in coupling RO desalination with solar energy providing a series of example applications with different TRL. More recently, Saidi et al. [4] discussed the performance of a solar-powered HDH desalination system. The authors carried out numerical studies and experiments to investigate how operating parameters affect freshwater production and the Gain Output Ratio (GOR). The numerical findings indicate that daily production of fresh water increases with the temperatures of the feed water and air in the humidifier, as well as the humid air temperature at the dehumidifier inlet. On the contrary, increasing the cooling water temperature in the dehumidifier has a negative impact on the system production of fresh water. Abedi et al. [5] investigated the integration of solar chimneys with HDH desalination systems, focusing on how the two systems need to be tuned to work together properly. Geng and Gao [6] discussed the integration of reverse osmosis (RO) desalination systems with Ocean Thermal Energy Conversion (OTEC) systems finding that a combined cooling desalination and power double Kalina cycle has higher net power output, thermal and exergy efficiency and SUCP. They also examined in detail the costs of all the components and the influence of different cycle parameters on its performance. Dezhdar et al [7] used TRNSYS to perform an optimization of a new solar-wind based energy system to produce clean water, electricity, cooling and heating with battery storage and fuel-cell-hydrogen tank and electrolyzer. They applied this concept to the city of Zanjan, exploring performance and optimization of the layout. They derived some best practice for sizing of components but still lacked a discussion on the high costs of this layout. Pietrasanta et al. [8] studied the integration of desalination with geothermal energy, developing a tool for the selection of the best configuration of the desalination system (RE vs MED) and the geothermal powerplant (single vs double flash) providing a full economic comparison of the various solutions. This manuscript investigates the possibility of building a REC on a small Mediterranean island, addressing the challenges of sizing the PVs in a scenario where energy demand increases by a factor of 5 during summertime and exploring how the current model of revenues for RECs in Italy are not viable in this context. However, including a desalination system (DES) in the mix of electric loads with a storage tank the latter can be used to store clean water and in so doing balancing the energy and financial flows of the REC and reducing the overall CO_2 emissions of the island. The combination of a REC incentive system based on self-consumption rather than renewable energy production, the DES, their interactions and the following drop in emissions and fuel consumptions are the major novelties of this contribution. Previous literature in fact reports on the use of a DES to achieve peak shaving in Diesel genset operations [9] while in this work it is demonstrated how the storage tank of the desalinator can store excess of PV production in form of clean water to be used later during the year. Moreover, this REC incentive system potential is not yet investigated in open literature. This work is organized as follows: first, an overview on the Ponza case study is given, then the numerical methodology for REC modelling is discussed, then two scenarios are considered, without and with desalination system. Finally, conclusions are drawn.

4.2 Case study: Ponza island

The case study is the island of Ponza, in the Mediterranean Sea, with a total surface of 7.5 km^2. The number of inhabitants is remarkably dependent on its touristic vocation and spans from 3,300 in winter to 55,000 in summer. This circumstance leads to severe issues in energy and water system management. Electric energy is supplied by two Diesel engine power stations. Respectively, a main power station of 6.2 MW with four engines, and a peak-shaving station with 2.6 MW installed power and two engines, typically operating only in summertime. On 31st December 2020, the total PV power installed was 300 kW, covering 3.4% of the electric load. In *Figure 48* the electricity demand during the year is shown and it is evident how during summertime the power demand peaks to more than 5MW, while during most of the year the power demand is between 0.5 and 1.5 MW.

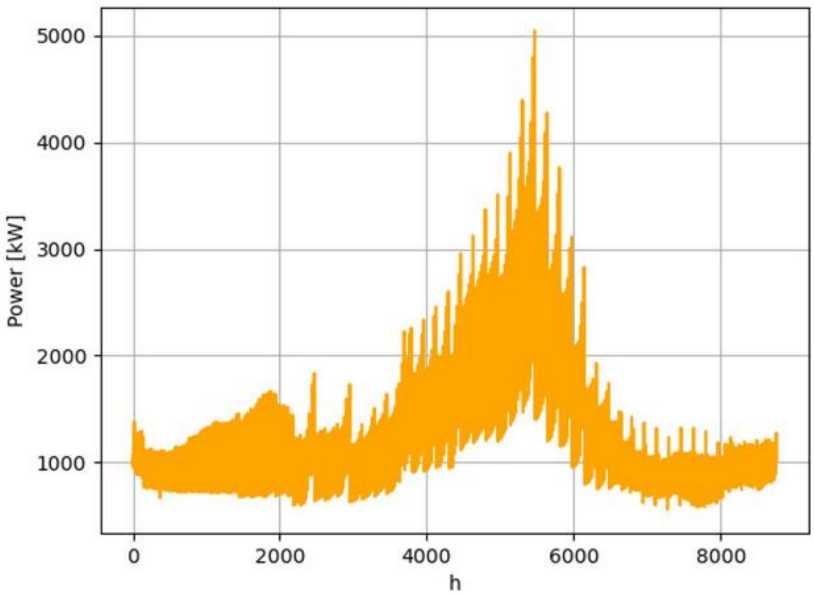

Figure 48. Electric power load of Ponza during the year [9].

Clean water is supplied by tanker ships from the mainland. The water demand amounts to 388,000 m3 per year corresponding to 229 ship trips and producing 2602 tons of CO_2, *Figure 49* [9].

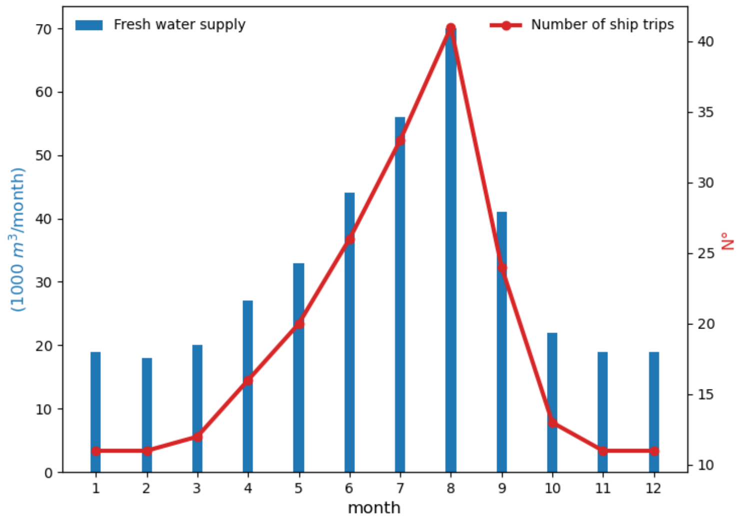

Figure 49. Clean water supply demand of Ponza [10].

The water distribution company responsible for the clean water supply on Ponza is scrutinizing the possibility of installing a reverse osmosis desalination plant with multiple units, and a total power between 300-350 kW, corresponding to a production capacity of 1500 m^3/day. A summary of the desalination system is given in *Table 5.*

Table 5. Desalination system description.

Desalination station	5 units x 300 m^3/day Water flow 5 x 12.5 m^3/h Electric power 5 x 70 kWp Global specific energy consumption 5.32 kWh/m^3

The introduction of a desalination plant on Ponza would of course increase the energy load (the increase is estimated for reverse osmosis plants between 4-6 kWh/m^3)[11][12]. So, the introduction of the desalinator should be compensated using RES. When dealing with RES in Ponza context, a series of restrictions need to be considered, regarding land and sea usage, environmental and historical heritage protection laws. The configuration of the REC must comply with the relevant legislation: European council directives [13][14] included Ponza and its surrounding seabed in the official list of SPAs (Special Protection Areas) and SIC (Site of Community Importance), respectively. The management plans of these areas are conferred to the regional institution. On Ponza, the realization of a renewable production plant is ruled by the national Legislative Decree 28/2011[15]. To conclude land availability and environmental regulations are factors limiting the possibility of installing large-size on-shore wind turbines and off-shore installations are prohibited. The conclusion is that PVs are basically the only viable RES available to assemble a REC on Ponza. The available solar radiation on this site was derived from quarter-hour data from PVGIS [16], that for a 1kW PV module estimates an annual energy production of 1468 kWh, with a year-to-year variability of 43 kWh.

4.3 REC prosumers and consumers characterization

The selection of potential REC members for Ponza relied on a GIS analysis of *Cala dell'Acqua* residential area (where the DES is supposed to be installed). This analysis allowed to identify four classes of actors for the REC: residential prosumers, residential consumers, restaurants, and hotel prosumers. For each of them, a typical electric load was provided by Ponza electric company that operates on the island and are in quarter-hourly format and used for the current study. PV plants were sized according to the roof and parking space availability on Ponza restaurants and hotels. For residential buildings, it was assumed a PV size of 3kW for all the prosumers. In the REC assembly phase, residential consumers and prosumers were treated as two separate classes, each spanning from 0 to 400 members. However, the sum of possible residential consumers and prosumers is set to a maximum of 400, given the total amount of residential spaces in that area, with the underlying idea that each of them can enter the REC as a prosumer or a consumer. The maximum number of restaurants and hotels was selected according to the actual number of structures present in this area, according to *Table 6.*

Table 6. REC consumers and prosumers.

Class	Description	Potential PV size [kW]	Electricity consumption [MWh/year]	Maximum number of members
1	Residential prosumers	3	4	400
2	Residential consumers	-	4	
3	Restaurants	7	21	10
4	Hotels	50	200	10

4.4 Scenarios

In the following, design of a REC in this context is discussed and a comparison will be made among two major scenarios: a REC dealing with the actual electric load, and another where a desalination plant is included accounting for the clean water supply scenario. A storage tank will also be considered to shift water production and usage. Economical revenue of the REC is calculated according to the directives listed in the Introduction.

4.5 Model components

Design, analysis, and management of the Ponza RECs were computed using pyRES. In *Figure 50* the pyRES model for Ponza REC is shown. For the present work, the pyRES modules for PV panels, and storage tank are used. In addition, a controller is developed to implement a strategy for balancing the energy production of the desalination system and its tank. Customized control logics and REC-specific incentive models based on the Italian legislation were implemented and tested. The optimization module is used first to identify the best prosumers and consumers mix in the REC and then to size the storage system.

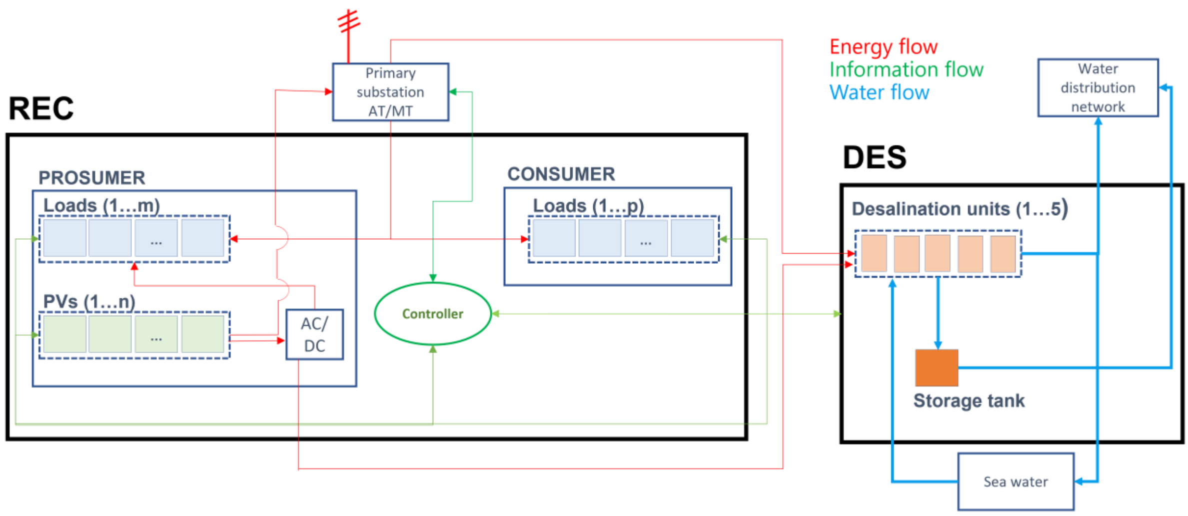

Figure 50: Scheme of Ponza REC with integrated DES in pyRES.

The desalination system in pyRES simulates one or more desalinations unit integrated with a water storage tank. The number of desalination units, the production capacity [m^3/h], the consumption curve [kWh/m^3] of each unit, the minimum and maximum level of the tank constitute the model parameters. This module calculates the electricity demand starting from the clean water demand. Size selection for the storage tank was based on an optimization analysis carried out with NSGA-II algorithm for multi-objective optimization [17]. This algorithm was selected in the library for the high-accuracy and short time to solution in two-objectives optimization problems. The reduction of water demand from the mainland and the minimization of on/off switches of the desalination units during the year were selected as objective functions to keep the desalination energy demand as constant as possible. The only considered constraint on the optimization was the total lack of wasted desalination water. A tank is also present and allows to store clean water exploiting overproduction energy from PVs. Energy and clean water flows are managed by the controller module. The control logic for energy and water desalination management is based on keeping constant the desalination load. This is achieved by a system that exploits the storage tank to level the water demand according to the logic shown in *Figure 51*.

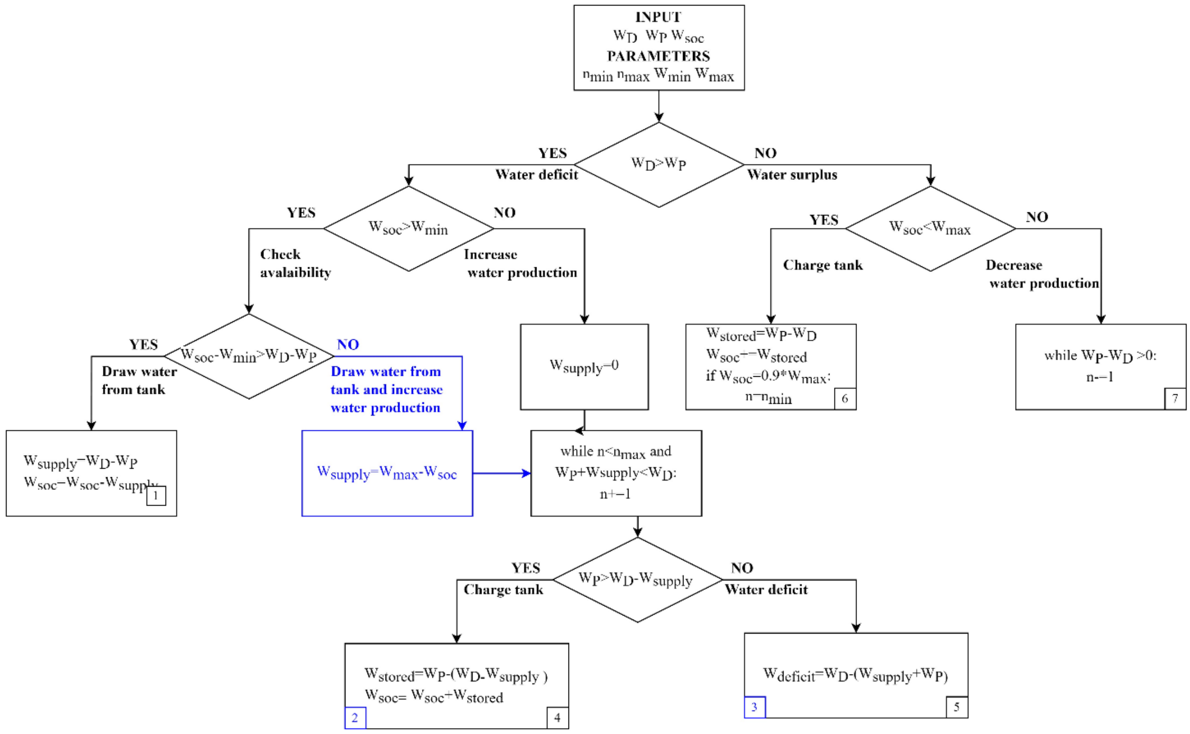

Figure 51. Flow chart for management of energy and desalination

For each time step of the simulation, the controller requires water demand, the tank state of charge and the water production calculated during the previous time-step. The control logic prioritizes the constancy of active desalination units. So, if $w_D > w_P$ the desalination units are not sufficient to cover the request and the controller first tries to fulfill the demand using the storage system. If the tank does not have a sufficient amount of stored water, the number of desalination units is increased up to fulfilment of the demand. Otherwise, if $w_D < w_P$ the controller tries to store the water surplus in the tank and if this is already filled up to the maximum the number of desalination units is decreased. In case the production is not sufficient to cover the demand the water deficit is covered with tankers from the mainland – in this case, the water is stored in the same tank, mostly during summertime as will be shown later.

4.6 Results

In the first scenario, a REC was assembled without accounting for the DES, using an NSGA-II optimization strategy that selected the best prosumers and consumers mix to maximize self-consumption and net present value (NPV). Pareto front of this optimization is shown in *Figure 52*, where solutions with a high value of annual self-consumption and increased coverage of the electric load results unfeasible because NPV is negative. Economically feasible solutions are therefore those in the upper-left portion of the front, that span from a 395 to 413 members, with a PV nominal power between 213 and 310 kWp. The coverage of the electric load never exceeds 20% of the yearly demand and this is mostly due to the abrupt increase of the load during summertime. In fact, considering only the load of the residential population, the coverage increases to about 50% of the demand. The lack of a diverse enough mix of prosumers and consumers, the limited number of available solar roofs and the lack of energy-demanding business activities on Ponza result in the REC model not being economically viable. One could argue that the current generation scenario is well above the average energy price and thus that the REC incentives should be tuned to make it more attractive, however, there is still a desalination plant to account for that could change the scenario.

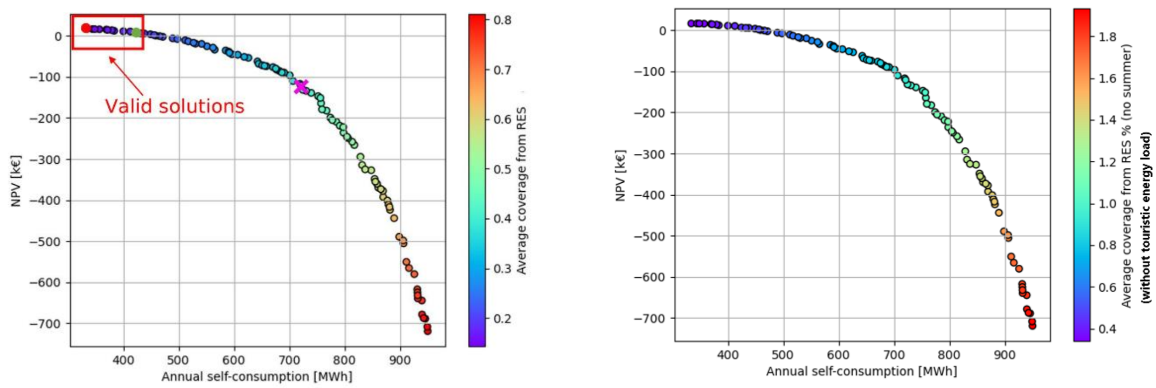

Figure 52. Pareto front for REC assembly without desalination plant. Solutions are coloured with average coverage of the energy demand of the whole REC (left) and that without the loads associated with summer tourists (right)

The introduction of the DES in the community was then investigated starting from a solution on the Pareto front that guarantees a coverage of the electric demand of 40% for the whole year, shown as a pink cross in *Figure 52.* A water storage tank was considered, with a capacity to be selected from

100 m3 to 3000 m3. The objective space of the optimization for the storage tank is shown in *Figure 53*. Given the fact that the four solutions on the Pareto front have a similar water deficit, the solution that ensured the minimum number of switches on/off of the desalination units was selected as optimal. This corresponds to a water tank with 3000 m^3 capacity.

