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Energy sharing based configurations and end-users' role towards energy efficiency and environmental sustainability

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Introduction

The contemporary global energy landscape is experiencing a profound and multifaceted transformation, aimed at addressing a set of critical challenges, including the mitigation of climate change and the attenuation of its associated impacts, the steadily increasing global energy demand, and the structural reconfiguration of energy production and consumption systems, in parallel with advancing processes of digitalization and technological innovation. Concurrently, growing emphasis is being placed on key dimensions such as energy independence and energy security, as well as on the capacity to respond to social challenges through the promotion of sustainable development.

Ensuring reliable and continuous access to energy represents a matter of primary importance, as it constitutes the foundation of technological development and the advancement of civil society [1]. The energy sector, therefore, emerges not only as an economic pillar, but also as a fundamental driver of sustainable growth, currently required to respond to increasingly stringent imperatives in terms of environmental and social sustainability [2]. Achieving long-term sustainable development entails not only improving energy efficiency but also promoting innovation and the widespread adoption of cleaner technologies [3].

Although global energy consumption is influenced by multiple factors in different ways across world regions, future outlooks point to an overall upward trend, driven primarily by global population growth and increasingly warmer global and local climatic conditions. Social, demographic, and economic factors are increasingly affecting the energy needs. Over the past decade, energy demand has declined in advanced economies, while it has grown significantly in emerging countries, particularly in China and India, with projections indicating further rapid growth by 2030 [4]. The Covid-19 pandemic represented a major global disruptive event: in 2020, total energy demand decreased by 5 % [5], before rising by 0.5 % [6] in 2021 compared to the pre-pandemic year, in conjunction with the resumption of economic activity following the crisis [7]. These dynamics highlight the close interconnection between social factors, economic activity and environmental impact. This scenario places environmental sustainability and the development of more efficient technological solutions for energy devices and systems at the forefront.

In this context, the restructuring of the global energy system emerges as an urgent priority, aimed at the accelerated integration of renewable energy sources (RES). A progressive yet structural transition is therefore underway, shifting from traditional fossil fuel–based energy

systems toward renewable solutions, thereby laying the foundations for a more sustainable, resilient, and lower greenhouse gas (GHG) emissions energy future [8].

The decarbonization of final energy consumption has been accompanied by a significant acceleration of electrification across both the residential sector and traditionally fossil fuel–dependent sectors, including industry and transport. Electrification of energy consumption represents one of the primary technological pathways pursued to promote the integration of RES through more easily deployable and widely distributed technologies. This multi-sectoral process has acted as a key driver of a profound restructuring of energy production systems, characterized by the emergence of an interconnected network of decentralized assets increasingly supplied by RES. However, achieving climate neutrality requires complementing this approach with the deployment of further strategies, including integration of hydrogen technologies and carbon capture techniques [9].

The implementation of global initiatives aimed at achieving significant changes in the energy sector constitutes a fundamental effort within the energy transition. Reducing GHG emissions, increasing the share of energy from RES, and improving energy efficiency [10] represent some of the main aspects of this complex process. In recent years, the transition toward clean energy has accelerated substantially, driven by government policies and industrial strategies that have promoted actions to enhance also energy independence in response to geopolitical instability caused by ongoing conflicts worldwide and the surge in energy prices [11].

The need to address unprecedented global climate change has led the European Union (EU) to set ambitious targets to accelerate the energy transition. In 2016, the EU formally ratified the Paris Agreement, with the primary long-term objective of limiting the increase in the global average temperature to well below 2 °C and, if possible, to 1.5 °C above pre-industrial levels [12]. Three years later, in 2019, the European Commission introduced the *Green Deal*, a roadmap aimed at achieving the ambitious goal of climate neutrality across the continent by 2050 [13]. This initiative was later reinforced in 2021 with the introduction of the *Fit for 55* package, which set the target of reducing GHG emissions by at least 55% by 2030 [14]. In line with the pursuit of these objectives, the *Clean Energy for All Europeans* package represents a significant step toward supporting European citizens in transitioning away from fossil fuels toward cleaner energy sources [15].

Accordingly to the objectives defined by the EU, electricity generation from wind and solar sources is rapidly expanding and is projected to reach about 30 % of total electricity production by 2030 [16]. While this transformation is environmentally beneficial, it is essential to consider its implications for the energy system and the electricity market, which must ensure security of

electricity supply [17]. Indeed, these changes entail structural challenges that require careful consideration of the stability of the existing system, including grid adaptation and detailed planning. Although research and development of innovative and sustainable solutions are often associated with high initial implementation costs [18], such investments are crucial to addressing these challenges and supporting the long-term stability and evolution of global energy systems.

Energy policies are also driving a fundamental transformation in the role of the end-users. The increased engagement of citizens, manifested through heightened awareness of their energy choices and proactive participation in achieving collective objectives, reflects a shift from passive consumption to active involvement. This evolution embodies the adoption of a bottom-up approach, which operates in conjunction with top-down strategies aimed at expanding renewable energy production and limiting fossil fuel demand.

The active involvement of citizens and the expansion of RES-based technologies are accompanied by the concept of energy sharing. Initially conceived as a novel approach to distributing surplus renewable energy from a single building to a group of interconnected buildings within the same microgrid [19], energy sharing has evolved into a model for utilizing RES-generated energy on a much larger scale. It represents an innovative model in which multiple actors produce, consume, and share locally available renewable energy, thereby optimizing self-consumption and minimizing energy waste.