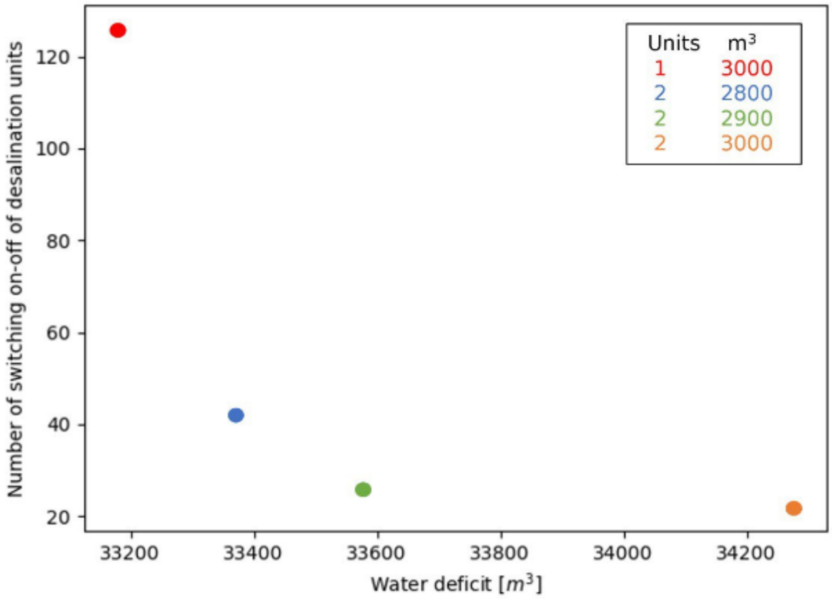

Figure 53. Objective space of NSGA-II optimization for the storage tank

The energy performance of the system is summarised in *Figure 54*, where the PV production is shown together with the demand of the REC and the DES. The solution without DES has an overall electric coverage of 40% for the whole year. However, this comes with a strong unbalance between seasons, as in fact across spring the coverage spikes to 140%. This is of course a problem as most of the incentivizing mechanism is based on self-consumption and all the over-production is acquired from the grid at a minimum tariff. Adding the DES electric load to the REC lowers the coverage to an average value of 22% and rebalances the uneven distribution between different months. In fact, in this case the energy coverage peaks at about 50% during May, resulting in a much more convenient tariff as self-consumption increases.

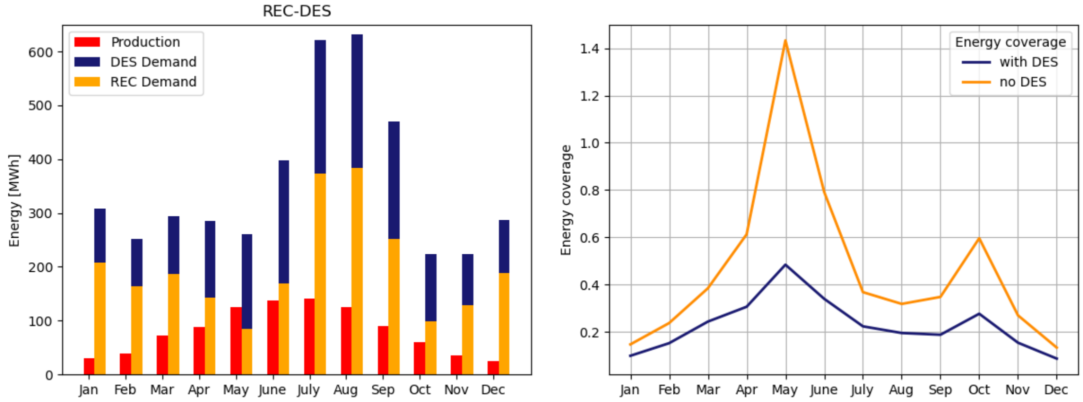

Figure 54. Energy performance of the REC when operating with and without desalination plant, monthly summary (left) and energy load coverage (right)

This is further confirmed when looking at the time-dependent metabolism of the system, *Figure 55*. For a typical spring week, in fact, the PV production exceeds 500 kW during the central hours of the day, with REC peak demand of 200 kW and DES constant demand of 200 kW. In summer the effect of tourism is to strongly increase both energy demands, with the PV systems now able to provide less than 2/3 of the demands at peak production. A similar scenario characterizes winter months, with both demand and production strongly reduced, while in autumn the conditions are like those of spring, in terms of power demand, but can be strongly affected by adverse weather/irradiance conditions for the production of PVs.

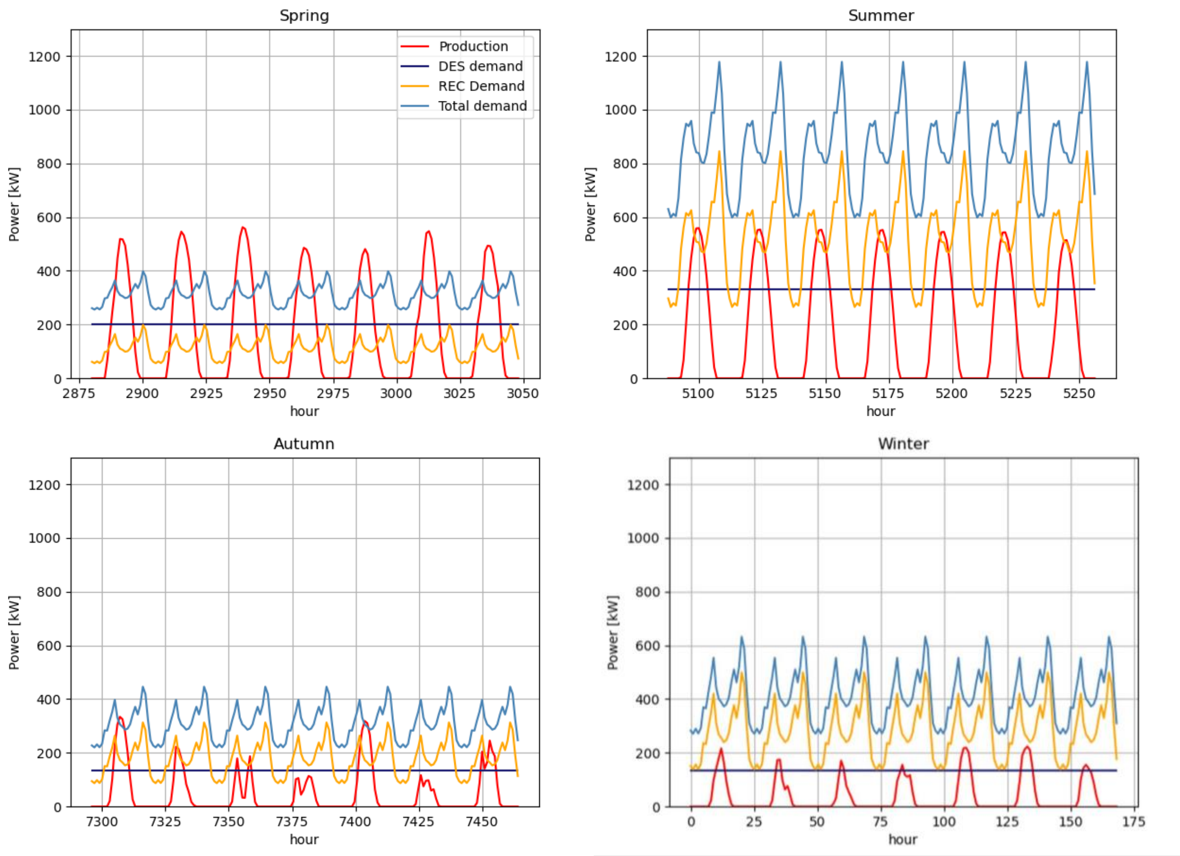

Figure 55. Energy performance of the REC when operating with and without desalination plant, weekly trends for each season.

The water supply scenario is summarized in *Figure 56* and *Figure 57*. The main advantage of the introduction of the DES is the strong reduction of the dependence on mainland supply as in this scenario this is required only during summertime at peak touristic season. The DES and the storage tank are in fact able to provide enough water to cover the demand for the rest of the year. The control logic implemented results in 2 to 5 units being active during the year, corresponding to the water production shown in *Figure 56* right. In the same figure water fluxes from and to the storage system are shown and it is evident how the tank is used continuously during the year.

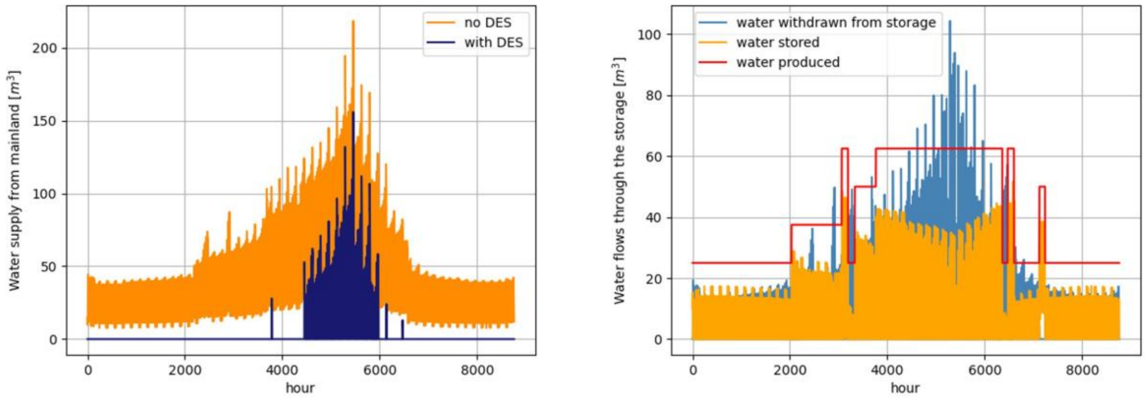

Figure 56. Water supply from mainland (left) and water fluxes from and to the storage tank (right) for 1-year operations.

The controller logic mode during the year is shown in *Figure 57*, with different modes summarized in the flow chart of *Figure 51* that highlight charges (mode 1,2,4) and discharges (mode 6) of the tank all around the year, the water deficit during summertime (mode 3 and 5). Mode 7 – a decrease of DES load due to 100% full tank is never achieved.

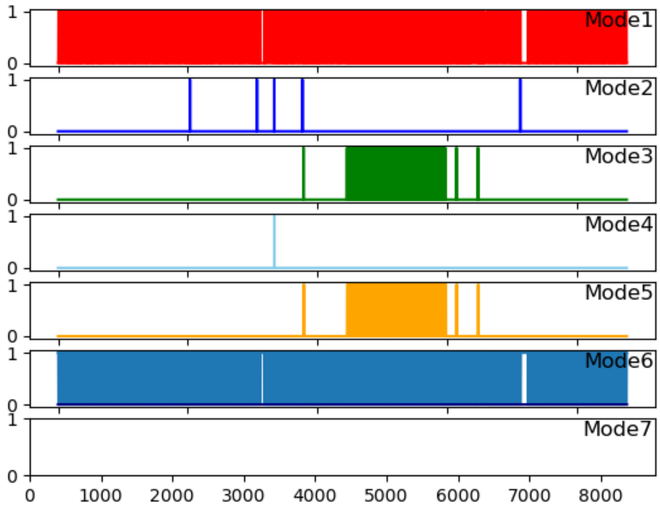

Figure 57 .Controller logic (right) for 1-year operations.

The overall performance of the two different scenarios is summarized in *Table 7*, together with the performance of the DES driven by the Diesel gensets already available on the island.

Table 7. REC performance.

	DES powered by Diesel gensets	REC w/o DES	REC with DES
Supply from mainland [1000 m^3]	34	388	34
DES water production [1000 m^3]	354	-	354
Electricity withdrawn from the grid by DES [MWh]	1876	-	1679
CO_2 emissions from water supply [tons CO_{2eq}]	228	2602	228
CO_2 emissions from water production [tons CO_{2eq}]	813	-	727
Total CO_2 emissions [tons CO_{2eq}]	1041	2602	955
REC energy production [MWh/year]		968	968
REC energy demand [MWh/year]		2379	2379
Self-consumption [MWh/year]	-	730	927
Surplus energy [MWh/year]	-	238	41
Initial investment [k€]	1200	1200	1200
Return on tariff [k€]		113	144
Awards on self-consumption [k€]		1518	1926
Revenues from the sale of surplus energy [k€]		234	42
NPV [k€]		-134	34

4.7 Conclusions

Dealing with isolated power systems of minor Mediterranean islands is necessary to address the challenges of clean energy transition. These power systems in fact heavily rely on fossil fuels and the intricate legal scenario limits the selection of RES mostly to PV systems. Even if these have the advantage of increasing their production in summertime, when the load on the island is higher, the increase in production is not able to withstand the increase in load associated with tourism.

In this scenario the current REC economical model was tested showing that on an island like Ponza, with a limited mix of prosumers and industrial activities, it is difficult to assemble REC able to self-sustain its capital costs, mostly because of a surplus of energy production during spring and autumn that corresponds to a low tariff from the TSO. However, these islands usually don't have direct access to clean water and rely on supply from the mainland. This means that the introduction of a desalination plant with a storage system in the REC can help increasing self-consumption and in so doing the NPV of the REC and at the same time it can have a significant impact in reducing more than 60% of CO_2 emissions for water supply, with a further 10% cut of emissions related to Diesel gensets. Even in these conditions, however, the scenario could be perfected. From a technical point of view, in fact, the REC could be extended to different communities of Ponza, maybe also to the whole island. The excess of electric load from the DES is in fact sufficient to stabilize the self-consumption of a much larger REC. From a social point of view the REC model implies also different strategies that could be related to services to the local community and, since part of the problems come from the number of summer tourist, strategies to remunerate the REC could involve the tourism on the island. Finally, the current Diesel genset scenario benefit from special tariffs for power generation that compensate the oversized system required for summertime operations. A possible way to promote RECs is to study a similar system for RECs on minor islands with better incentives with respect to those on the mainland. Further extension of this work could be the inclusion within the REC of the whole Ponza residents and small-sized enterprises. Finally, since the REC legislation leaves the redistribution of incentives within the users to private agreements, a deeper investigation of the revenue sharing between prosumers and consumers would be necessary to understand how revenue should be split to cover capital costs of prosumers. The methodology proposed to investigate the energy and economics of the REC is general and relies on transient modelling of the energy system. For different applications, minor changes are required to the financial module to account for local tariffs or different incentive schemes. Further applications however can include different technologies and control strategies. In this case the major changes required are related to adjust the control logic described in *Figure 51* to account for different energy conversion and storage systems, and. To tackle this problem, we are currently working on an improved controller based on reinforced learning, able to learn how to control the system. This method and the pyRES software can be used to design and optimize a REC and to simulate different power and storage scenarios, including thermal loads. They can be used to provide information to local governments that plan to increase the number of RECs on the territory – this work is in fact financed by Regione Lazio (the regional government for Rome area in Italy), that decided to help stakeholders like municipalities, schools, churches, technicians and engineers or simple citizens in assembling their local REC. A user-friendly and simplified version of the code will in fact be made available in the near future to possible stakeholders to help them in sizing and planning new RECs. Further stakeholders include banks, that finance installations of PV and other renewables, small, medium and large enterprises, that want to reduce their energy costs and carbon footprint increasing their quota of renewable energy creating a REC with their neighbours.

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5. Renewable Energy Communities based on solar panels and batteries: optimal aggregation of prosumers and consumers

5.1 The role of batteries in a REC

In this work we want to investigate whether it is more convenient for a prosumer with an excess of photovoltaic production to install an electrochemical storage or to share the excess in a REC. A private producer is considered and the economic benefits that can derive from an increase in self-consumption thanks to the use of storage are compared with those that can derive from sharing the excess energy in a REC. In this study the two configurations are considered as alternatives. In this work, we also perform a parametric analysis as a function of energy cost: while the incentives remain constant throughout the 20 years lifespan of a REC, electricity prices are highly variable. Based on PUN, which is the benchmark for the electricity market in Italy, the market has been highly unstable in the past years (*Figure 58*). In fact, after a sharp drop at the beginning of 2020, PUN increased from a minimum of 21.8 €/MWh (May 2020), to an all-time high of 543 €/MWh (August 2022).

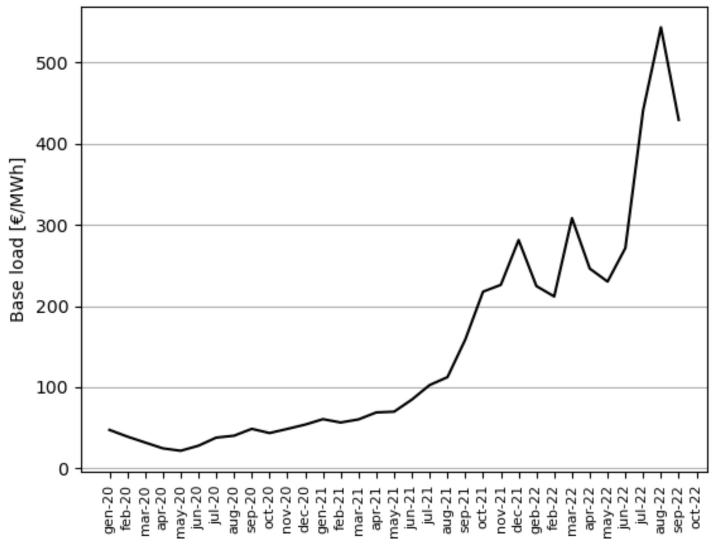


Figure 58. Trend of PUN over three last years [1].

The savings resulting from energy self-consumption vary greatly with the energy price, however storage systems can play a key role in managing power grids by providing various services, including reducing grid congestion, increasing hosting capacity, regulating voltage, and shifting peak loads. However, the specific methods for providing these services still need to be defined and regulated [2]. The total power of storage system in Italy is 1,590 MW corresponding to an equivalent capacity of 3,000 MWh. More than 95% of these are combined with photovoltaic systems and have a power ranging between 0.5 and 500 kW. The remaining part are pilot projects supported by TERNA for the dissemination of large-scale storage systems [3][4].

5.2 Case study: a small municipality in the Lazio region

The case study is a municipality in the Lazio region with approximately 2300 inhabitants and an area of 64 km^2. The municipality has a population density of 44 inhabitants/km^2, with about 1100 families and an average of 2.2 members per family. The main economic sectors are services and agricultural sectors, with the presence of construction companies [5]. It provides a reference for small Italian municipality. With the support of the Lazio region, the local administration has launched an initiative to engage citizens who own an electricity POD, with the aim of establishing a REC. A preliminary analysis of the area was carried out to identify key factors that could influence the development and implementation of a REC. The availability of solar source was calculated using PVGIS [6]. The maximum and the average values of hourly global radiation on horizontal plane are respectively 700 W/m^2 and 250 W/m^2, the potential yearly photovoltaic production is 1415 kWh/kWp. The local administration intervention has accelerated the process of collecting data to estimate the REC energy demand. The electricity consumptions of three typical residential users *Figure 59*, a 500 m2 supermarket with a large parking area and a restaurant with seating for 30 are summarized *Table 8.*

Table 8. Electricity consumptions of potential users.

Description	Available space for RES technology [m^2]	Electricity	
		Consumption [MWh/year]	Peak power [kW]
Supermarket	1000	350	80
Restaurant	-	26	20
Residential 1	-	2.6	3
Residential 2	-	3.4	4
Residential 3	-	2	3

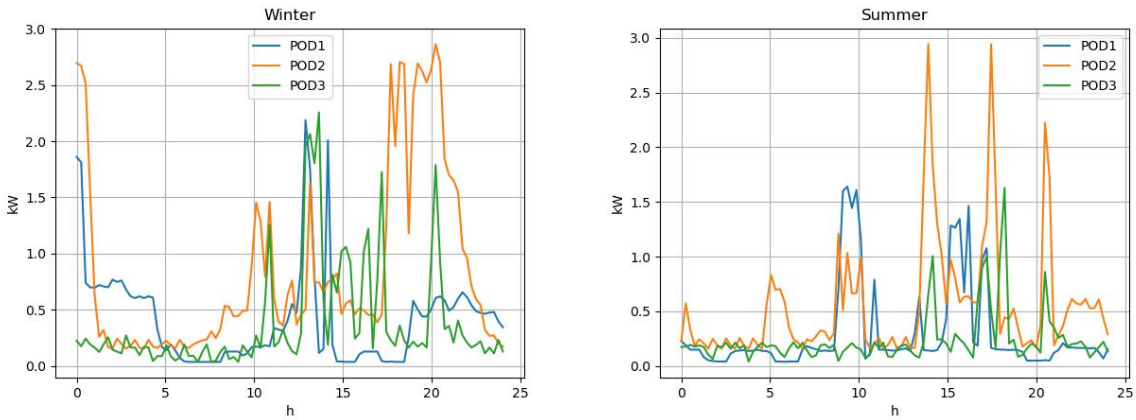


Figure 59. Quarter hourly consumption of three residential consumers in a random day for winter (left) and summer (right).

5.3 REC prosumers and consumers characterization

The supermarket is a significant energy consumer in the local contest and is therefore selected as a potential candidate to become a prosumer of the REC. A parametric analysis based on the PUN (*Figure 58*), which ranges from a minimum of 21.8 €/MWh recorded in May 2020 to all-time high of 543 €/MWh recorded in August 2022, is carried out to evaluate the potential benefits of installing a photovoltaic system to satisfy the supermarket energy demand. The potential benefits of integrating the photovoltaic system with a battery energy storage are investigated. The optimal size of the battery is identified using a multi-objective optimization approach based on the NSGA-II genetic algorithm. Objective functions are the net present value (NPV) of the prosumer and the energy self-consumption. The potential benefits to establish a REC powered by the excess energy produced by the supermarket photovoltaic system are investigated. The best mix of consumers to include in the REC is determined using a multi-objective optimization analysis with the NSGA-II genetic algorithm. Objective functions are the NPV of the REC and the revenue shared with each consumer. The REC cash flows are calculated under the assumption that the REC will exclusively bear the management costs of the REC while prosumer bears the investment and maintenance costs of its own production systems. The revenues from the sold energy go to the prosumer, while incentives from the shared energy are split between prosumer and consumers with a variable proportion: prosumer receives 80% of the incentives until it recoups its investment, after which the percentage drops to 20%. The partition of incentives derived from shared energy is not regulated. The financial model of the REC must be defined in an arbitrary way with the deed of partnership. The only constraint is that the REC must provide environmental, economic, or social benefits to its members or the local areas in which it operates, rather than financial profits [7][8]. Moreover, if a renewable energy system is installed as part of an energy efficiency measure, incentives from REC configuration can be combined with 50% bonus. 50% Bonus is a tax relief that allows to recoup up to 50% of the original investment, with a cap of 96,000 €. The economic parameters of the simulation are summarized in *Table 9.*

Table 9. Economic parameters.

Investment time [years]	20
Discount rate [%]	3
Annual decay of PV producibility [‰]	6
PV CAPEX [€/kW]	1500
BESS CAPEX [€/kW]	720
Inverter CAPEX [€/kW]	140
O&M PV cost [€/kW/year]	40
PV management cost (GSE) [€/kW/year]	0.65
PUN [€/MWh]	20-545
Taxes on energy sold [%]	20
Energy shared award (2022) [€/MWh]	118.37
REC management cost (GSE) [€/POD/year]	4
Bonus50%	True
Replacement inverter after 10 years	True

5.4 Scenarios

The study is based on the comparison of four scenarios with increasing complexity:

1) Prosumer: a single consumer who is physically connected to a photovoltaic system which is purchased and managed in total autonomy.
2) Prosumer + BESS: a single consumer who is physically connected to a photovoltaic system and a battery system (BESS), which are purchased and managed in total autonomy.
3) Small REC: a single prosumer who remains the owner of the plant and its management but shares the excess production with a limited number of consumers.
4) Big REC: a single prosumer who remains the owner of the plant and its management but shares the excess production with the maximum number of consumers.

The black-box scheme of the four analyzed scenarios is shown in *Figure 60* .

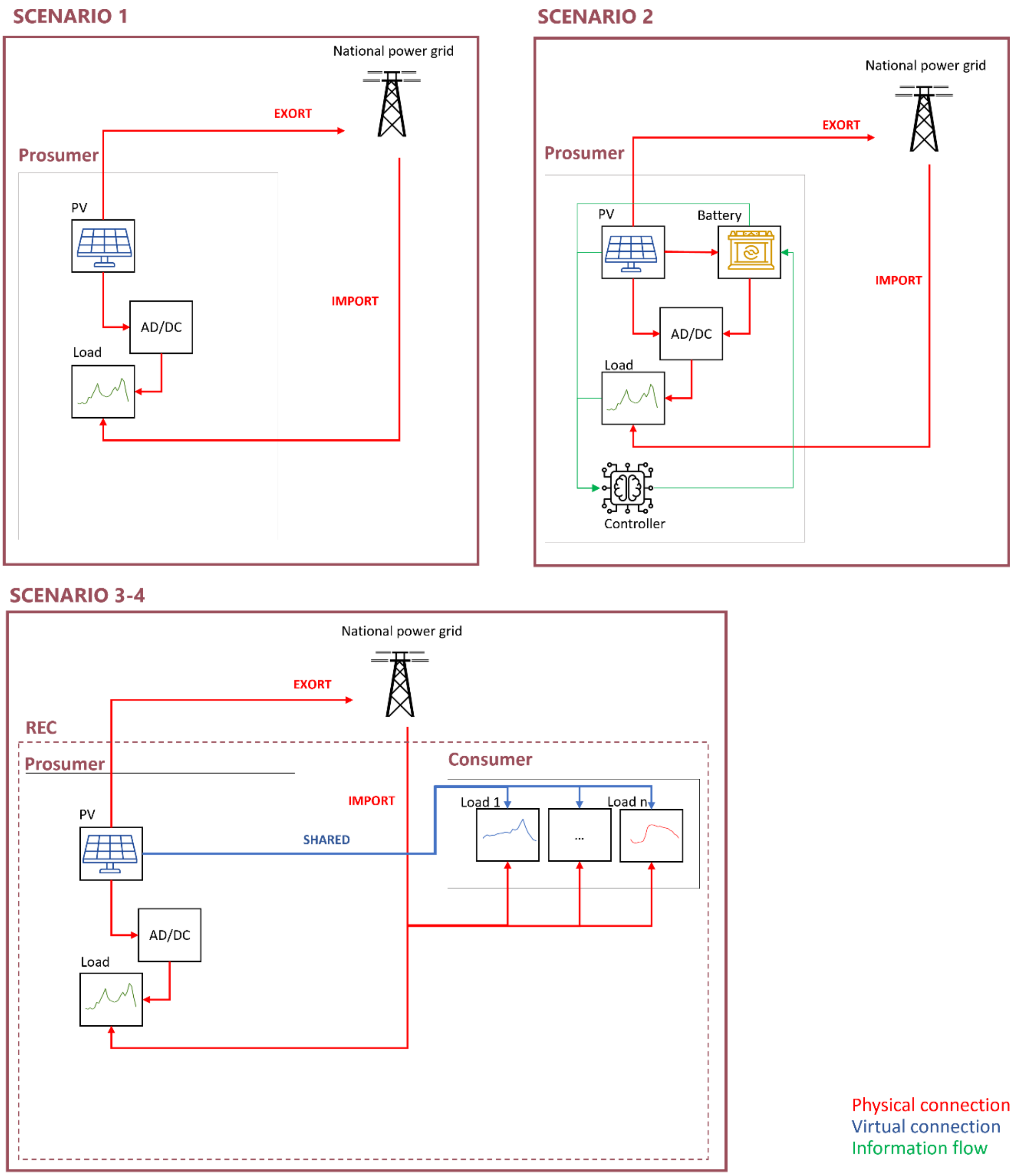


Figure 60. Modelling of four scenarios in pyRES.

5.5 Performance indicators

This work focuses exclusively on the technical and financial aspects of the REC. 14 indexes were defined to quantify energy, economic and environmental performance.

Energy:

- C_{pro}: defined as the ratio between the annual photovoltaic production and the annual electricity demand of the prosumer.
- $\check{C}_{pro}$: defined as the ratio between the annual self-consumption and the annual electricity demand of the prosumer.
- SC_{pro}: defined as the ratio between annual self-consumption and annual photovoltaic production.
- C_{con}: defined as the ratio between the excess annual photovoltaic production and the annual demand of consumers.
- $\check{C}_{con}$: defined as the ratio between annual shared energy and annual consumer demand.
- C_{REC}: defined as the ratio between the annual photovoltaic production and the annual demand of the REC.
- $\check{C}_{REC}$: defined as the ratio between, the sum of self-consumption and shared energy, and the annual REC demand.
- SH_{REC} defined as the ratio between the excess annual photovoltaic production and the shared energy.

Economics:

- NPV_{pro}: net present value of cash flow related to the prosumer.
- PBP: payback time of the photovoltaic system investment.
- NPV_{REC}: net present value of the REC cash flow.
- R_{con}^{tot}: total revenue generated for each consumer.
- R_{con_YEAR}: annual revenue for each consumer.

Environmental:

- tCO_2/year: Avoided annual CO_2 emissions. This is calculated by multiplying renewable production by the average CO_2 emissions associated with generating 1 kWh of electrical energy. According to [9],the emission factor for the power sector in Italy in the year 2022 is 482.2 grams of CO_2 per kilowatt-hour (g CO_2/kWh). This implies that for each kWh generated by photovoltaic systems, 482.2 grams of CO_2 emissions are avoided.

5.6 Model components

Design, analysis, and management of the RECs were computed using pyRES, following this rationale:

1. Analysis of the electricity loads from prosumer and users: from monthly bills to quarter-hour meters, when present. For PODs without quarter-hour meters these were estimated from user profiling and an artificial neural network.

2. PV panels of the prosumer were sized following a parametric analysis based on PUN to ensure the profitability of the investment under possible market fluctuations.

3. A multi-objective optimization problem with an NSGA-II type genetic algorithm was solved to select the battery size and the best mix of consumers to include in the REC.

4. The optimization results are analyzed, and the most significant solutions were compared through a comparative analysis based on energy and economic performance indices.

In *Figure 60* the pyRES model for 4 considered scenarios are shown. For the present work, the pyRES modules for PV panels, and electrochemical batteries are used. In addition, a controller is developed to implement a strategy for balancing the energy production of the PV panels and batteries. The optimization module is used first to to size the storage system and then to identify the best prosumers and consumers mix in the REC. In addition, the battery module is integrated with a controller to regulate the maximum input and output currents and the SoC. A flow chart of the control logic is shown in *Figure 61*. The controller has in input the energy PV production calculated by the PV model, the energy demand by the prosumer and the SoC of the battery from the previous timestep, the maximum and minimum allowed for the SoC to avoid battery degradation. The controller tries to store the PV energy in excess with respect to the load in the battery; when this is at maximum capacity the excess is sold to the national grid. In case of deficit of energy from PVs, the controller tries to satisfy the demand using the battery and in case of further deficit buys energy from the grid. For each simulation time step, the controller calculates the amount of energy stored or supplied by the battery, as well as the amount fed into or withdrawn from the grid.

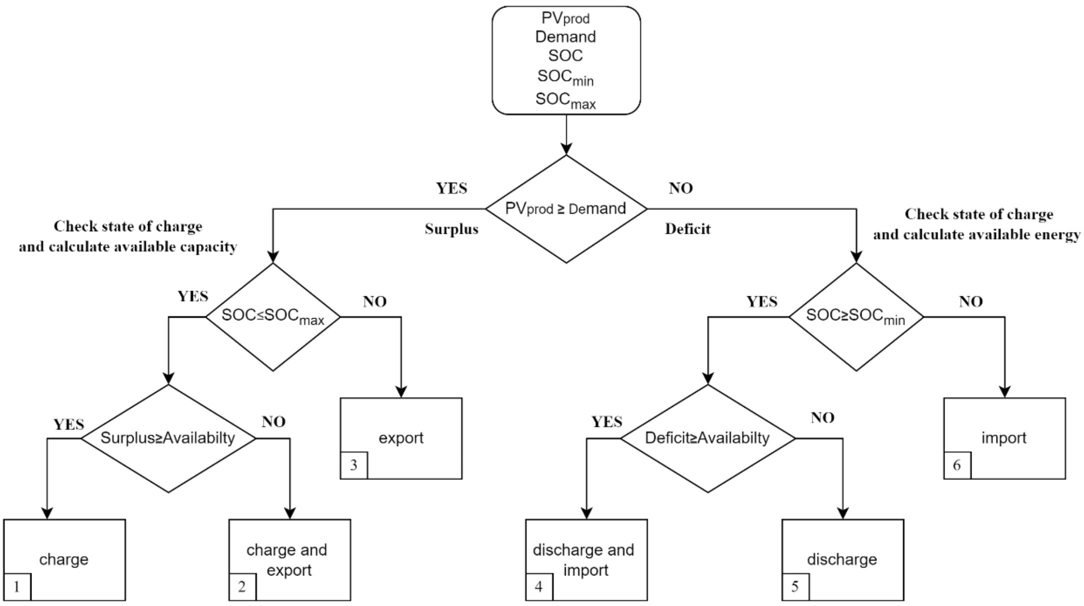


Figure 61. Flow chart of the PV+BESS system controller.

5.7 Results

The photovoltaic system was designed based on the available area of 1000 m^2, taking into account shading, safe access, and maintenance, resulting in a utilization factor of 0.4. By selecting a single 400 kW panel with a size of 1.65 m2, a 120 kW photovoltaic system was sized, which has an annual production capacity of 155 MWh. This plant guarantees a self-consumption of 94 MWh corresponding to 27% of the prosumer consumption. The presence of an energy surplus of 61 MWh is highlighted in *Figure 62* where the energy metabolism of the prosumer is shown for four typical days of the year. The surplus is most pronounced in the summer months when there is a natural increase in photovoltaic production.

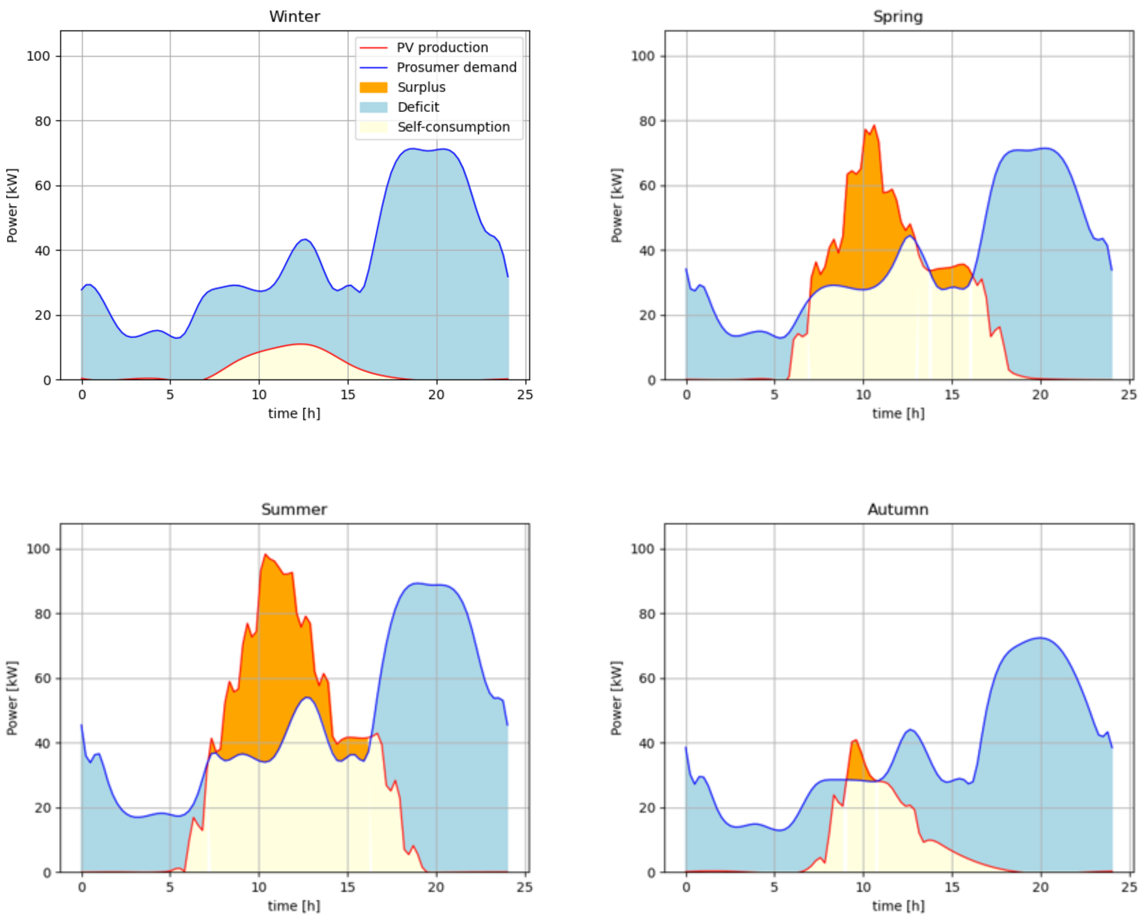
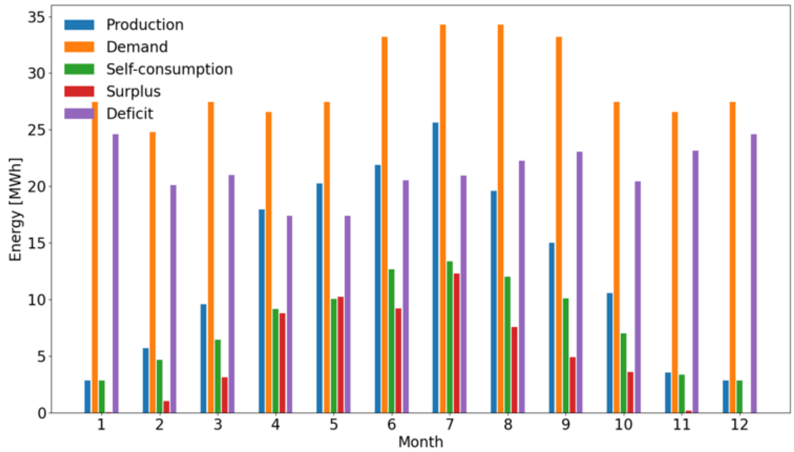


Figure 62. Prosumer energy performance daily trends for each season.

The energy performance of the prosumer for each month of the year, and the corresponding values of the energy indices are represented in *Figure 63*.



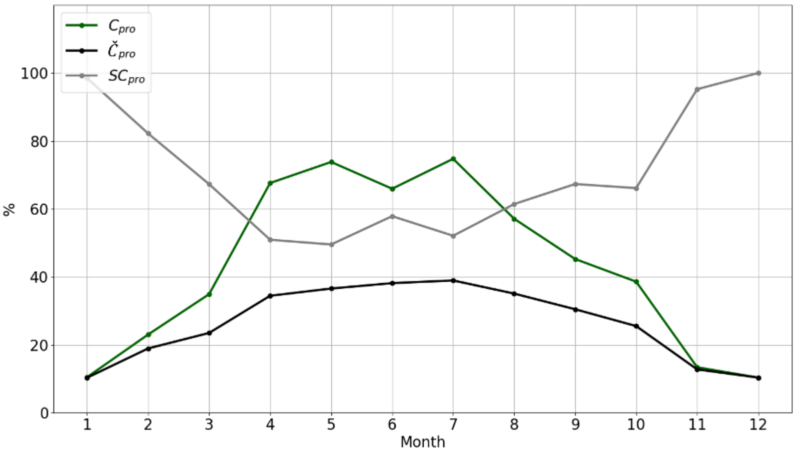


Figure 63. Monthly trend of prosumer energy indices (below) and energy performance (above).

The energy demand of the prosumer is about 30 MWh/month, while the renewable energy production ranges from a minimum of 4 MWh/month to a maximum of 26 MWh/month. The production is totally used by the prosumer during the winter months when the self-consumption index (SC_{pro}) reaches the maximum value, while it never drops below 40% for the rest of the year. The maximum value of effective coverage ($\check{C}_{pro}$) is 40% which is recorded during the summer months, while the potential coverage (C_{pro}:) is 75%. The difference between these two values is proportional to the non-simultaneity of renewable production and consumption. The results of the parametric analysis are presented in *Figure 64*.