This approach enables the mitigation of the impact on the power grid (PG) resulting from the non-dispatchability of RES, while simultaneously delivering environmental benefits through the reduction of GHG emissions associated with energy generation and lowering energy costs for end-users. Within this evolving energy landscape, the central actor is the energy user, whether consumer, producer, or prosumer, defined as a final user capable of both consuming and producing energy, who seeks to minimize interaction with the grid while contributing to the resilience of the energy system. In the new configurations, emerging from the need to transform the energy system by introducing an alternative paradigm to the traditional centralized model, changes in citizens' behaviour are also required, encouraging greater awareness of energy and environmental issues and the adoption of more sustainable practices in daily life [20]. These objectives collectively converge in the concept of Renewable Energy Communities (RECs).

However, RECs does not represents the only sharing based configurations pivotal for the achievement of energy transition goals. New forms are being born and will continue to evolve in response to the system's development and the changing needs of the energy scenarios. Indeed,

district and community-oriented approaches have been promoted in the European regulatory framework for achieving the "zero-energy" or even the more challenging "positive energy" target [25,26]. In this context, Positive Energy Districts (PEDs) have been introduced, as mixed-use energy-efficient districts that have net zero CO_2 emissions and actively manage an annual local surplus production of renewable energy. They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations [27]. The deployment of PEDs is expected to significantly improve the sustainability of urban energy systems [28]. In 2018, the European *Positive Energy Districts and Neighbourhoods for Sustainable Urban Development* program was started as a part of the Strategic Energy Technology Plan Action 3.2 *Smart Cities and Communities* [29]. In addition, PEDs have been supported by Horizon 2020 Lighthouse Projects [30], the Urban Europe Joint Programming Initiative [31] and the Annex 83 of the International Energy Agency, *Energy in Buildings and Communities* [32]. In this framework, PEDs are expected to play a major role in the energy transition of cities.

European policies include a substantial transformation of the economy and society, with a green revolution in more energy-intensive sectors such as industry, residential and transport. A more efficient use of primary energy at the same energy demand directly enhances environmental sustainability, resulting in decreasing energy consumption. Despite significant investments in energy efficiency measures with efforts to promote optimal management actions and advancements in appliance technology, the future global energy demand increase is inevitable. At the same time, the rapid expansion of RES adoption for electricity generation is underway. In this context, the mitigation of the environmental impact linked to end-users electricity consumption can also be achieved by adjusting load profiles answering an environmental signal. Shifting loads for end-users implies their active participation in the energy transition process. Greater awareness of the impact of their energy choices allows a central role to be assigned to citizens also individually acting.

Aim of the research

Formally introduced within the European legislative framework through the *Renewable Energy Directive* (RED II) [21], RECs represent a concrete implementation of the paradigm outlined above. They constitute energy-sharing systems that involve residential users, small and medium-sized enterprises, and local authorities within a defined geographical area, primarily

relying on energy generated from RES. By integrating local production, storage, and consumption, RECs deliver economic, environmental, and social benefits to all participating members while mitigating grid-related challenges associated with the variability of renewable generation. Through the direct involvement of citizens, RECs implement a user-centred energy model. Community engagement fosters social cohesion and supports the adoption of more democratic governance structures [22]. Moreover, reduced energy expenditures, improved environmental conditions, and new employment opportunities generated by RECs contribute to strengthening local communities and enhancing public participation in the energy transition. At the same time, reinvesting financial benefits into community-based initiatives promotes social acceptance of sustainable development pathways and facilitates the wider deployment of RES installations [23]. The inclusion of several user categories within RECs, together with the pursuit of social objectives such as alleviating energy poverty, further positions these configurations as enablers of energy justice [24].

Within this evolutionary framework, the study presented in this thesis concentrates on a comprehensive analysis of energy-sharing configurations and the role of end-users who, even when acting independently, can mitigate their environmental impact through conscious energy consumption behaviours.

Regarding RECs, several European Member States have transposed RED II into their national legislation to enable the establishment of these energy-sharing configurations across the European territory. However, the resulting regulatory frameworks are not uniform, as each Member State has adapted the Directive to its existing cultural, institutional, and legal context.

In recent years, RECs have been widely discussed in the scientific literature. Many research groups have performed detailed analyses of RECs from different angles, such as legal frameworks, management strategies, development guidelines, and optimization models using mathematical algorithms applied to case studies. The literature offers a fragmented view of the REC implementation process, mainly emphasizing the pre-implementation phase, such as analyzing regulatory frameworks and choosing features for optimal setup, and the post-implementation phase, which involves optimization models to enhance benefits and strategies to improve energy flow management. In this context, the study presented in the first chapter aims to fill the research gap by integrating these perspectives into a comprehensive framework for REC implementation. The proposed roadmap adopts a multidisciplinary approach, beginning with a comparative analysis of legal provisions for the transposition of RECs and highlighting fundamental objectives and key characteristics of the configurations. Building on this foundation, the study aims to define a realistic and standardized process that outlines the

main phases of REC implementation. Legal, regulatory, and economic aspects are closely intertwined with energy-related, engineering, and social considerations, converging into a single, complex and articulated implementation process. In this framework, the multidimensional nature of RECs has been in-depth investigated to present a comprehensive overview of the main aspects. Technological components, optimization and simulation methods, management and monitoring strategies, as well as policy, business models and future directions have been explored, pointing to provide a toolkit for interested stakeholders. Moreover, to explore several potential advantages of RECs, case studies based on numerical and experimental investigations have been analysed and compared, also giving attention to the various application fields and highlighting different types of stakeholders.