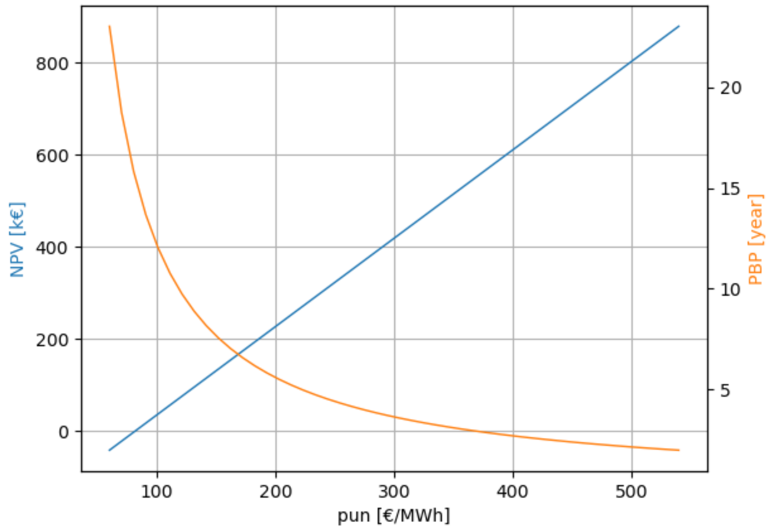


Figure 64 Parametric analysis of PV investment with different values of PUN.

As the PUN increases, the NPV increases linearly while the payback time decreases according to an exponential law. The absolute values of the NPV should be considered with caution since it is not possible to predict the trend of the electricity market over the next twenty years. Quite the opposite the results on the PBP are indicative of the fact that if the PUN stabilizes at a value of 300 € /MWh in the near future, the PBP for the PV plant will be less than 2.5 years. This analysis demonstrates the current convenience of installing PV panels. The savings on the bill, the revenues from the sale of energy, and costs for the purchase are calculated and shown in *Figure 65*, considering a PUN value of 320 €/MWh equal to the average value of the year 2022.

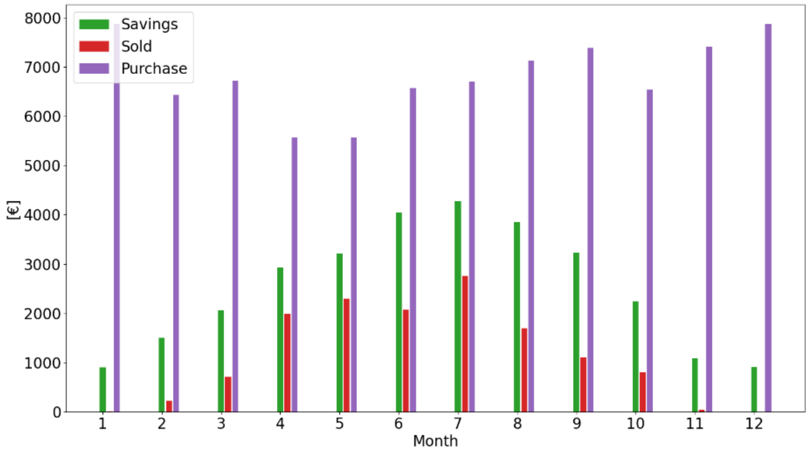


Figure 65. Monthly trend of prosumer economic performance. Qui io ci metterei qualcosa di più parametrico con il PUN

The prosumer has the potential to save up to €4,000 per month, which corresponds to 50% of their electricity costs, and can earn up to €3,000 per month from the sale of energy. The cash flows, NPV, and payback period are calculated iterating this analysis for each year of the investment. The results show an NPV of €402,000 and a payback period of 4.5 years. The results of the optimal integration with batteries are summarized in the Pareto front of *Figure 66*. The storage capacity ranges from 0 to 160 kWh. While the introduction of batteries can increase self-consumption by up to 20%, the NPV can decrease by up to 25%. This demonstrates that the increase in initial costs outweighs the increase in bill savings.

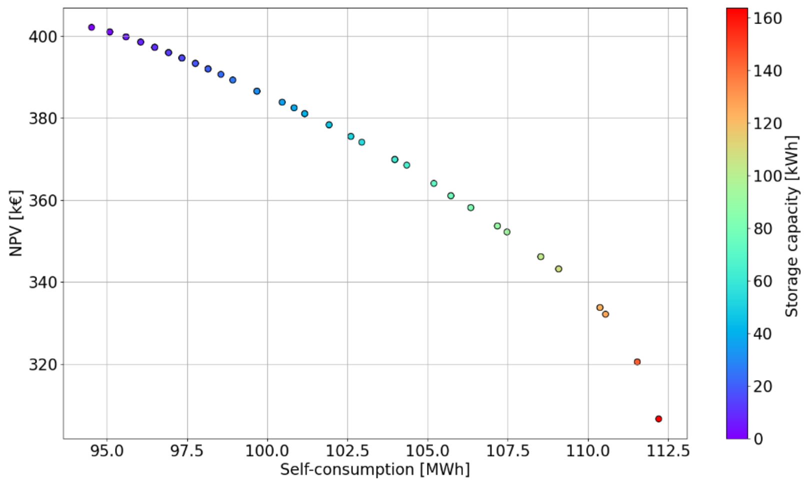


Figure 66. Optimization results of BESS sizing.

Figure 67 illustrates the SoC, current, and voltage trends for the solution with a maximum storage capacity of 160 kWh. The batteries are used up to 70% of the year, the charge and discharge phases are constantly alternated. The controller guarantees a proper operation of the batteries, which is critical for the optimal performance of the system.

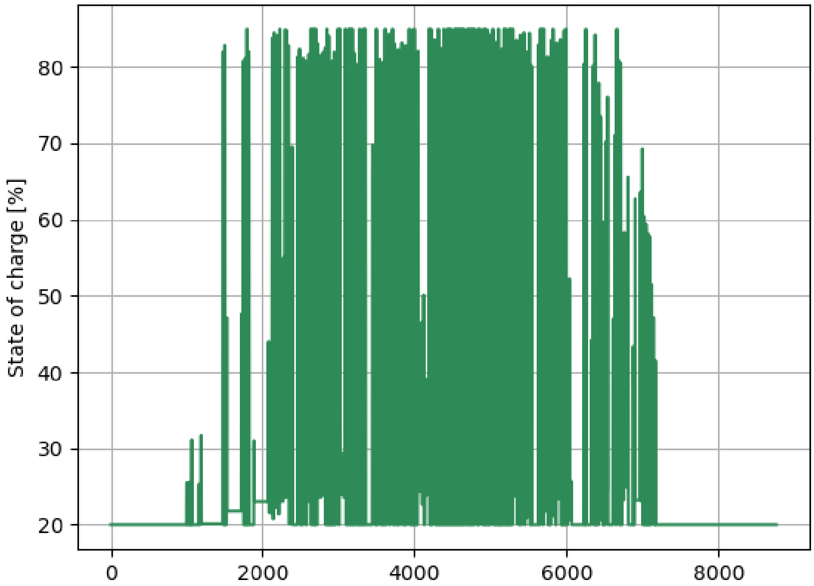


Figure 67. Annual trend of state of charge in the BESS.

The energy flows to and from the battery for four typical days of the year are shown in *Figure 68*.

There is no surplus energy to be stored in the battery during winter. In autumn, the amount of surplus is not sufficient to activate the charge. During spring and summer months, the batteries are charged in three hours before the production peak and transfer the surplus in the early evening hours when discharge occurs. This transfer of energy increases the energy coverage from 27% to 32%.

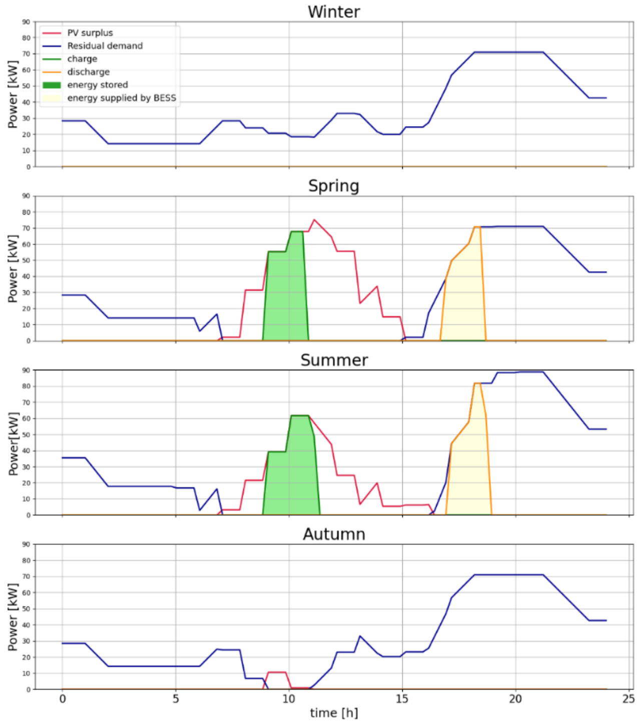


Figure 68. Prosumer + BESS energy performance daily trends for each season.

The optimization results of the REC are summarized in the Pareto front of *Figure 69*. Among the optimal population, the total number of REC members spans from 8 to 307. The algorithm prioritizes the most energy-intensive users and then users with lower consumption. Starting from the lower right portion of the front, the knee indicates that all commercial users are included in the REC. From this point onwards, the algorithm starts to add residential users and the variation of the economic benefits becomes smaller since the weight of the residential is lower than of commercial users. In the REC configuration the prosumer NPV can increase up to 7%. The REC generates its own cash flow and revenues for each individual member ranging from €180 to €6,630, corresponding to €9/year and €331/year respectively.

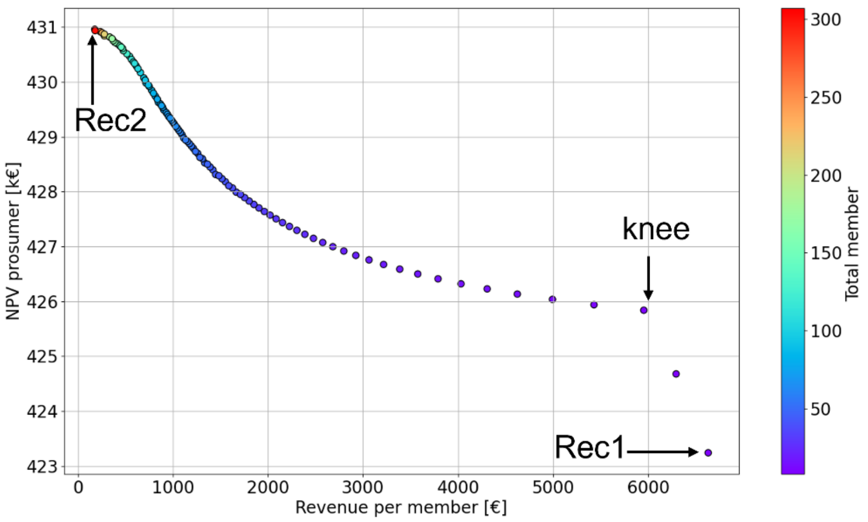


Figure 69 Optimization results of the best consumer mix.

The most extreme RECs of the Pareto front are compared in *Figure 70* . Rec1 is a very large community with a total of 307 members able to absorb 100% of the PV surplus. The revenue per single member is negligible (€9/year) and the average coverage of consumption (COVconsumers) is 6%. On the other hand, Rec2 corresponds to a community of 8 members, which can absorb 72% of the surplus. The revenue per single member is €331/year and the average coverage of 21%.

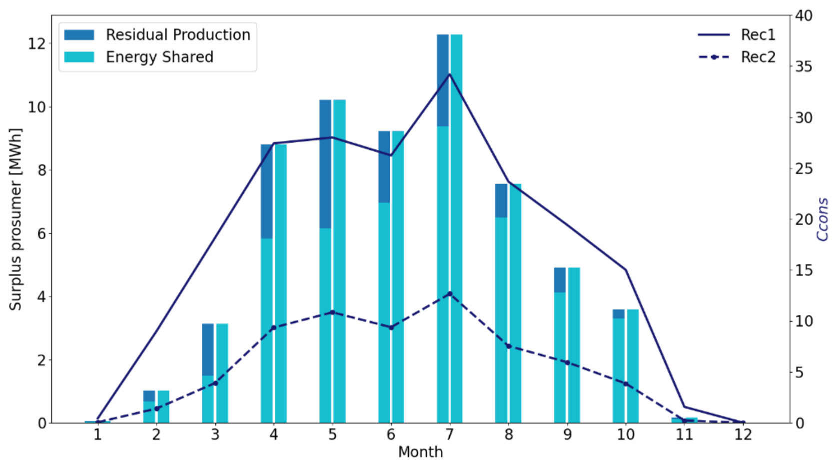


Figure 70. Comparison between two RECs corresponding to opposite individuals in the Pareto front.

The comparison of the four analyzed scenarios is summarized in Table 10.

Table 10. Comparison of all scenarios.

	Prosumer	Prosumer +BESS	Rec1	Rec2
Total member	1	1	1+8	1+307
Prosumer demand [MWh/year]		350		
Consumers demand [MWh/year]	-	-	208	1059
Total demand [MWh/year]	350	350	558	1409
PV production [MWh/year]		155		
Self-consumption [MWh/year]	94	112	94	94
Surplus [MWh]	61	43	61	61
Shared energy [MWh/year]	-	-	44	61
Stored energy [MWh/year]	-	18	-	-
C_{pro}[%]	44	44	0	44
$\check{C}_{pro}$ [%]	27	32	27	27
SC_{pro} [%]	61	84	61	61
C_{con} [%]	-	-	29	6
$\check{C}_{con}$ [%]	-	-	21	6
C_{REC} [%]	-	-	28	11
$\check{C}_{REC}$ [%]	-	-	25	11
SH_{REC} [%]	-	-	72	100
Initial investment [k€]	180	279	180	180
NPV_{pro}[k€]	402	306	423	430
PBP [year]	4.5	7.4	4.3	4
NPV_{REC} [k€]	-	-	53	55
R_{con}^{tot} [k€]	-	-	6.6	0.178
R_{con_YEAR} [k€/year]	-	-	0.33	0.008
[tCO_2eq/year]		75		

5.8 Conclusions

For self-generating energy producers seeking to enhance their revenue, the choice to install batteries involves a higher initial investment cost and overall reduced income. While batteries contribute to increased self-consumption of locally generated energy and greater savings, the increased investment cost outweighs the benefits. It is crucial to recognize that economic performance of prosumer which decides to install battery is intricately linked to the dynamics of the electricity market. It is essential to consider that the cost-effectiveness of battery installation varies with fluctuating energy prices; higher energy prices tend to promote self-production and energy storage. In contrast, RECs do not offer the advantage of energy time-shifting but do facilitate a boost in on-site energy self-consumption without initial investment costs. However, our results underscore the necessity of aligning incentive programs with the energy cost. While the incentives remain constant throughout the 20 years lifespan of a REC, electricity prices are highly variable. When the energy price exceeds €300/MWh, the incentives that the prosumer receives from the REC become negligible compared to the bill savings resulting from self-production. In these cases, the REC model may be economically unattractive for the prosumer who is already generating substantial income from their installations. Furthermore, by joining the REC, the prosumer, despite being the owner of the installation, must consider the input of other members according to the democratic decision-making model. Incentives specifically dedicated to batteries and the development of an incentive mechanism that can incorporate electricity market fluctuations are essential to encourage the widespread adoption of RECs and energy storage systems.

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6. Optimal integration of solar panels and biomasses in an Italian renewable energy community

6.1 RECs with Combined Heat and Power loads

In this manuscript the following issues are addressed:

- the design and analysis of a REC that includes biomass-fuelled cogeneration and photovoltaics. Only one of the two sources is dispatchable and can be controlled to match the energy demand. Both electricity and heat consumptions are taken into consideration;
- understanding how the REC scenario changes when forcing the cogenerator to follow the electric or the heat load of the prosumer;
- investigating the technical and economic challenges associated with customizing a REC and the synergies can be created in the territory.

The selection of energy sources, prosumers and consumers is based on the specific territorial context. The case study is a small municipality in Lazio, located in a mountainous area with about 100 small and medium enterprises (SMEs). There is a mountain community that has access to the local wood resources that include multiple solid biomass supplies. Given the presence of activities requiring both electricity and heat, the proximity of suitable areas for the construction of storage warehouses, and the availability of more than one biomass supply source, the municipality is well suited for the biomass energy production.

The new legislation on Italian RECs increases the nominal power of each power plant from 200 kW to 1 MW and extends the local area to the HV-MV substation: RECs can therefore integrate multiple renewable sources and energy vectors. The first step in the potential evolution of RECs is the integration of thermal production to meet heating and cooling demand. Currently, most established RECs include only renewable electricity generation technologies, while thermal energy systems used for heating, cooling, and domestic hot water production are less common. Considering that approximately 60%-75% of energy consumption of European households is related to heat production, there is a need for thermal energy communities [1]. The Thermal Energy Communities (TECs) involve heat production integrating multiple renewable energy sources. The renewable sources exploited by TECs include solar, biomass, and geothermal energy. Waste heat from other processes also represents an opportunity for TECs in cases where there is a renewable source downstream of the process.

The development of TECs in Italy is currently blocked by the lack of government guidelines as regulations only establish rules for sharing electricity. Recent initiatives are exploring the feasibility of virtual heat sharing among REC members and incentive mechanisms for shared thermal energy, but there are no indications regarding the establishment of thermal RECs. If the virtual model cannot be applied, heat sharing could involve the implementation of district heating. Another option is to provide an additional incentive for electric RECs that also integrate heat production. Denarie et al. [2] have estimated the potential of district heating in Italy which amounts to 38 TWh. Thermal energy could contribute to covering 12% of the heating demand. The implementation of district heating systems would result in the shutdown of 4 million boilers and avoid the emission of 5.7 million tons of CO_2.

TECs may play a crucial role in achieving energy transition. In Italy, biomass is fundamental for the development of TECs for several reasons. First, the spread of biomass-powered plants depends on local resources and is promoted by local actors, which matches well with the local character of TECs. Second, biomass is a controllable source that can compensate for the intermittent nature of solar and wind sources, helping to achieve 100% coverage of energy demand. Finally, involving biomass businesses rooted in the local community can create specific synergies and accelerate the establishment of TECs. Furthermore, the use of cogeneration systems, which generate simultaneously electricity and heat, can improve the efficiency of biomass utilization. The Ministerial Decree of August 4, 2011, [3] establishes rules to incentivize electricity produced through high-efficiency cogeneration. These incentives can be cumulated with the REC incentives when the cogeneration system is powered by renewable sources. Several European initiatives aim to promote TECs. For instance, the ConnectHeat project, launched in October 2020, aims to establish a regulatory framework for promoting energy communities focused on heating and cooling. This initiative, involving seven EU countries including Belgium, Bulgaria, Croatia, Germany, Italy, Portugal, and Spain, has allocated a budget of 1.5 million euros to fund seven pilot projects, one for each country.

In a typical scenario with electric and thermal loads to satisfy several strategies can be followed, from the electrification of heat generation to cogeneration. The latter is of particular interest when dealing with local availability of biomasses. For example, Tiwary et al [4] studied the use of solid biowaste as a source of power and how to couple it with wind turbines, PVs, biogas generators and BESS in Gateshead (UK) and Sofia (BG). They performed computations with HOMER concluding that the biowaste of the two communities could cover between 60% and 65% of the energy demand, offering a stable basis to build up with solar and wind. Mahzouni, [5] reported on the experience carried out in St. Peter (DE), where a local community decided to build an energy co-operative for a biomass heating district plant. He concluded that the role of institutional entrepreneurship was the key for the success of the operation, that is now seen as an example from neighbouring communities. He also highlighted that the same conditions do not apply to any generic communities but only to those with similar conditions. Yana et al, [6] provide a review of experience in Indonesia with local communities developing biomass waste powered RECs. With a potential close to 50 GW, Indonesia is in fact a possible key player in the development of RECs. Di Silvestre et al. [7] discussed the role of RECs in Italy, providing an analysis of RECs, emphasizing their primary features and their relevance to power system aspects. They also focussed on the integration of the new REC model with the phase-out of coal and in general with the topic of clean energy transition. Aste et al. [8] discussed the case of a nearly zero energy district in Milan (IT) with a combination of low-energy building design, small-size wood biomass, groundwater heat pumps and PV systems. The core of the operation is a biomass boiler coupled with a twin-screw heat expander. They concluded that the key aspect for the success of the operation is the selection of temperature levels to ensure a low interaction with the energy grid as especially during wintertime the PV production is scarce. Paletto et al. [9] discussed the role of biomass power plants to increase the social acceptance of RES. They concluded that the size of the biomass energy plant (< 1 MW or >1 MW) and the feedstock used (forest or sawmill woodchip) are two main variables that influence the environmental impact. Perea-Moreno et al. in [10] discussed the role of biomass in worldwide research trends, highlighting an overall increase in the subject. Xu et al. [11] performed an evaluation on the integration of solar, wind, biomasses and batteries into and hybrid renewable energy system in four locations of China, accounting for technical, economical and environmental aspects. They concluded that decarbonization of Chinese cities require to find an optimal mix of renewables specific to each location and that a comprehensive enough mix of sources allows to overcome the shortcomings of each specific technology. Ennemiri et al. [12] performed a similar study for an off-grid energy system in Morocco with solar panels, biogas and batteries. In this case they mostly focused on the economics of the system, basing their optimization on LCOE and NPC. They managed to find a series of configurations able to provide the expected technical performance at reasonable costs, reducing the overall CO2 emissions with respect to the status quo by a factor of 40%. Design, however, is only part of the problem of fitting multiple RES into an energy system. In fact optimal management of the energy and financial fluxes during operations is the other key aspect. Bahlawan et al. [13] addressed this problem in a complex energy system in Milan achieving an 8% reduction of opex. Ibrahim et al. [14] used a fuzzy-logic based management approach to achieve a reduction of average electricity costs by almost 12% with respect to a basic optimization carried out on HOMER.

6.2 Case study: a small municipality in the Lazio Region

The case study concerns a municipality located in the Lazio Region with approximately 11,000 inhabitants. A preliminary analysis was conducted to identify the key factors that could impact the development and establishment of RECs. The municipality covers an area of about 16 km^2, has a population density of 670 inhabitants/km^2, with 4700 families, and an average household size of 2.36 members. The main economic sectors are services and industrial sectors, with about 100 SMEs [15]. The northern area of the municipality is occupied by woods and is periodically maintained, with a residual biomass productivity estimated using land-use maps to 24,057 tons/year [16]. The solar resource potential is obtained from PVGIS [17] and corresponds to an average hourly radiation of

150 W/m2. The energy demand of the REC is derived by collecting and summing the consumptions of 50 residential users, a school, and an industrial laundry, as summarized in

Table 11. The total electricity consumption of residential users is 196 MWh/year, with an average consumption of 3.9 MWh/year per single user, and the contractual power ranging from 3 to 6 kW. The school has 1000 students and available space for photovoltaic systems with a maximum nominal power of 60 kW. The industrial laundry works for hotels and restaurants with approximately 40 employees and an average production of 4,500 tons/year of washed and ironed products. The main phases of the laundry process include washing, drying, ironing, pressing, folding and packaging. Machinery and equipment include a water treatment system, washing machines, dryers, ironing, pressing and folding machines. The thermal load is mainly associated to hot water and steam for the washing, drying, and ironing phases. The electrical load covers power supply for water treatment and industrial washing machines. The machines operate for an average of 3500 hours. In the current configuration, the thermal load is satisfied by five methane gas boilers with a combustion efficiency of 91%. Electricity is bought from the national grid.

Table 11. Characterization of the members of the REC.

Description	Area [m^2]	Potential PV size [kW]	Electricity		Heat	
			Consumption [MWh/year]	Peak power [kW]	Hot Water [MWh_{th}/year]	Peak power [kW_{th}]
Residents	-	-	196	3-6	-	-
School	2500	60	180	58	-	500
SME	20000	500	826	800	6134	2800

Based on the energy demand, a REC in which the school and the SME act as prosumers is assembled and analysed in pyRES, *Figure 71*.

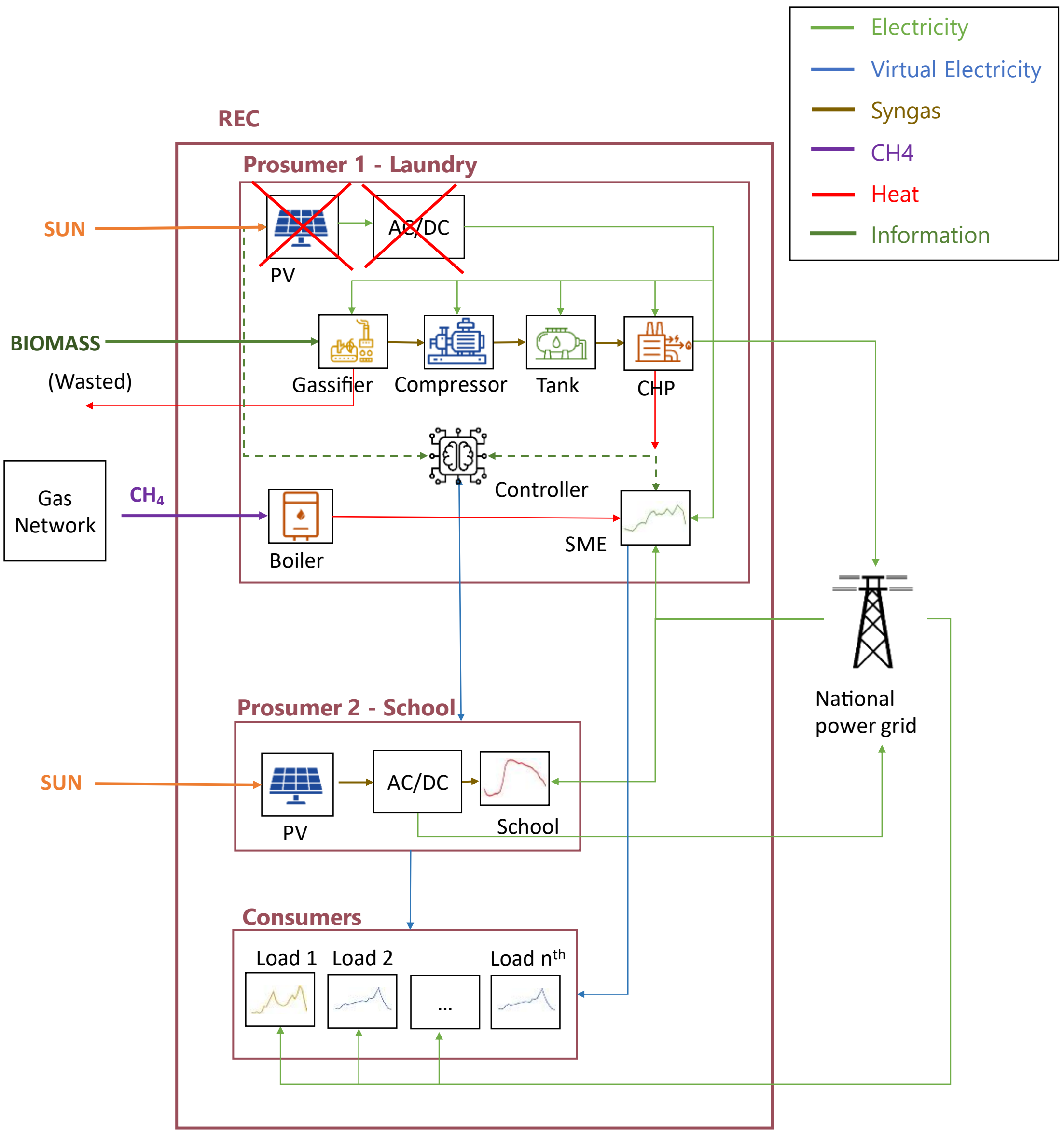

Figure 71. REC model in pyRES.

In pyRES, energy flows are calculated with a resolution of 15 minutes; hence, the inputs are the quarter-hourly demand curves, reconstructed using RAMP [18] in cases where real consumption data are unavailable. The integration between boilers and a biofuel-powered CHP system to self-produce heat is evaluated for the laundry, here labelled as Prosumer1. The new configuration exploit wood chip to produce syngas through a gasification process. The syngas is then compressed and stored in a gas tank to feed the CHP system. A controller guarantees the track of the electrical load and the optimal operations of the CHP system to access the high-efficiency cogeneration incentives [3].

The introduction of a PV to self-produce electricity is evaluated to the school, which is labelled as Prosumer 2. The establishment of the REC allows to share the prosumers surplus of electricity with community members via a virtual connection; on the contrary, sharing of heat is not possible due to the absence of a district heating network.

6.3 Scenarios

The REC analysis is carried out using pyRES. In this work, the digital twin development involves several phases: first, a territorial analysis is carried out to identify the energy demand, the potential number of consumers and prosumers and the availability of renewable sources. Second, the demand curves of each user are built based on real consumption data or through an energy audit when real consumptions are not available. Third, the type of renewable production systems is selected for each prosumer and the production curves are estimated. Finally, a multi-objective optimisation problem is carried-out to size the systems and select the best combinations of REC members. The aim is to identify the consumers who contribute the most to increase the amount of shared energy and thus to increase the economic incentives of the REC. To achieve this, all potential consumers loads are defined, and a genetic algorithm of NSGA-II type is used to compare all possible combinations of consumers [19]. Since the thermal consumption is also considered, modules for biomass gasification system, gas compressor, gas storage and the combined heat and power (CHP) have been developed and integrated into pyRES components. Furthermore, a controller has been developed to optimize the CHP operations of the system.

The biomass gasification module in pyRES is designed to estimate the electricity consumption, heat production, and syngas production, *Figure 72*. To simplify the description of the thermo-chemical process involved in transforming biomass into syngas, the module relies on manufacturer specifications (*Table 12*). The main variables include electric power [kWel], thermal power [kWth], the type of fuel, fuel consumption [kg/h], syngas composition [Vol%], lower heat value [kJ/kg] of syngas. Assuming that input biomass and output syngas properties at a specific working point are provided by the manufacturer, the module calculates the syngas production per kilogram of biomass fed to the gasifier. The model does not consider the dependence of the thermos-chemical performance on the specific characteristics of the input biomass or the environmental conditions. Results were validated using experimental data obtained from literature [20][21].

Table 12. Main parameters of biomass gasifier from technical data sheet.

Electric power [kW_{el}]	200
Thermal power [kW_{th}]	261
Fuel	Natural wood chips (DIN ISO 17225-1)
Fuel consumption [kg/h]	225
Syngas composition [Vol%]	CO (17-20%), H_2 (13-16%), CH_4 (1-5%), CO_2 (7-12%) C_nH_n (0,1-0,5%), N_2 (residual)
Lower heat value [kJ/kg]	5580

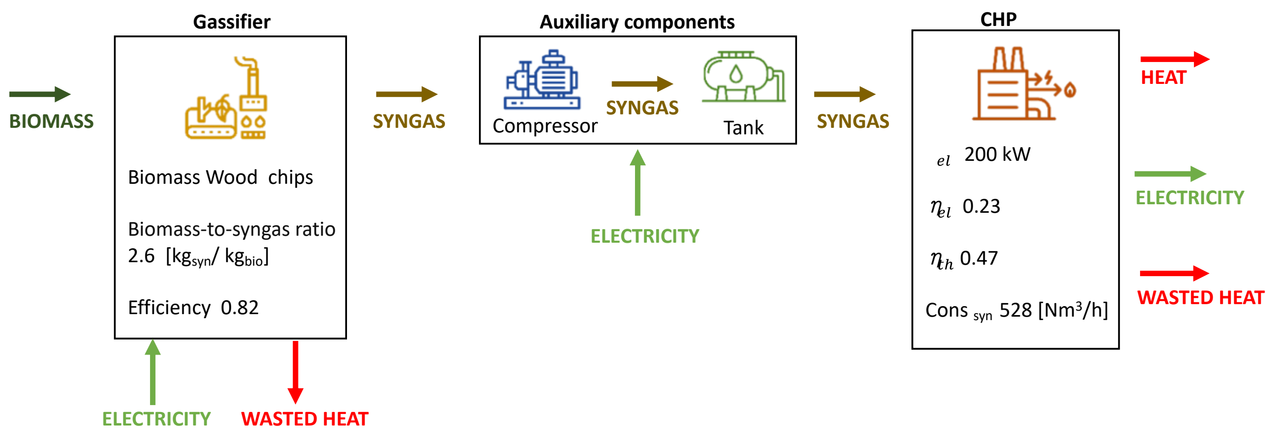

Figure 72. Biomass-fuelled cogeneration system for Prosumer 1 (Industrial Laundry).

The CHP module simulates a generator set. The module is based on the characteristic curve that indicates the fuel consumption for each power regime, which can be found directly on the manufacturer's data sheet. The characteristic curve in case of syngas is shown in *Figure 73*.

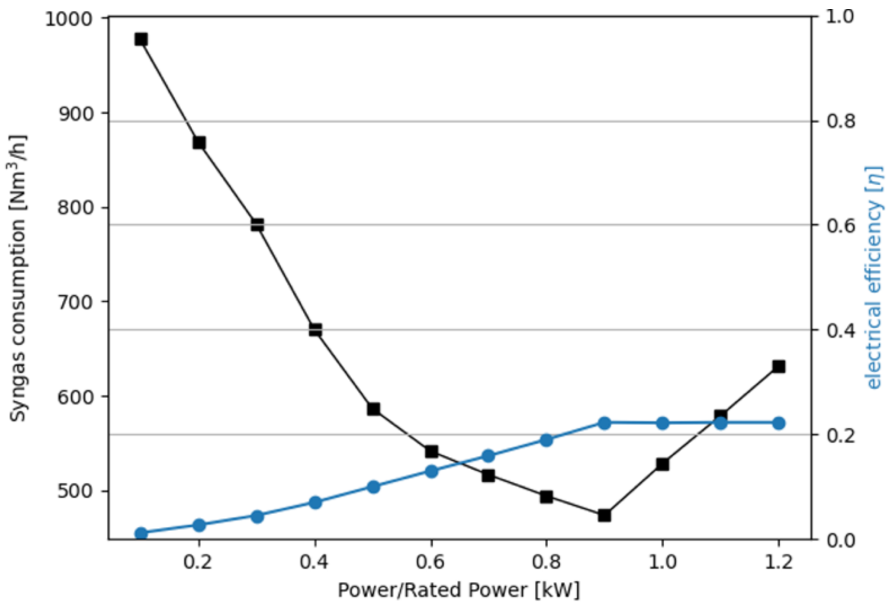

Figure 73. Fuel consumption curve of a 200 kW cogenerator fuelled by syngas.

In the following two different control strategies were implemented, one to set the generator to follow the prosumer electrical load, another to follow its heat demand. In the first case, the controller (*Figure 74*) ensures the integration of photovoltaic power (PV_{prod}) with the power generated by a CHP system. The CHP system consists of a group of engines with nominal, maximum, and minimum power equal to P_n, P_{max}, and P_{min} respectively. When the photovoltaic production cannot match the demand (D), the controller calculates the number of engines (n) to activate and the power (P) of each engine to meet the residual demand not satisfied by photovoltaic production. If *n* exceeds the maximum limit (n_{max}), the controller increases the power P and if necessary, sets it to the maximum (P_{max}). If there is still an unsatisfied demand, the controller buys energy from the national grid. Conversely, if *n* falls below the minimum (n_{min}), the controller decreases the power P, and if necessary, sets it to the minimum (P_{min}). If there is still surplus production, the controller sells energy to the national grid. When the demand (D) is completely satisfied by photovoltaic the controller sets the number of engines and the power supplied by each to the minimum level (n_{min}, P_{min}). The presence of a minimum number of working engines ensures a constant production of heat, which guarantees the stability of the heat production.

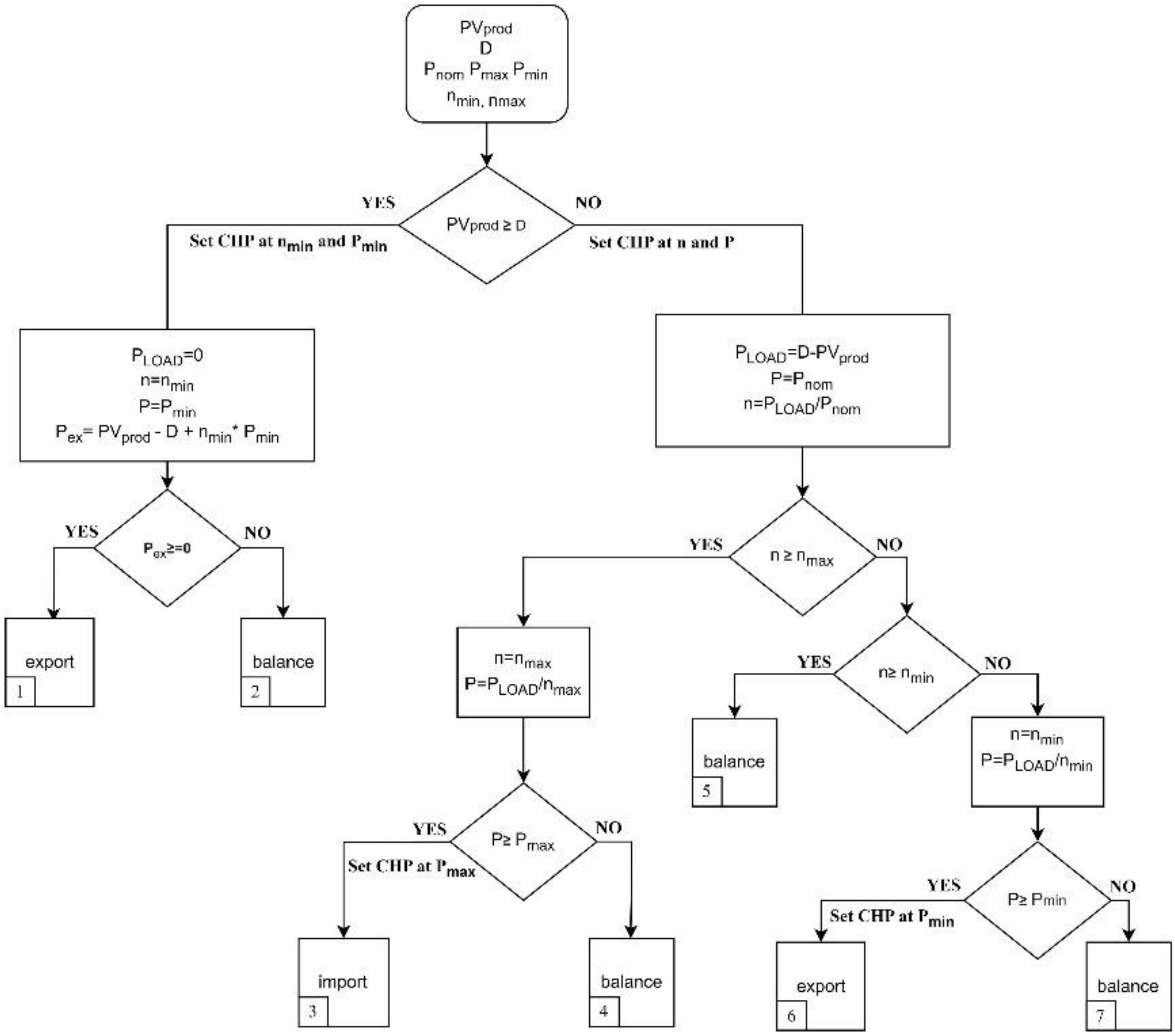

Figure 74. CHP and PV control logic scheme.

6.4 REC prosumers and consumers characterization

For Prosumer 1, the process of identifying the size of the plants involved a multi-objective optimization problem, which included the following steps:

- *selection of independent variables*: PV and CHP nominal power;
- *definition of range of variables*: the photovoltaic power ranges between 0 and 500 kW. The maximum value was determined considering the availability of spaces, with an utilization factor of 0.4 to account for safety access spaces, shading, and maintenance activities. The CHP power varies discretely from 0 to 300 kW, *Table 13*. Each configuration has a specific gasification system, while the syngas tank size remains the same for all configurations;
- *selection of objective functions:* objectives of the problem are to maximize the Net Present Value (NPV) of the investment and minimize the initial investment;
- *problem formulation:* from pyRES modules it is possible to calculate the energy metabolism of the prosumer. Once the annual self-consumption, export, and import values have been calculated, savings on the bill and revenues from energy sales can be determined. By comparing revenues with costs and repeating the analysis for all years of the investment, the cash flow is calculated. The initial investment and NPV are calculated based on the photovoltaic power and the cogeneration power. Integrating the pyRES modules with an NSG-II type genetic algorithm, the analysis is repeated for all values of the independent variables within the defined intervals. Finally, the algorithm selects only those solutions that maximize the objectives.

Table 13. Potential sizes for CHP and biomass tanks.