The second chapter explores how the integration of multiple sectors can foster the advancement of innovative energy systems that represent a viable alternative to conventional models. Indeed, RECs offer the opportunity to incorporate a wide range of technologies and use domains. To expand upon the applications discussed in the scientific literature, several case studies are proposed, including electric mobility, industrial users, and energy storage systems, in order to assess both the direct and indirect benefits achievable in each scenario. With particular reference to the first case study, a highly innovative research layout is introduced. Specifically, the concept of energy sharing is combined with service integration through the deployment of electric vehicles (EVs) in a car-sharing scheme embedded within a photovoltaic-based REC. Energy, economic and environmental performance of this system is compared with that of an EV car-sharing system whose energy demand is met by the PG and a conventional vehicle car-sharing system. Additionally, the adoption of battery energy storage systems is evaluated to enhance system flexibility and efficiency. A dynamic simulation model is developed to predict the real time operation of a REC based on photovoltaic panels coupled also with energy storage. Furthermore, a REC case study involving industrial members, characterized by complex and variable energy demands, has been conducted, filling the gap in the literature which lacks studies focused on industrial RECs. Overall, this diversity of applications highlights the potential of RECs as adaptable and scalable solutions within the evolving energy landscape.

The heterogeneity of regulatory frameworks and implementation strategies adopted across European countries has played a crucial role in shaping the development of RECs. Such diversity has not only influenced the design and operation of these initiatives but also created favourable conditions for the emergence of comprehensive studies. Nevertheless, the scientific literature reveals a gap mainly concerning the comparison between the application of real

sharing models and the assessment of the direct economic impact on individual REC members. Therefore, the last study presented in the second chapter closes the analysis of RECs with the aim to present a numerical evaluation of real REC under different sharing schemes, starting from the model proposed by the Italian and Spanish normative contexts. These two have been selected for their effective focus on energy sharing, also from an economic perspective, despite adopting different approaches. The potential benefits, limitations, and performance of different implementation models have been evaluated through a comparative approach adopted to better understand how regulatory and contextual factors affect outcomes at both the community and individual levels.

As previously introduced, PEDs are also emerging among energy-sharing configurations as enabling frameworks for sustainable urbanism. The scale of intervention expands from individual buildings and building blocks to the broader neighbourhood or district level, allowing for integrated energy strategies across urban systems. However, their limited practical implementation across the EU reflects critical barriers, including the lack of a clear and universally accepted definition, the absence of a dedicated design guideline and the insufficient development of urban-scale energy planning strategies. With a view to facilitating its dissemination, ongoing research is focusing on identifying a specific definition and developing support tools, which, in any case, do not yet come to embrace the complexity of these systems and to maintain a territorial and not generalized scale. Available tools indeed mainly focus on strategies for renovating the existing building stock and mapping existing initiatives. According to the findings of the literature review on this topic, some of the main gaps challenging district-level environmental analysis include the right balance between accuracy and easy implementation, which may also encourage citizens to be eager to alternative energy systems characterised by high pervasiveness of renewable-based technologies. Within this context, in the third chapter, a novel methodology useful for district energy and environmental analysis, intended to support the accomplishment of the targets of PEDs at the district or community level, is introduced. To make the proposed evaluation framework accessible to as many user categories as possible, the calculation steps have been translated into a user-friendly tool, aimed at the technological design of the district, with the ambitious target of being defined as PED. Due to its structure, the tool overcomes the need to predefine the type of district with reference to the users included, since the user directly provides this information by uploading energy consumption data. It supports the replicability of configurations that facilitate the energy transition and provides general guidance for the system design required to approach targets of positive energy balance and carbon neutrality. Among the novelties introduced by this pre-

feasibility tool for PED design is its ease of use. The tool has been developed in an environment designed to enhance usability and accessibility, allowing it to be effectively used even by users without specialized computational skills.

Finally, the role of end-users is examined within an energy landscape that places them as central to pursuing environmental objectives in the energy transition. The analysis builds on evidence of a decreasing trend in the environmental impact of the PG, driven by the growing share of electricity generated from RES, while also highlighting the pronounced hourly variability of associated CO_2 emissions, closely mirroring the temporal patterns of renewable generation. In this context, a novel consumption paradigm for end users is proposed, based on load-shifting strategies guided by environmental signals. This represents a departure from the prevailing approaches in the scientific literature, where such strategies are primarily employed in response to economic and operational signals, typically aiming to reduce peak demand and lower costs. In contrast, the approach introduced in the fourth chapter focuses on optimizing end-user load profiles with the explicit objective of minimizing CO_2 emissions. It demonstrates how users can actively contribute to reducing the overall environmental footprint of electricity drawn from the PG by aligning their consumption with periods of lower carbon intensity, even through individual actions. Unlike conventional demand response programs, in which emissions reductions are generally treated as a secondary outcome, this study places environmental impact mitigation, directly linked to changes in consumption patterns, at the core of the optimization framework, thereby offering an original contribution to the literature.

In light of the investigated topics, it emerges that energy-sharing-based configurations, together with the active role that end-users can assume within these frameworks and individually, play a pivotal role in supporting the energy transition process. Such approaches contribute to improvements in energy efficiency and reductions in environmental impacts, in alignment with sustainability goals aimed at addressing the most pressing global challenges.

Chapter I: Renewable Energy Communities: main aspects and potential benefits

Renewable Energy Communities (RECs) represent an innovative energy model founded on the principles of production, consumption and sharing of energy from renewable energy sources (RES). In the current scenario, RECs emerge as a key instrument to support the objectives of the energy transition, promoting management models that place the end-user, who assumes an increasingly active and participatory role, at the centre of the energy system. Their implementation enables the pursuit of multiple goals, including the enhancement of energy efficiency, the reduction of environmental impacts, and the generation of both economic and social benefits.

The concept of REC is inherently multidisciplinary: originating from energy-related issues, it extends to legislative frameworks, multisectoral applications, business models analysis and the assessment of social implications within the territories in which these communities operate. This multifaceted nature constitutes the basis for an in-depth investigation of the topic, aimed at exploring the various dimensions and potential of RECs in fostering a more sustainable, inclusive and participatory energy future.