Variable	Configuration					
	1	2	3	4	5	6
CHP [kW]	19	35	50	100	200	300
CHP [kW_{th}]	28	51	73	146	292	438
Biomass consumption [kg/h]	20	40	55	110	225	250
Tank [m^3]	10					

For Prosumer 2, the PV system is sized based on peak demand leading to a size of 60 kW. The best mix of consumers of the REC is determined in a multi-objective optimization analysis with the NSGA-II genetic algorithm. The objective functions are the NPV of the REC and the revenue for each consumer. The REC cash flow is calculated under the assumption that the investment and maintenance costs of the systems are paid from the prosumers, that also receive revenues from energy sold, while incentives from shared energy are split 50/50 between prosumers and consumers. The optimal configuration is determined by comparing 2^{50} possible combinations, where 50 corresponds to the maximum number of potential consumers. Reference parameters for economic performance calculations are summarized in *Table 14*.

Table 14. Economic parameters.

	Investment time [years]	20
	Discount rate [%]	3
Annual production decay	PV [‰]	6
	Biomass Gasifier and Cogenerator [‰]	4
Initial cost	PV [€/kW]	1500
	Biomass systems [€/kW]	4100
O&M	O&M PV cost [€/kW/year]	40
	Replacement inverter after 10 years [€/kW]	140
	Biomass Gasifier and Cogenerator [€/kWh]	0.025
Resource cost	PUN [€/MWh]	130
	Wood chips [€/ton]	80
	Gas [€/Sm3]	0.75
Taxes	PV management cost (GSE) [€/kW/year]	0.65
	Taxes on energy sold [%]	20
	REC management costs [€/POD/year]	4
Incentives	PV Bonus50%	
	High efficiency cogeneration [€/MWh]	250
	REC shared energy [€/MWh]	118

6.5 Results

Prosumer 1 – Laundry

CHP set to match the electric load of Prosumer 1

The results of the optimization problem designed to identify the best combination of solar panels and CHP in the configuration of Prosumer 1 are shown in *Figure 75*. The combination that maximizes the NPV corresponds to 200 kW_{el} of CHP without PV systems. In fact, when the cogenerator follows the electric demand of the consumer it is able to completely match that demand most of the time. The peaks in the electric load, even if aligned with solar production during summertime, are limited and do not justify the economical expenditures of a separate PV plant. The drawbacks of this configuration come with the cogenerator operations. In fact, in *Figure 76* the electric and heat performance of the CHP is shown for a typical winter and summer day. The controller logic that follows the electric demand is able in both cases to match the load of the prosumer. There is no over-production so when the CHP is working no electricity is sold to or bought from the national grid.

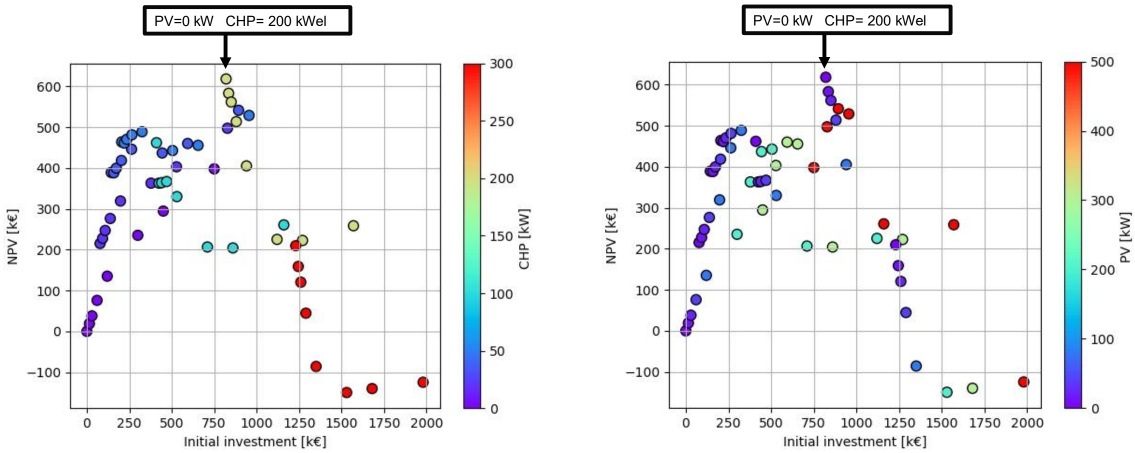

Figure 75. Optimisation analysis for sizing of Prosumer 1 with CHP matching the electric load.

When the electric load is below the threshold of 80 kW, the CHP switches off, e.g. twice on the winter day and three times for the summer day shown in *Figure 76*. This behavior is detrimental for two reasons: first the cogenerator is forced to work at partial load, increasing the amount of required syngas (*Figure 73*). Furthermore, continuous switches on/off of the system increase the maintenance costs [22]. Finally, in a REC scenario this prosumer is not able to share electricity to users and therefore would act as a normal user in case of over-production from Prosumer 2.

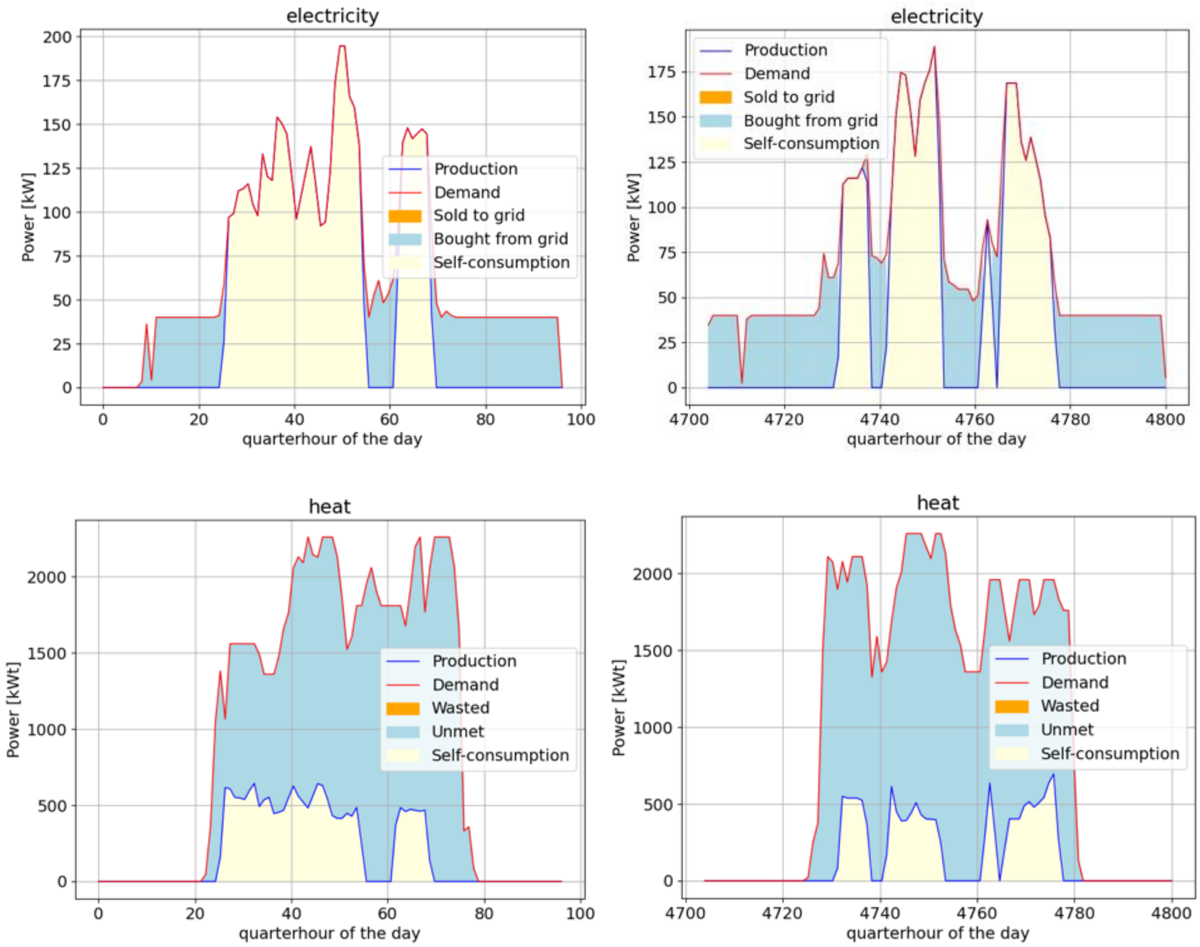

Figure 76. Electric and heat performance of Prosumer 1 for a typical day in winter (left) and summer (right) with CHP matching the electric load.

The electricity and heat balances for typical weeks for each season are shown in *Figure 77,* confirming that the trend is basically the same over the year. As a general comment also, the heat load is mostly constant over the year, as it is strongly related to the laundry operations and goes to zero during the weekend and holidays. On the contrary, part of the operations in the laundry result in spikes of the electric consumptions, related to specific processes.

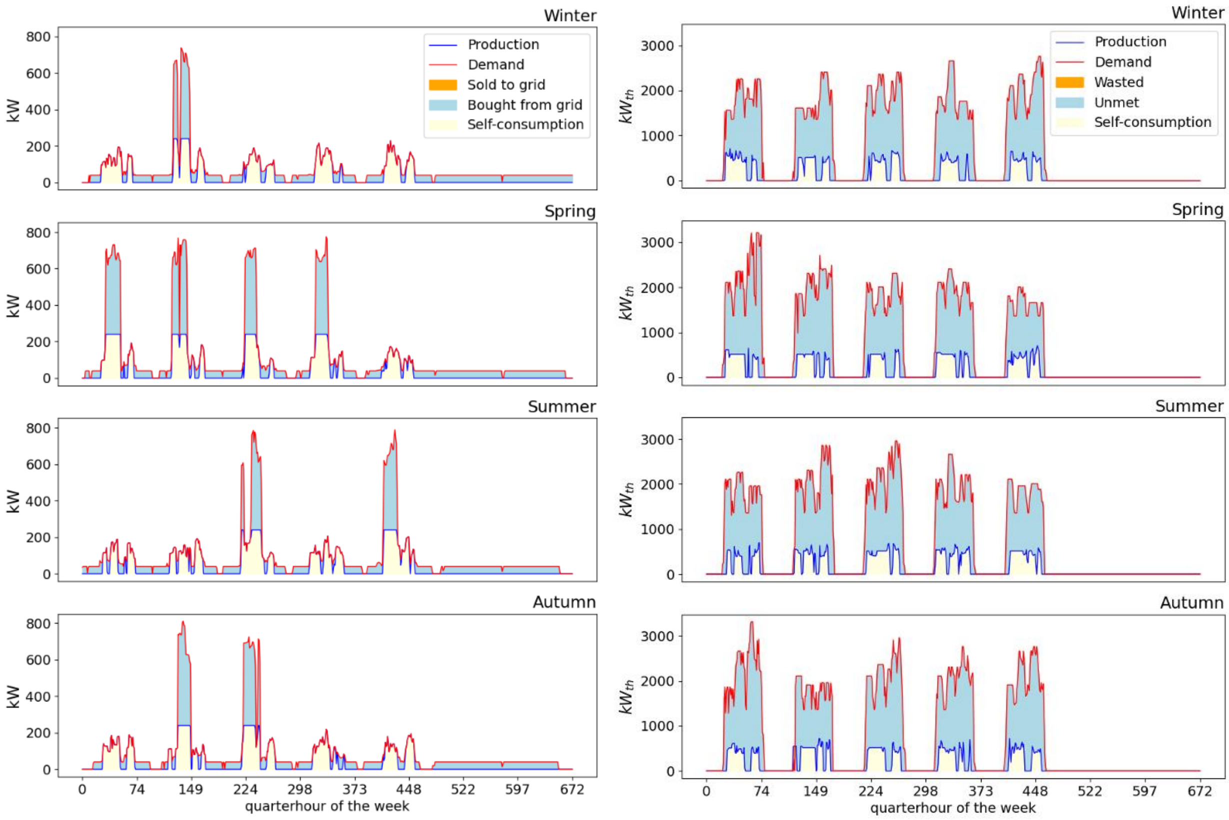

Figure 77. Production and demand of electricity (left) and heat (right) for Prosumer 1 in a typical week of each season with CHP matching the electric load.

In *Figure 78* monthly summaries of the electric performance further confirm that production is always fully consumed by Prosumer 1 and no electricity is sold to the grid. The grid however is responsible for 4/7 of the overall electricity load. On the other hand, cogeneration heat production never exceeds 1/10 of the demand. This behaviour is consistent throughout the year and is not affected by seasonality effects typical of PV systems production since the CHP adapts to the electric demand.

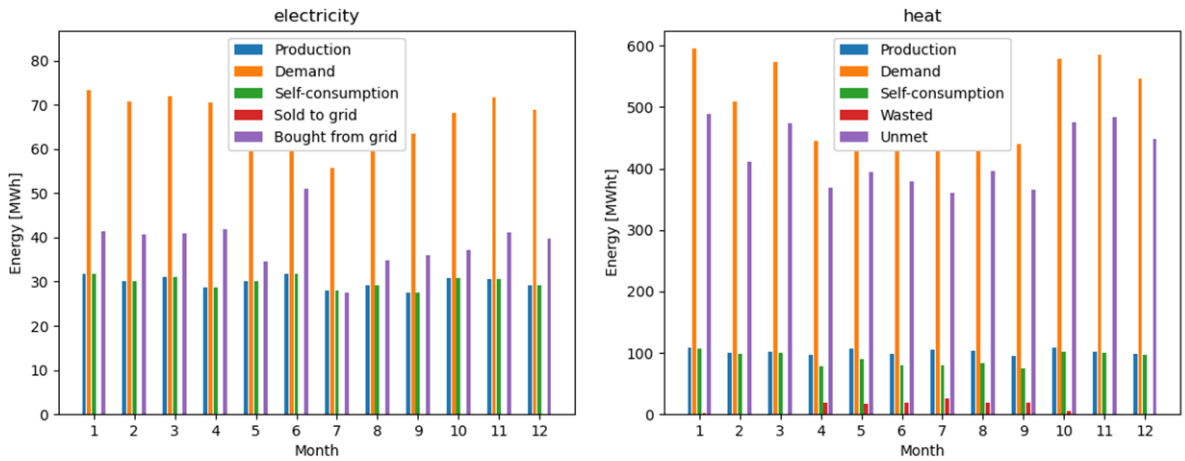

Figure 78. Monthly electricity (right) and heat (left) fluxes of Prosumer 1 with CHP matching the electric load.

The annual demand for wood chips amounts to 595 tons, corresponding to a syngas production of approximately 1.3 million Nm^3. The calculation of energy flows allows to assess costs and revenues associated with this configuration (*Figure 79*). Under the assumption that the analysed year represents a reference for the entire investment duration, it is possible to calculate the cash flow.

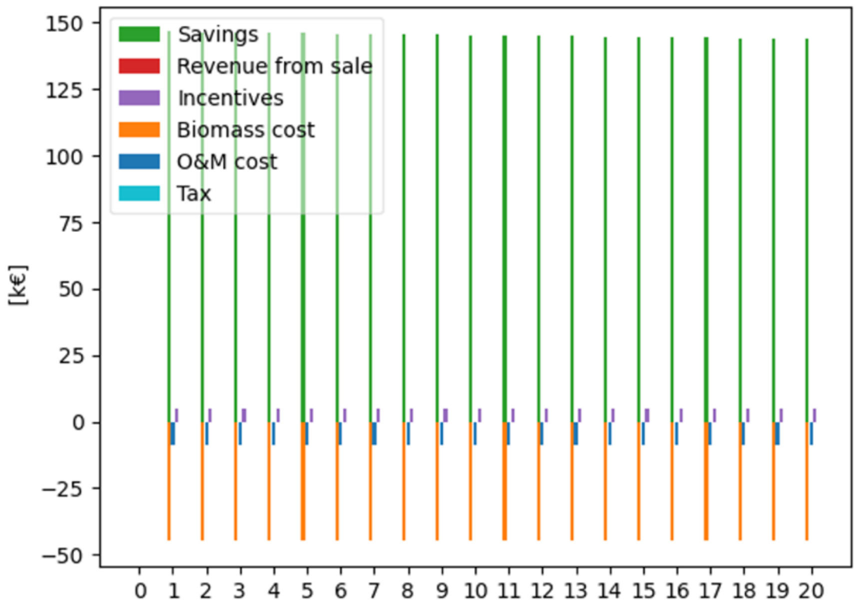

Figure 79. Main costs and revenues of Prosumer 1 with CHP matching the electric load.

Savings on gas and electricity bills represent the main revenues and are approximately six times the costs for purchasing wood chips. Cogeneration incentives and incentives represent the second part of the revenues. The last part is derived from energy sales. The list of costs includes purchasing of wood chips, maintenance costs for the gasifier and the CHP. The balance is positive, resulting in an NPV of 618 k€ and a PBP of 8.5 years.

CHP set to match the thermal load of Prosumer 1

Given the limitations highlighted with a CHP matching the electric load of the prosumer, the possibility of operating it matching the thermal load was explored. In *Figure 80* the electric and heat performance of the CHP is shown for a typical winter and summer day. The controller logic that follows the thermal demand results in the CHP working at full load during daytime, as the demand always exceeds the maximum heat production. This leads the CHP to full power and results in an excess of electricity that is sold to the grid (orange). Electricity is only bought from the grid only during night-time. In this mode of operations, the CHP switches on in the morning when laundry operations start and then is switched off when daily operations end.

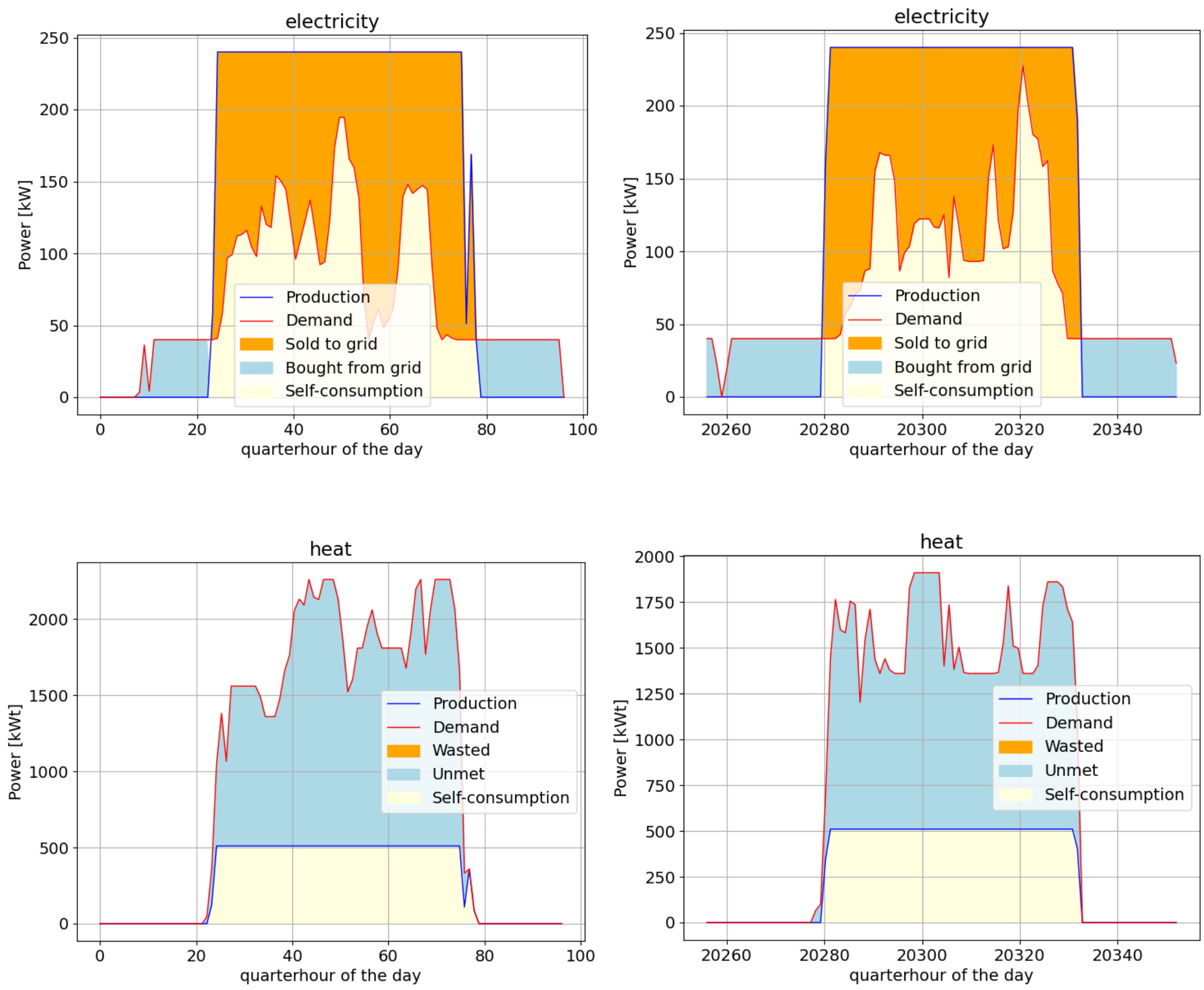

Figure 80. Electric and heat performance of Prosumer 1 for a typical day in winter (left) and summer (right) with CHP matching the thermal load.

In *Figure 81* the electricity and heat balances for typical weeks for each season are shown, confirming that the trend is basically the same over the year. The only differences occur in the days when electric load spikes and the CHP is not able to fully cover the demand.

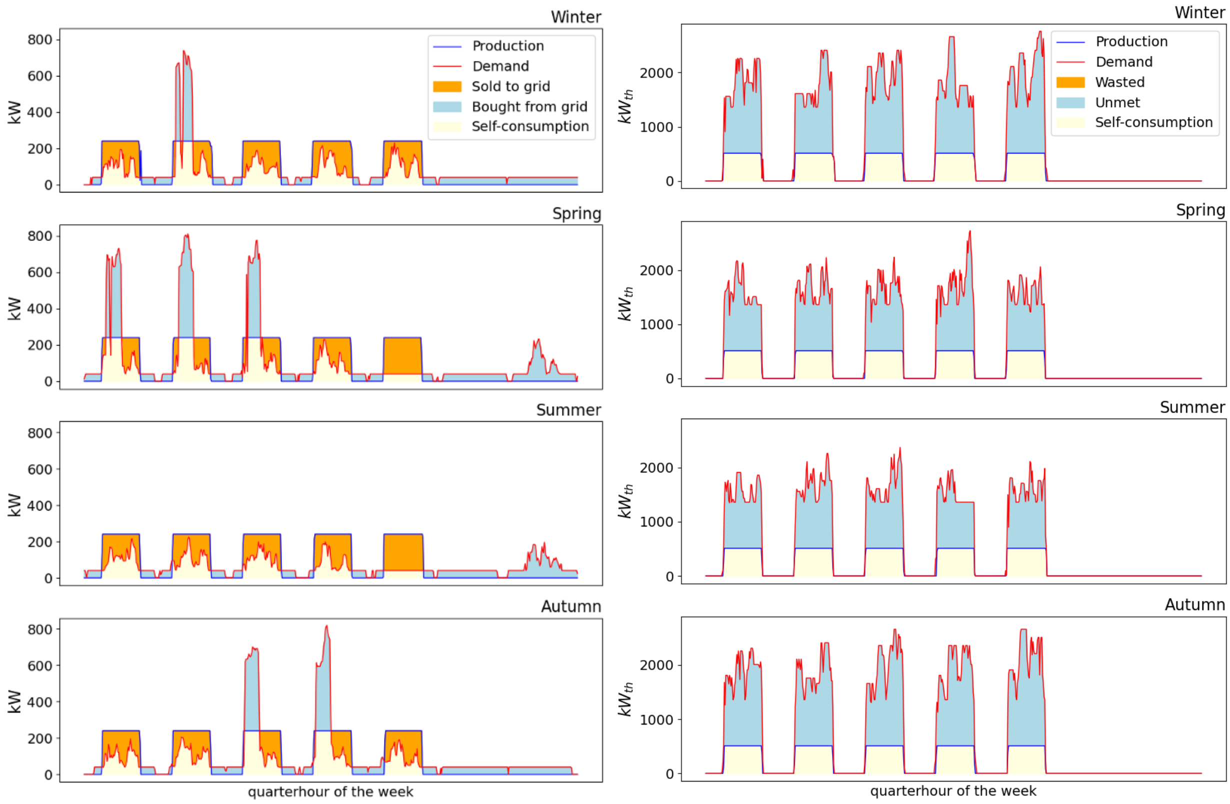

Figure 81. Production and demand of electricity (left) and heat (right) for Prosumer 1 in a typical week of each season with CHP matching the thermal load.

In *Figure 82* monthly summaries of the electric performance show a balance between production and load, with the grid acting as a storage system as the amount of electricity sold and bought are very close to each other. The heat production is basically constant over the year and covers 25% of the total load, with the rest provided by boilers.

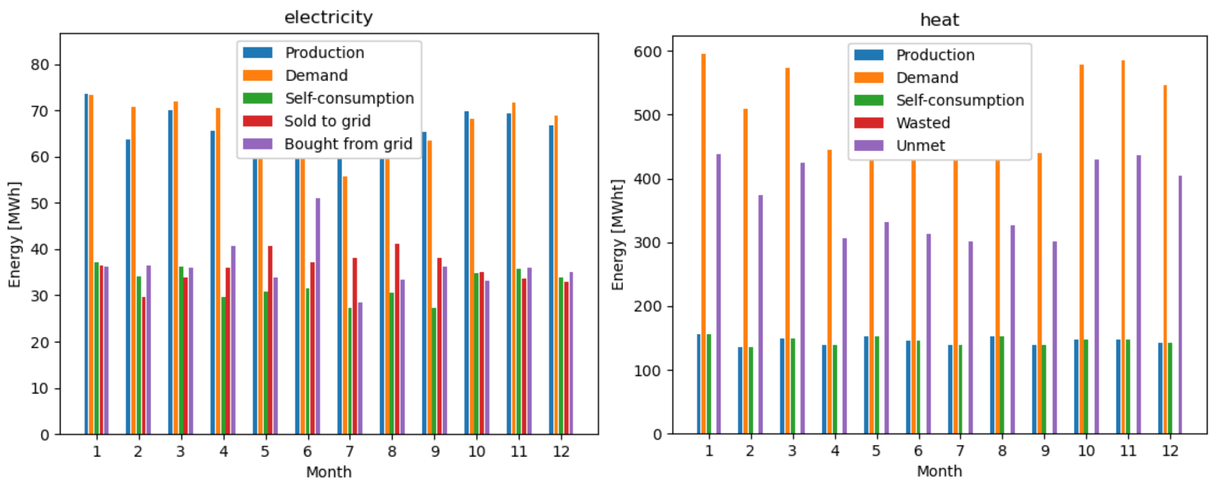

Figure 82. Monthly electricity (right) and heat (left) fluxes of Prosumer 1 with CHP matching the thermal load

The annual demand for wood chips amounts to 930 tons, corresponding to a syngas production of approximately 2.2 million Nm^3. The calculation of energy flows allows to assess costs and revenues associated with this configuration (*Figure 83*). Under the assumption that the analysed year represents a reference for the entire investment duration, it is possible to calculate the cash flow.

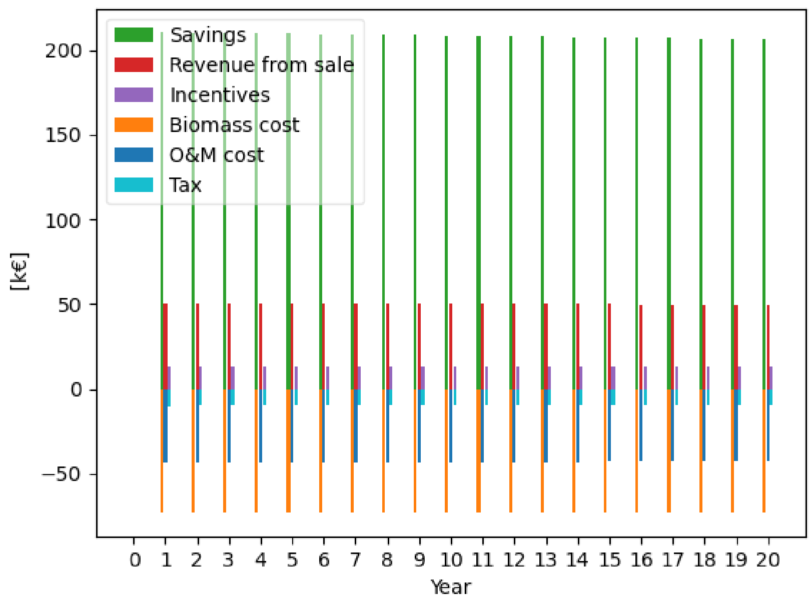

Figure 83. Main costs and revenues of Prosumer 1 with CHP matching the thermal load.

Savings on gas and electricity bills represent the main revenues and are approximately four times the costs for purchasing wood chips. The cogeneration incentives represent the second part of the revenues. The last part is derived from energy sales. The list of costs includes purchasing of wood chips, maintenance costs for the gasification and CHP. The balance is positive, resulting in an NPV of 1.34 M€ and a PBP of 5.6 years. In *Table 15*, a comparison of the Prosumer 1 performance is given when the cogenerator is controlled to match the electric or the thermal load. It is evident how the second solution results in better overall performance as the demand of biomass increases by 56% but in so doing the amount of energy sold and bought from grid result balanced, heat production increases by a factor of 60% and from an economic point of view the NPV of the investment increases by 116%, the PBP decreases from 8.5 to 5.6 years.

In terms of environmental impact, the savings in CO_2 emissions increase by 70% when the cogenerator is set to follow the thermal load. These savings refer to the reduction of emissions with respect to those associated with the savings in electricity bought from the national power grid and those from methane savings. Carbon neutral CO_2 emissions from biomass combustion, however, also increase with a factor of 70%. In this scenario matching the thermal load is more convenient under most of the aspects that are considered and provide Prosumer 1 with an excess of electric production that can be shared with users of a REC.

Table 15. *Comparison of Prosumer 1 performance when CHP matches the electric or the thermal load.*

Resource/Vector		Laundry CHP matching	
		electric load	thermal load
Wood chips	Demand [ton/year]	595	930
Syngas	Demand [Nm3/year]	1,323,706	2,161,332
	Production [Nm3/year]	1,402,647	2,191,636
	Stored [Nm3/year]	78,941	30,304
Electricity	Demand [MWh/year]	826	826
	Production [MWh/year]	359	821
	Self-consumption [MWh/year]	359	389
	Sold to grid [MWh/year]	-	432
	Bought from grid [MWh/year]	467	437
Heat	Demand [MWh/year]	6,134	6,134
	Production [MWh/year]	1,220	1,745
	Self-consumption [MWh/year]	1,091	1,745
	Wasted [MWh/year]	129	-
	Import from gas turbine[MWh/year]	5,043	4,389
Economy	Working in High efficiency cogeneration [%]	30	100
	Initial investment [k€]	820	820
	Incentives from high-efficiency cogeneration [k€/year]	5	13
	NPV [k€]	618	1,341
	PBP [year]	8.5	5.6
Emissions	Saved emissions [tCO_{2eq}/year]	400	694
	Carbon neutral emissions [tCO_{2eq}/year]	231	362

Prosumer 2 - School

For Prosumer 2, the PV system was sized based on the school peak demand which is equal to 60 kW. Analyzing the energy flows for four weeks of the year (*Figure 84*), it is evident that, excluding public holidays, the daily demand profile of Prosumer 2 matches well with the production profile of the PVs. However, the typical seasonality of school energy demand is opposite to that of PV energy production, which reaches its maximum during the summer months when demand is at its lowest. Analyzing the monthly flows in *Figure 85*, in August the export to national grid becomes 11 times larger compared to January, and self-consumption is approximately halved. The coverage reaches the maximum in May, when production is 80% of the demand, and the minimum in November, when the production is only 25% of the demand.

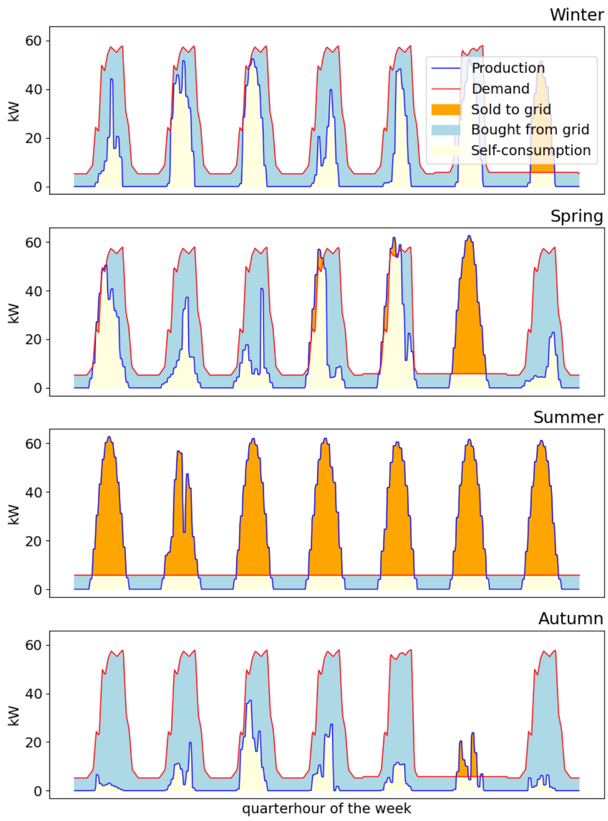

Figure 84. Production and demand of electricity for Prosumer 2 (school) in a typical week for each season.

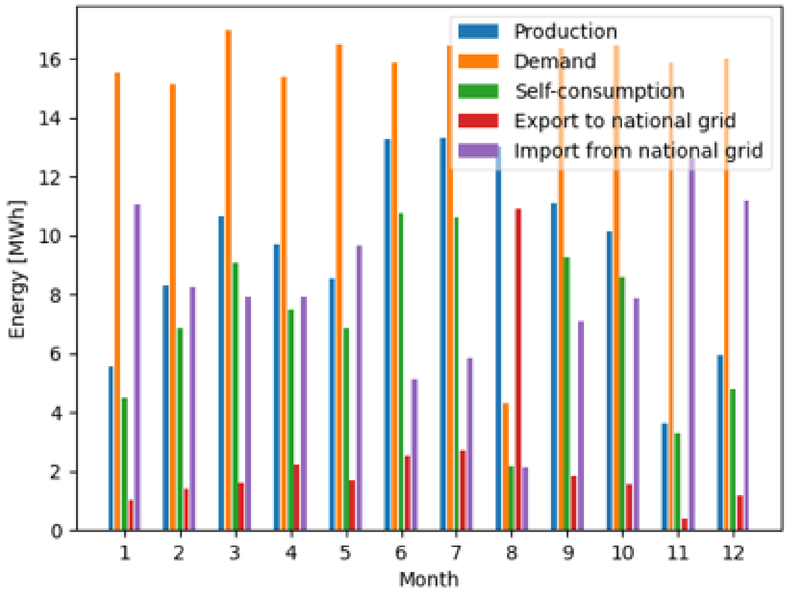

Figure 85. Monthly electricity fluxes of Prosumer 2 with PV=60 kW.

The main cost and revenue items for Prosumer 2 are shown in *Figure 86*. Savings on electricity expenses are the main source of revenue, amounting to approximately €12,000 per year compared to the €4,800 per year generated from electricity sales. This demonstrates how maximizing self-consumption brings both economic and energy benefits. The last revenue item consists of the Bonus50% incentives, which are only available for the first 10 years of the investment. Maintenance costs are the highest, reaching a peak of €11,000 in the tenth year due to inverter replacement. Finally, there are taxes on revenue from energy sales. The balance is positive, resulting in a NPV of €99,000 and a PBP of 7.3 years. In this case the reduction of CO_2 emissions accounts for 72 tCO_{2eq}/year.

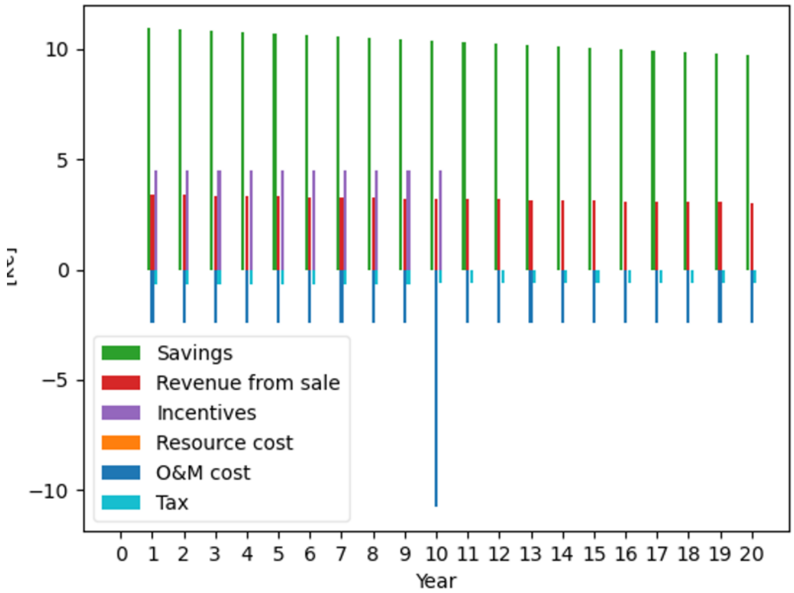

Figure 86. Main costs and revenues of Prosumer 2.

Renewable Energy Community

Both the laundry (with the CHP that match the thermal demand) and the school present an excess of production available to share within a REC. The best combinations are identified and represented in the Pareto front of *Figure 87*. As the number of consumers increases, NPV increases because the probability to absorb the surplus of prosumers and to increase shared energy, on the other hand the revenue for each consumer decreases. The choice of the best mix depends on the purpose of the REC. If the community aims to generate a common fund and use it for social interventions, it is advisable to include all available consumers. Otherwise, if the goal is to divide the incentives among the members, finding the best combination becomes essential. In the optimal solutions, the total number of consumers ranges from 15 to 33. The selected combination corresponds to a NPV of 33,000 € and a revenue of 71 €/year for each of the 23 members.

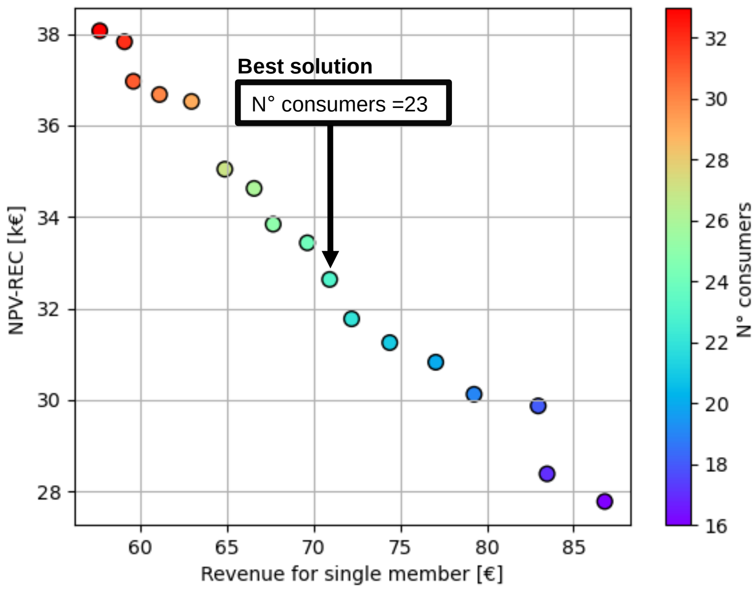

Figure 87. Pareto front of the optimal REC considering a maximum of 50 potential members.

Analyzing the energy flows for four weeks of the year, *Figure 88*, the excess of prosumers, ranges from 20 to 200+ kW while the peak of the total demand ranges from 17 to 600 kW. The excess of prosumers satisfies almost 100% of the demand during the summer months when the CHP is in operations. In the other months, the excess is unable to meet the demand peaks, and the electricity continues to be imported from the national grid. From the analysis of the monthly flows in *Figure 89*, the REC guarantees a minimum of 7 MWh of shared energy in all months of the year.