1.1 Introduction to Renewable Energy Communities

In 2018, the European Commission introduced RECs through the Renewable Energy Directive (EU) 2018/2001, commonly referred to as RED II [21]. RECs are energy-sharing systems that involve residential users, small-medium enterprises (SMEs), and local authorities in a specific area. These communities primarily use energy produced by RES-based plants, resulting in economic, environmental and social benefits for all members. These are seen as alternatives to conventional fossil fuels-based energy production in collective systems. Since their introduction, European citizens have considered RECs a democratic and bottom-up solution that allows them to actively participate in the energy transition [19]. RECs have a

significant social impact as they facilitate access to alternative energy sources for many citizens [33] and help to address energy poverty, a social issue highlighted by the World Energy Outlook of International Energy Agency (IEA), which projects that around 75 million people will face difficulties paying for electricity due to economic pressures in the next years [4].

The REC's concept concerns the sharing of energy choices among more members and is linked with the broader subject of Smart Energy Communities (SECs). SECs, which has been researched since the 70s [34], can be characterized as clusters of energy service providers, whether private, public, or a combination thereof, situated within a defined geographical region. In such communities, end-users, including citizens, businesses, and public administrations, fulfil their energy requirements by embracing a collaborative strategy. This involves the implementation of decentralized energy generation solutions that are often based on RES technologies, but they may also include high-efficiency fossil-based energy conversion systems able to meet both thermal and electric energy community needs. The overarching goal is to derive advantages in terms of cost efficiency, sustainability, and safety. In this scenario, the topic of this chapter is priority referred to a specific subcategory of SECs, which are the RECs as understood in European regulations. In these communities, members share facilities based on RESs for electricity generation, including virtual sharing schemes. Nevertheless, some RECs also involve the sharing of thermal energy.

1.1.1 Initial European Regulatory Framework for RECs

To achieve the decarbonisation objectives by 2030, the EU revamped its energy policy framework in 2016 with the publication of the *Clean Energy for all European Package* (CEP) [15]. CEP, which came into force only in 2019, consists of eight new laws introducing legislative measures across various sectors: energy performance in buildings, renewable energy, energy efficiency, and the electricity market. Two of these directives are particularly relevant in terms of end-users' role in the transition process: Directive 2018/2001, also known as RED II [21], focuses on promoting the use of energy from RESs and introduces renewable energy self-consumers and RECs. Directive 2019/944, International Market Energy Directive (IEMD) [35], establishes common rules for the internal electric energy market and introduces Citizen Energy Community (CEC). Unlike from RECs, CECs do not have membership restrictions or geographical constrains [36]. RED II sets a binding target of at least 32 % share of consumption from renewable energy by 2030, collectively achieved over a decade (2021–2030) by the Member States, based on the gross domestic consumption of the EU. In particular, the Directive aims to promote the development of energy production from RESs within the EU by actively

involving citizens. It introduces models of participation of increasing complexity, defining and regulating individual self-consumption, collective self-consumption, and RECs. According to RED II, a REC is defined as a legal entity "*based on open and voluntary participation, autonomous and effectively controlled by shareholders or members that are located in proximity of the renewable energy projects that are owned and developed by that legal entity*" [21]. These shareholders or members can be natural persons, SMEs, or local authorities, including municipal administrations. The primary objective of the REC is to provide environmental, economic or social benefits to community shareholders or members or to the local areas where it operates, rather than financial profits. The aim of RED II is to support acceptability of RES-based projects among Europeans and in the electricity market, while the IEMD contributes to the completion of internal market. The consumer is at the core of the energy market, and both directives emphasize its central role [37]. By June 2021, European Member States were expected to transpose RED II into national law to introduce common guidelines for establishing RECs, with the aim of removing unjustified regulatory and administrative barriers. However, due to differences among European States in terms of regulatory and cultural aspects, a one-size-fits-all approach was not the best solution.

Some Member States have adopted measures to enable self-consumption and the establishment of RECs in their territories, even before the issuance of RED II by the European Parliament . [17]Below is a summary presentation of the initial regulatory provisions on RECs in some EU Member States.

Spain

The Spanish government introduced two forms of self-consumption through Royal Decree 244/2019 [38]: self-consumption with and without surpluses, allowing or disallowing the injection of excess energy into the grid respectively [39]. In 2020, Royal Decree 23/2020 [40] officially introduced RECs in Spain, with the aim to increase participation in RES-based projects. In April 2023, a public consultation was lunched regarding the new Royal Decree on RECs and CECs.

Germany

Germany currently has the highest number of communities in Europe [41], thanks to the Renewable Energy Act (*Erneuerbar e-Energien-Gesetz*, EEG) [42] which introduced incentive tariffs for renewable energy generation lasting 20 years. It has been updated over the years [43].

In Germany, citizens, SMEs or cooperatives which own renewable energy assets are considered RECs and are eligible for incentives or loans [44].

Ireland

The Sustainable Energy Authority of Ireland also provides incentives for renewable energy schemes that include RECs, and it is expected that their number will increase from 580 in 2021 to 1500 by 2030 [45]. Irish RECs can include various generation technologies, such as Combined heat and power (CHP) systems, to meet end-users' thermal demands [44].

Greece

Greece introduced a net metering system in 2014 and a virtual version in 2016 for independent producers. Then, Law 4513/18 [46], approved in 2018, made this metering effective for energy communities. Unlike in other European states, RECs in Greece are classified as non-profit organizations without economic distribution among members, or for-profit cooperatives, where economic distribution is possible under certain conditions as long as some conditions are observed [47].

Portugal

The Portuguese Government introduced RECs in Decree Law 162/2019 [48] in October 2019, as part of the implementation of the EU framework and the formalization of RED II, following the previous regulatory framework for individual self-consumption.

Austria

In 2017, the concept of collective-self consumption was introduced in Austria for the first time through the enactment of the Austrian Electricity Act [49]. The transposition of RED II by the Austrian Government took place in July 2021 with the Renewables Expansion Law (*Erneuerbaren-Ausbau-Gesetz*„EAG) [50], which established that RECs can provide energy services in addition to traditional generation and storage of energy from RESs.