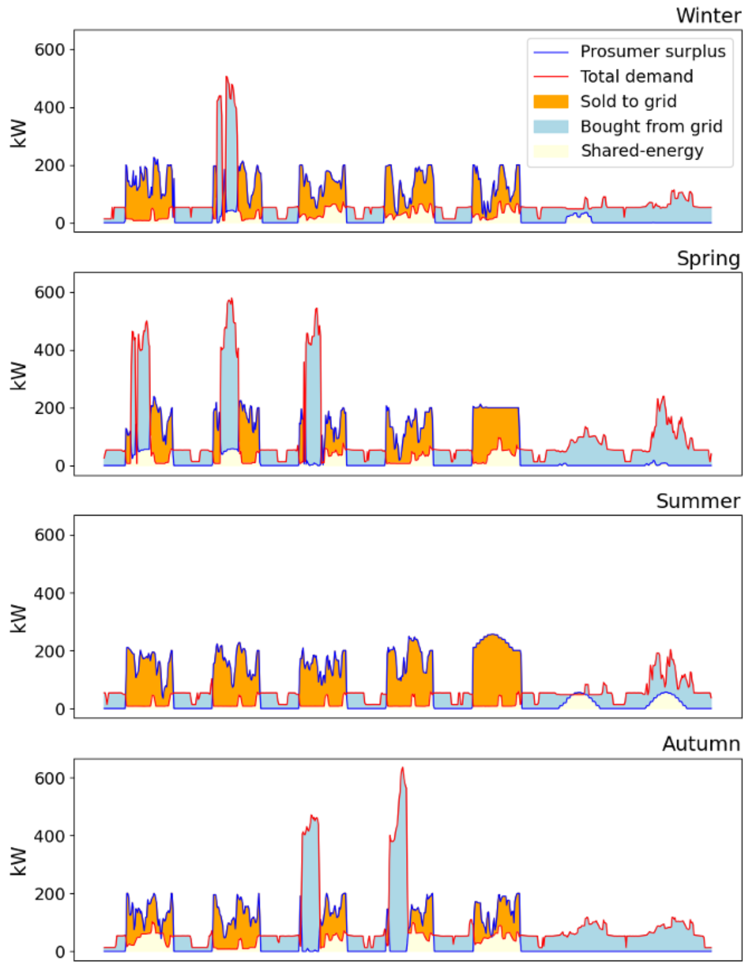

Figure 88. Prosumers surplus and consumer demand for the REC with 25 members in a typical week for each season.

Table 16 summarizes the energy and economic performance of the REC, which has a total of 25 members, (23 consumers and 2 prosumers). The overall electric demand of the REC accounts to 628 MWh/year, calculated as the sum of the amount of energy that prosumer still need to buy from the grid – blue values in the table - and that of all the consumers).

Twenty-five percent of the export of the two prosumers is converted into shared energy which contributes to satisfying about 40% of the consumers demand. The aggregation of the REC results in a NPV of €33,000 and a revenue of approximately €71 per year for each consumer. Based on the proposed financial model for sharing of REC incentives, prosumers earn a total of €190,000.

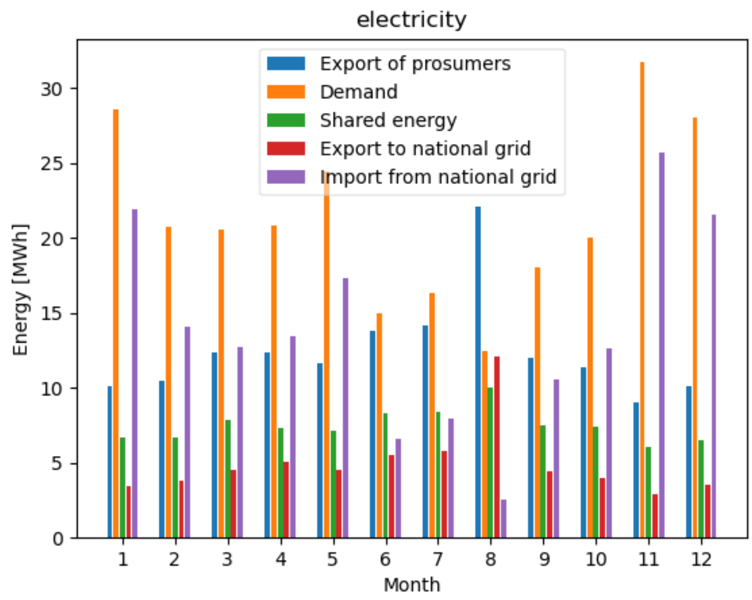

Figure 89. Energy performance of REC (resolution of a month).

In terms of environmental impact, the total savings in CO_2 emissions are 766 tons/year. These savings refer to the reduction of emissions with respect to those associated with the savings in electricity bought from the national power grid and those from methane savings. Carbon-neutral CO_2 emissions from biomass combustion are estimated as 362 tons/year.

Table 16. Summary of REC energy and economic performance.

	Prosumer1	Prosumer2	REC
	Laundry (th mode)	School	
Number of members	-	-	25 (**2 pros** + 23 cons)
Demand [MWh/year]	826	181	628 (**437**+**97**+94)
Production [MWh/year]	821	113	-
Self-consumption [MWh/year]	389	84	
Sold to grid [MWh/year]	432	29	
Bought from grid [MWh/year]	**437**	**97**	
Shared energy [MWh/year]	-	-	96
Initial investment [k€]	820	90	0
NPV [k€]	1341	99	33
PBP [year]	5.6	7.3	-
Revenue from REC in 20 years [k€]	95	95	-
Consumer revenue in 20 years [k€]	-	-	1.5
Saved emissions [tCO_{2eq}/year]	694	72	
Carbon neutral emissions [tCO_{2eq}/year]	362	0	

6.6 Conclusions

The new directive for RECs in Italy is mainly focused on incentives on shared electricity within members. However, especially in communities with wide availability of biomasses, incentives on the systems can play a major role in the aggregation of members of the community and in general in the reduction of carbon emissions. Starting from real data for electric and thermal loads, a REC was assembled around two prosumers, an industrial laundry with combined heat and power fueled by wooden biomass, and a school with PV panels. In the study the cogenerator in the laundry can be set to either follow the electric or the thermal load. A throughout analysis of the quarter-hour energy and financial performance, however, points out that the latter setting performs better, as the cogenerator can work at its rated power reducing the syngas consumption and increasing the amount of electricity that is sold to the national power grid and made available to the REC.

Also, the school PV plant has a production curve aligned with the electric load for most of the months. In fact, only during summertime the school is closed with reduced consumptions and the excess of electricity is shared to other REC members.

Selecting an optimal number of residential consumers around these two prosumers allows to have a financially valuable REC, to maximize the NPV and revenues of the members and save 766 tons/year of CO_2 emissions, with further 362 tons/year coming from biomass combustion.

The takeaway is that a small-size 200 kW cogenerator fueled with wooden biomass can fit very well in a small REC with a significant thermal load and that the REC financial incentives can significatively reduce the costs of installation. This scenario can be found and easily replicated in multiple communities in Italy and other countries.

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7. Conclusions

The spread of RECs, as new model for energy production and sharing, can be attributed to policies against climate change and the widespread adoption of renewable technologies. Furthermore, the spread of RECs has been made possible by the liberalization of the electricity market and the direct involvement of consumers in selling of self-produced energy.

Particular emphasis was placed on the fundamental principles promoted by the RED II and IEM directives, and on the transposition status in the member States. The transposition in various States is nonuniform. On one hand, allowing States the freedom to interpret certain concepts such as “participation freedom” and “proximity to renewable systems” can be positive as it preserves autonomy in decision-making. On the other hand, this flexibility can result in situations of poor transposition and departure from fundamental principles, as seen in the cases of Luxemburg and Greece. The transposition should incorporate the principles of social justice and energy democracy, encourage the complementarity of multiple renewable sources, introduce requirements for the heterogeneity of involved actors, and promote flexibility and demand control. In addition, it should prioritize the development of rules that ensure the priority of RECs in dispatching and incentivize smart technologies improving member connections. From a national perspective, Italy represents a case of successful transposition. It is also one of the few states to have included RECs as a tool to combat energy poverty. However, regulations for heat production and sharing are crucial to expand the mix of technologies within the REC and the application of RECs to the industrial sector.

RECs have impacts in various sectors, the quantification of which is achieved through the definition of indicators that can be categorized as energy, economic, environmental, and social indicators. The impacts of RECs on the electrical grid have been not fully quantified, the only positive impact recognized by national regulations is the reduction of network losses.

An analysis of commercially available software was conducted to identify the main limitations in modelling of RECs and identify the requirements for new modelling tools. The main challenges include the integration of novel calculation methods, implementing customized management and control logic, simulating new incentive mechanisms, and sharing models and results in their original form, with individuals lacking licenses, given that this software is not open source. The aim behind the development of an open-source Python tool for the design, analysis, and optimization of RECs is a response to these limitations.

The development of pyRES represents the major contribution of this work. It is a tool that expands the research group's capabilities and is currently used for educational purposes, supporting the analysis of RECs within the project conducted in collaboration with the Lazio Region, and carrying out scientific analyses focused on RECs. Specifically, within the scope of this work, pyRES was initially used to investigate the challenges of implementing a REC in a minor island scenario, with Ponza island as a case study. Subsequently, it was employed to compare the REC model with that of the prosumer, and finally, to explore the potential for REC development through the integration of multiple energy vectors and the implementation of configurations specifically customized to the local context. pyRES has proven to be a valuable tool for managing the complexity of the REC system, which is extensively described in this work, and for testing the REC model in various contexts. The main advantage is the flexibility, allowing it to adapt to the specific requirements of each REC. Its main limitation is the absence of a graphical interface, which can pose a challenge for non-expert users. A crucial next step may involve sharing pyRES on official Python platforms to expand its user base and initiate an improvement process through contributions from external authors.

In this study, the REC model has been tested in different energy contexts with the aim of identifying key advantages and challenges. In the case of the island of Ponza, the establishment of a REC based on the integration between renewable energy systems and conventional systems for clean water production ensures the profitability of solar systems. The NPV increases by 125%, rising from -34 000 to 134 000 €. This result is particularly significant in a context characterized by highly variable energy demand, where the economic viability of renewable installations is not guaranteed. Establishing a REC allows for greater control over the territory and enables specific synergies aimed at maximizing on-site consumption of renewable energy. Furthermore, the REC allows for a 60%

reduction of CO_2 emissions. In the case of an individual prosumer, the REC results a more economically viable configuration than batteries for maximizing on-site consumption of renewable energy. With the installation of batteries, there is a 55% increase in the initial investment for the prosumer and a 24% reduction in NPV, while the increase in self-consumption is only 20%. In contrast, in the REC configuration, with the same initial investment, not only is there a 65% increase in on-site consumption of the produced energy, but also a 7% increase in NPV. In the case of cogeneration with a higher demand for thermal energy than electrical energy, the REC allows for sizing the system to match the thermal load and sharing the excess electrical production. In this way, not only is the regular operation of the cogenerator ensured, avoiding close cycles of shutdown and restart, but also the surplus electrical production generates incentives worth 96 000 €, making the investment in new technologies more attractive. Even in the case of strongly seasonal loads, such as that of a school, the presence of the REC ensures the on-site consumption of the produced and unused energy.

Generalizing it is possible to conclude that:

- From an economic perspective, establishing a REC generates a cash flow, that would not otherwise exist, without incurring initial investment costs;
- From an energy perspective, establishing a REC changes the sizing logic of production systems, no longer sized based on the consumption of individual prosumers but based on the energy demand of consumers near the installation. This increases the usage of available spaces and the penetration of renewable sources;
- From an environmental perspective, establishing a REC results in a reduction of CO_2 emissions since the energy is produced from renewable sources.

It is advantageous to adopt the REC configuration in energy setups where:

- Production installations are oversized compared to the energy demand;
- Production systems cannot adapt to the demand;
- There is a seasonal energy demand in all situations where production cannot adapt to the seasonality of demand.

On the contrary, the REC model may be less attractive when the incentives derived from shared energy are divided among REC members rather than generating a common fund. In all analyzed configurations, the annual gain per individual member never exceeds a few hundred euros. This result reinforces the collaborative nature of the REC.

7.1 Ongoing projects and potential development

Since pyRES allows for a detailed analysis of the performance of individual components and their interaction at the level of a single REC, the analyses presented here are focused on a single community. To analyse the behaviour of multiple communities and expand the scale to regions or even nations, it is necessary to utilize tools capable of simulating the aggregated behaviour. Scaling the analysis from a single REC to multiple RECs is essential for quantifying the impacts of these systems on the electric power grid. An analysis aimed at quantifying the impacts of RECs on the electric power grid is currently in the development phase. This analysis utilizes Calliope [1] to create a digital model of Lazio Region in Italy including existing RECs and potential ones, and to reconstruct the energy flows between these RECs and the electric power grid.

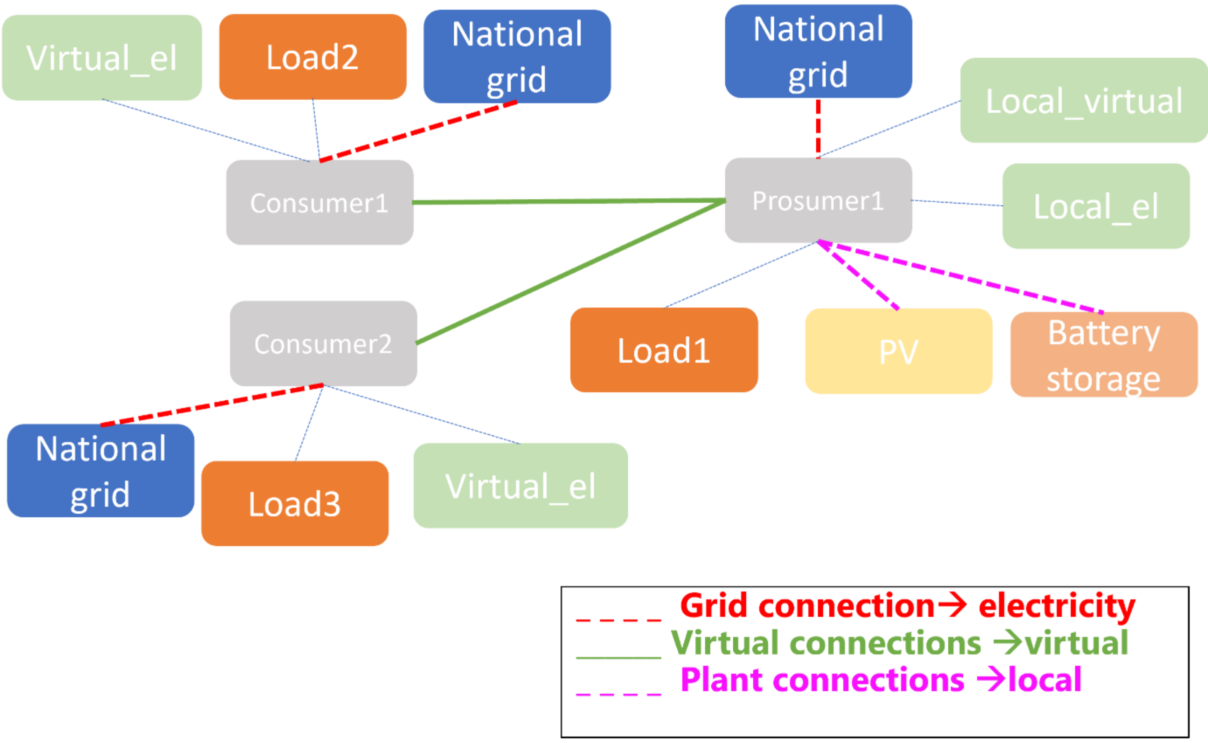

Figure 90. Modelling of the REC in CALLIOPE.

To simulate the incentive mechanism of the REC in CALLIOPE three vectors must be defined:

1) *Electricity*: corresponds to the energy demand of users and the interface with the power grid.
2) *Local*: corresponds to the energy produced by the photovoltaic systems and the interface with the prosumer.
3) *Virtual*: corresponds to the surplus of production circulating on the virtual connections and the interface between prosumer and consumers.

The model of the simplest REC in CALLIOPE is shown in *Figure 90*. In the prosumer node a local-electricity converter converts the energy produced by the photovoltaic system into energy consumed by the prosumer (self-consumption). Additionally, there is a local-virtual converter that converts the energy not consumed by the prosumer into virtual energy to be shared on the virtual connections (shared energy). In the consumer node a virtual-electricity converter converts the energy from the virtual connections into electricity which is consumed (shared energy. This schematization allows to distinguish the main energy variables of the REC, which include self-consumption, shared energy and interactions with the electric power grid.

The analysis is based on comparison of two scenarios:

1) NO-REC scenarios: refers to a scenario in which renewable systems are installed and prosumers are not included in a REC configuration.
2) REC scenarios: refers to a scenario in which renewable systems are installed and prosumers are included in a REC configuration that enable the sharing of the energy produced through a virtual connection.

The assessment of impacts on electric power grid is based on the calculation of the following variables:

1) Installed power of photovoltaic systems [kW]: the model allows for the calculation of the optimal size of photovoltaic systems based on an optimization problem aimed at minimizing costs.

3) Batteries capacity [kWh]: the model allows for the calculation of the optimal size of batteries based on an optimization problem aimed at minimizing costs.

4) Energy fluxes exchange between the power systems and the electric power grid [kWh].

5) The total absorption probability index: determines the amount of the time in which the power generated by production systems is completely converted in self-consumption or energy shared; correspond to the probability of fully consuming the energy production in the medium-low grid.

6) Space utilization index: is defined as the ratio between the actual installed power of photovoltaic systems and the maximum power calculated based on available spaces.

The model is in development phase because the data collection process (*Figure 91*) for the RECs is still ongoing.

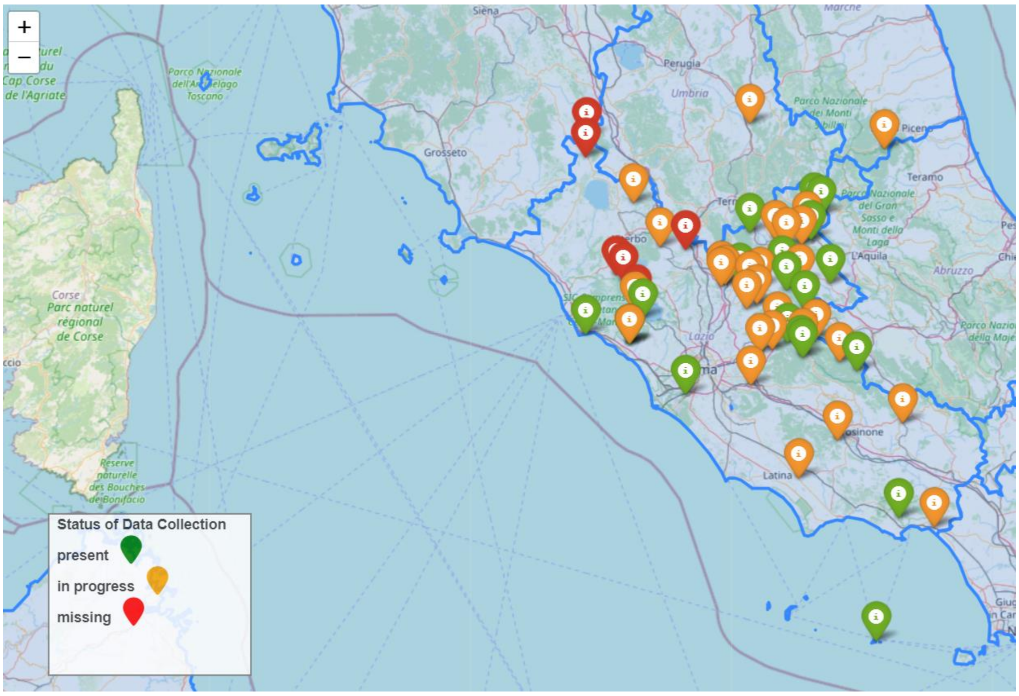

Figure 91. The data collection status for the RECs located in Lazio Region, Itay.

The data collection involves approximately 70 RECs, out of which 20 have been comprehensively assessed, 40 are currently in the reconstruction phase, and data collection has not yet commenced for the remaining 10. Based on preliminary results RECs have a positive impact on the power grid, as they increase the penetration of photovoltaic systems without altering the energy flows to and from the grid, guarantee 100% utilization of the available spaces for PV and a REC behave like a battery system with zero initial cost.

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