Italy

Italy also introduced self-consumption regulation before RED II, through regional laws in Piemonte, in the North of Italy, in 2018 [51] and in Apulia, in the South of Italy, in 2019 [52]. Between the end of 2019 and 2020, the transposition process of RED II regarding RECs and collective consumption schemes began in Italy through art. 42 bis of Decree Law *Milleproroghe* (DL 162/19) [53], then converted in Law 8/2020 [54]. The introduction of some specific

constraints was marked: REC plants must have a maximum power of 200 kW and members must be connected to the same electrical substation MV/LV, from medium (MV) to low voltage (LV). The overall transposition of RED II took place with Legislative Decree N. 199 [55] entered voltage (HV) to MV and the possibility of access to the REC was extended to religious, third sector officially in force in December 2021, and the constrains were revised: the maximum power of RES plants increased to 1 MW, REC members have to be linked to the same electrical substation HV/MV, from high and research bodies. In January 2023, ARERA, the Italian Energy Regulatory Authority, published the Integrated Text Widespread Self-Consumption (TIAD) [56], which introduced an obligation for electricity distribution companies to identify areas underlying the same electrical substation HV/MV and publish them on their websites, with the aim of facilitating the data acquisition by all interested parties.

Latvia

Not all European Member States have introduced national regulations to govern RECs, although in some countries initiatives to promote the use of RES-based plants in a community-based configuration are implemented. In Latvia these initiatives are conducted by citizens' cooperatives or local municipalities for biomass-based plants [44].

Poland

In Poland, the government introduced energy clusters in 2016. Members of these clusters could be physical persons, local authorities, or research institutes linked to the grid with a 110 kV voltage constraint and a maximum of five communes [57]. Later, the Polish Parliament received the draft amendment of the Energy Law which was approved by the Council of Ministers.

Bulgaria

In Bulgaria, to support the use of RESs, the owners of RES plants are allowed to use the generated electricity for self-consumption, facilitated by shorter time limits for connection and no permits required for systems up to 30 kW of peak power. The share of non-self- consumed electricity may be sold to a supplier at a price set by the regulator [58].

The regulatory frameworks in European States have similarities and differences, but more and more countries are introducing legal guidelines to implement RECs on their territories, aiming to make them common instruments to address the energy crisis. An overview of the early regulation of RECs in some European countries is presented in *Figure 1.1*.

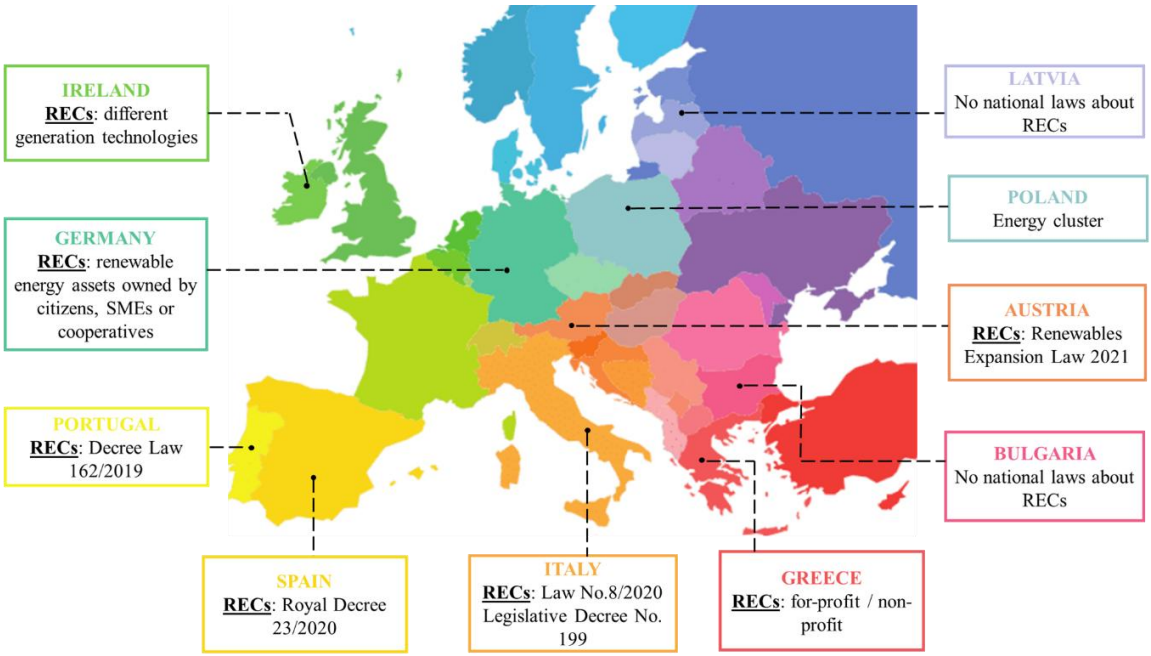

Figure 1.1 Overview of the initial regulation on RECs in some European countries.

The European regulatory framework has undergone several updates over time, as Member States have amended or revised some of the previously introduced regulations. While some countries have already aligned their national frameworks with the existing rules, others are still in the process of defining specific aspects. Both the legislative context and the concept of RECs are continuously evolving across Europe, resulting in regulatory changes being implemented at different paces and through diverse approaches in each country. Some of these national developments will be discussed in greater detail later in the following sections.

1.2 Roadmap for the implementation of a REC

The implementation of a REC proves to be a rather complex process, even when considering the rules established by the various European regulations. This complexity mainly arises from the need to integrate technical, legal, and economic expertise to ensure the successful development of such projects. Although RECs have been widely discussed in the scientific literature in recent years, studies providing practical insights and comprehensive perspectives on the concept remain limited. Many research teams have conducted analyses on RECs focusing on legal frameworks, management methods, development guidelines and optimization models based on mathematical algorithms applied to case studies. However, an overview of these three aspects for RECs is necessary in order to adequately address three issues of equal importance

and essential to each other. Scientific literature on RECs phases accomplishment mainly focuses on the pre-implementation process, involving the analysis of the regulatory framework, and the post-implementation phase, which includes proposing optimization models to increase benefits and methods to improve the management of energy flows. In light of this consideration, this paragraph is focused on the development of a standardized process outlining the main phases for REC implementation with a realistic approach. It is applicable in every context, with necessary adjustments based on national regulations. This standardized method will be beneficial not only for REC developers, but also for stakeholders and key players.

The complexity of implementing a REC is the reason why there have been several attempts to standardise the essential steps. The goal is to simplify the whole process and make it immediately understandable for anyone interested in getting involved in this ever-changing field. The presented procedure for implementing a REC has been developed through a comparison with professionals involved in real projects, taking into account the features and problems they encountered during the creation process. The main phases of the process are: feasibility study, aggregation, operating phase and management. These phases, along with their sub-phases, are presented in *Figure 1.2*. Each step will be analysed in detail within this paragraph. The starting point should certainly be acquiring knowledge of the regulations, analysing the necessary requirements and subsequently being able to operate accordingly.

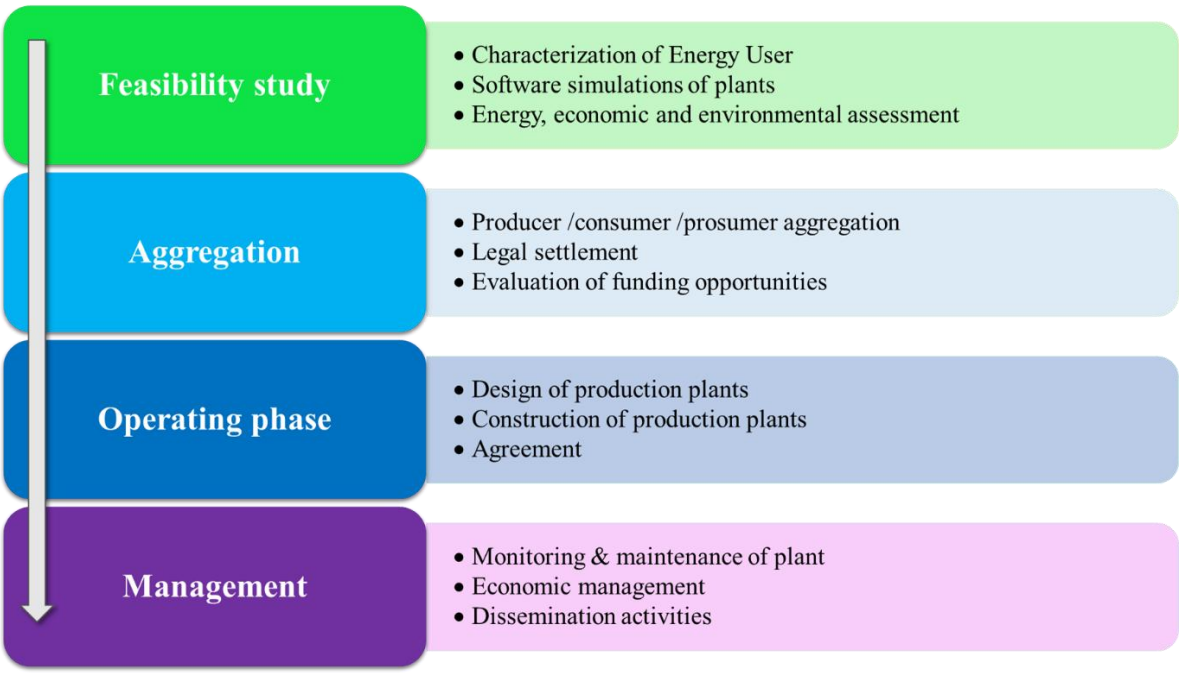

Figure 1.2 REC implementation roadmap: phases and sub-phases.

1.2.1 Feasibility study

The first phase for REC creation is the feasibility study, which aims to identify the current state of the concerned site and propose possible modifications based on this assessment. The feasibility study can be further divided into sub-phases that cover essential aspects.

- Characterization of Energy User: it involves understanding the electric and thermal energy needs and profiles of the potential REC members. Also energy modelling at the building or urban scale are conducted to estimate the potential energy demands;
- Sizing renewable energy system using software: here, software simulations are conducted to assess the potential energy production and evaluate different plant configurations;
- Energy, economic, environmental and social assessment: it focuses on analysing the energy, economic, environmental and social implications of the proposed REC.

Additionally, the feasibility study can also serve as a phase for defining the primary objective of the project. Social entrepreneurship can also be declined through REC according to aims, forms of governance and ownership, and social impact of the project [59]. Community energy entrepreneurship is inherently rooted in the local context in which it operates, guided by mutualism, its pluralistic and reciprocal nature are described as “associative entrepreneurship” [60]. In accordance with the RED II, participation in the REC is voluntary and free [61], therefore, it becomes essential to define the interaction layers among stakeholders, their roles, and the modes through which each participant is engaged. The active involvement of stakeholders within a framework of collaborative governance fosters value co-creation [62], although in such contexts the individual contribution of each member is rarely clearly visible [63]. Moreover, the collective behaviour of a community and its capacity to generate value are influenced by several additional factors [64], including collaboration arrangements, the economic interactions of participants, whether based on sharing or trading, the degree of centralization or decentralization of management, and the relationships of trust.

Characterization of Energy Users

Analysis of end-users’ energy consumption during the preliminary phase is undoubtedly approximate, as it depends on the consumers expected to be included in the REC. The process of consumption forecasting is referred to as "Characterization of Energy Users” (CEU). The CEU is useful for accurately assessing the size of the plants serving the community and

determining the types of utilities to be included in order to maximize shared energy and, therefore, energy and economic benefits. If the utilities that will be part of the same REC are already known, their energy consumption data can be easily obtained from their bills; in this case, it is possible to use these data as input for the following phase. Otherwise, if the actual consumption data are not available during the preliminary phase, estimation methods are needed to collect the data for the CEU implementation based on extensive databases with information from different spatial levels and various time resolutions [65]. Since the users' behaviours and occupancy patterns strongly influence the load profiles [66], given the extensive scope of application, one can conduct energy modelling at the level of specific structures, known as Building Energy Modelling, or on a broader scale within an urban context, referred to as Urban Building Energy Modelling (UBEM). Concerning the spatial domain of RECs, UBEM approaches seem to be most suitable, and are widely discussed in the literature, comprising two categories: top-down and bottom-up models [67]. Top-down models utilize macroeconomic variables and statistical data to make energy forecasts. Conversely, bottom-up models consider and design clusters of buildings sharing similar characteristics (both geometric and non-geometric parameters) across various modelling scales [68]. According to with previous research [69], the bottom-up approach has demonstrated its suitability for conducting thorough analyses of buildings at the urban scale to create load profiles for representative buildings within a specific area over a given period of time.

Among the bottom-up UBEM modelling approach, three methods can be distinguished: physics-based, data-driven and reduced-order. The physics-based approach utilizes simulation techniques along with building characteristics, construction details, climate data, and system information to compute end-use energy consumption. Most bottom-up engineering models predominantly utilize distribution, sample, or archetype-based methodologies. The distribution approach evaluates energy consumption by analysing regional or national distributions, while the sample modelling approach relies on real building data, requiring a comprehensive dataset. The archetype approach classifies buildings according to factors such as dwelling types, size, climate, and construction year [70]. The bottom-up data-driven approach is applied in urban energy modelling to forecast building energy consumption based on key building features. These approaches rely on accessible data sources, such as building stock datasets, utility billing details, survey data, and socio-economic variables, and generally involve a combination of statistical and artificial intelligence (AI) methodologies [71]. Reduced-order models are also gaining increasing attention due to their ability to provide rapid assessments with fewer input requirements. A unique aspect of this approach is the estimation of model parameters through

standardized procedures, such as those developed by the European Committee for Standardization and the International Organization for Standardization, which define calculation methods for building and system characteristics across different building types [69]. Overall, bottom-up UBEM approaches have experienced significant growth in recent decades.

Sizing renewable energy system using software

Knowledge of available resources and existing infrastructure in a specific territory is crucial for evaluating the effectiveness of proposed changes. The preliminary analysis phase includes examining various constraints, including size and location. The analysis of constraints refers, for example, to the positions of electric substations and the identification of connected users, in cases where the sharing of electric energy among end-users is considered. Other constraints may include any landscape-type restrictions that limit the installation of RES-based plants in specific areas or on buildings subject to certain regulations. Environmental problems should also be considered: a comprehensive understanding of the territory's hydrogeological structure helps avoid potential issues before implementing new installations. RES-based plants are usually considered environmentally friendly due to their contribution to GHG emissions reduction during the energy production process. However, they have significant negative impacts. For instance, solar photovoltaic (PV) installations can impact the visual aesthetics of an area or the building on which they are installed and have adverse effects on wildlife, resulting in bird fatalities due to the heat generated by solar modules [72]. Similarly, wind turbines also have non-negligible impacts, including visual disturbances, human health issues such as hearing loss and sleep disorders caused by noise pollution, and effects on wildlife, including bird collisions with turbine blades [73]. Additionally, before designing new plants, it is essential to assess the existing plants within the designated territory. This step is crucial for several reasons. First, it prevents overlap between existing and new facilities powered by the same RES, which may be insufficient to support multiple installations (for example biomass or hydropower). Second, assessing existing RES-based facilities enables evaluation of various scenarios for their inclusion in the community. However, the feasibility of such integration depends on the legislation in force in each country and the community's legal settlement.

Based on the CEU results derived from real data or UBEM approaches, and considering site-specific energy and environmental constraints, as well as RES availability and existing plants, RES-based systems within the energy community can be optimally sized using specialised software. Determining the size of RES-based systems is a crucial step in establishing each

plant's capacity. Inadequate sizing poses a risk of either undersizing or oversizing the system. In addition, the "plants 'sizing problem" is strictly connected to the need to achieve a large self-sufficiency and self-consumption in the REC. Indeed, given the community load, a large generation facility can increase self-sufficiency; however, it generates a surplus of energy in some periods of the year that exceeds local storage facilities and must thus be sold to the grid. On the other hand, a smaller generation can be totally self-consumed but is not able to fulfil all community energy needs. A totally self-sufficient and self-consuming community is thus almost unreachable. The plant size, the storage capacity and their management must be selected to ensure the best solution meeting REC performance. Some software tools enable optimization of this process, enhancing plant flexibility. Among the available options, one of the most widely used is Hybrid Optimization Model for Electric Renewable (HOMER Pro), which allows for modelling, sizing and optimization of a wide range of RES-based plants as production systems grid-connected or off-grid by achieving specific electric or thermal loads as input [74]. TRNSYS is a versatile, graphically based software environment used to simulate transient system dynamics, with a primary focus on evaluating the performance of thermal and electrical energy systems. It allows users to modify existing components or develop new ones within flexible modelling frameworks [75]. iHOGA/MHOGA represent two iterations of the Hybrid Optimization by Genetic Algorithms (HOGA) designed for simulating and optimizing electric RES-based systems. The iHOGA version is intended for systems ranging from a few watts up to 5 MW power, while MHOGA is tailored for power systems in the megawatt-scale. The system can incorporate various components, encompassing PV systems, wind turbines, hydroelectric turbines (with or without pumped hydro storage), auxiliary generators (diesel, gasoline, etc.), inverters or inverter-chargers, batteries (both lead-acid and li-ion), chargers, batteries charge controller, as well as hydrogen-related components (electrolyzer, hydrogen tank, and fuel cell) [76]. The Hybrid2 software is a product of the Renewable Energy Research Laboratory at the University of Massachusetts, USA, with assistance from the National Renewable Energy Laboratory. Hybrid systems—comprising both fossil- and RES-based technologies—are typically modelled using two main types of simulation approaches. Logistic models are used for long-term performance predictions and economic analyses, while dynamic models capture rapid fluctuations and system responses to changing parameters. Hybrid2 falls into the former category, using statistical analysis to enhance the accuracy of event modelling at a given timestep [77]. The RETScreen Clean Energy Project Analysis software serves as a decision-support tool developed through collaborative efforts involving government, industry, and academia. Its global applicability enables users to assess energy production and savings,

costs, emission reductions, financial feasibility, and risk associated with diverse RES-based and high energy efficiency technologies [78]. RETscreen employs a five-step analysis for each model: energy model, cost analysis, GHG's analysis and financial summary. It is important to underline that traditional software tools, while widely used for technical, economic and environmental analyses, may not always identify the optimal configuration. In some cases, codes written in dedicated programming languages are employed to solve optimization problems or simulate complex energy plants. Recently, the focus on economic and environmental assessment has expanded to include social criteria, enabling evaluation of the community's social impact [79]. Hereinafter, *Table 1.1* presents a comparison of the aforementioned software used for the sizing process of RES-based plants and useful in the REC's constitution [80].

Table 1.1 Pros and cons of software used for sizing process of RES-based plants.

	Pros	**Cons**
HomerPro	- Straightforward to use; - Sizing optimization tool.	- Solutions are based on first degree linear equations; - Limited libraries for models of energy conversion systems.
TRNSYS	- Dynamic simulation of any energy conversion system for electric and thermal energy production with high resolution; - Modelling of both buildings and plants.	- Time consuming; - Technical expertise.
HOGA	- Multi objective optimization; - Simulation with high time resolution	- Lack of sensitivity and risk analysis; - Maximum limits on daily electric loads.
Hybrid2	- Availability of several electric load options; - Comprehensive dispatching alternatives.	- Absence of models from own library; - Ignore the dynamic behaviour of the thermal and electric energy systems.
RETscreen	- Large weather database; - Excel based tool.	- Ignore the dynamic behaviour of the thermal and electric energy systems; - Disregard the dynamic performance of thermal and electric energy systems

Energy, economic, environmental and social assessment

RECs provide people with the opportunity to address energy poverty, support the energy transition from fossil fuels to RESs, mitigate environmental issues, and promote social inclusion in specific areas [81]. While the specific goals of RECs may vary, the consistent aim

is to achieve energy and environmental benefits. Furthermore, social objectives, such as combating energy poverty, and economic goals, facilitated by European countries' shared energy incentives, are pursued. In most countries, remuneration for residential prosumers is not time-dependent, but is based on the time-flexible wholesale price, which already accounts for the realistic future price [82]. To assess the existing system and alternative solutions, an evaluation can be conducted by assessing energy, economic, environmental, and social impacts. The energy analysis allows for a comparison of alternative systems in terms of primary energy savings; the environmental impact analysis evaluates the amount of GHG emissions avoided; the economic analysis enables an assessment of whether the proposed solution (REC), allows for the recovery of the investment costs within a reasonable timeframe, as well as the achievement of further benefits through plant operation and incentives related to shared energy. Social analysis considers changes in the energy poverty condition of end-users, whether they are member of a REC or not. These analyses compare a traditional energy system (TS) with the new REC in terms of energy demanded by users (specifically electric energy), as shown in *Figure 1.3*.

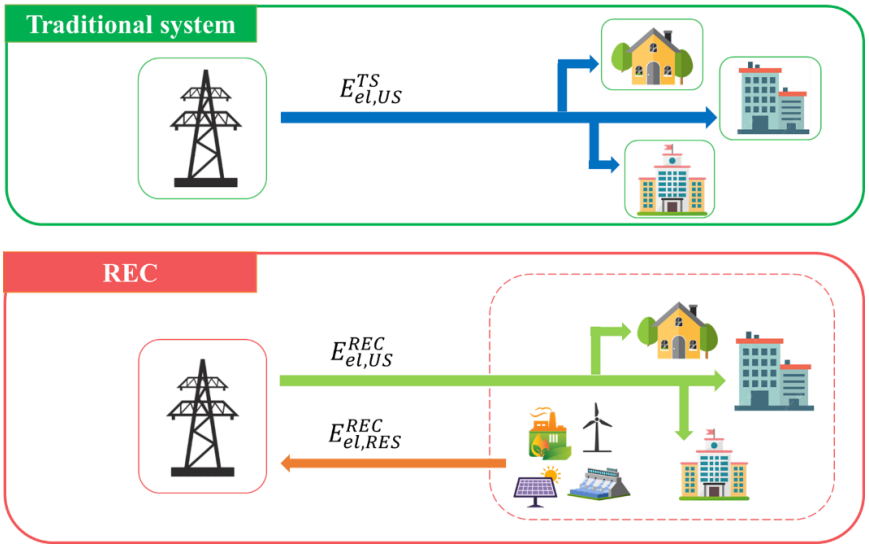

Figure 1.3 Layouts of traditional system and REC.

The dependence on the location where the REC is implemented prevents a general analysis. Therefore, certain elements, such as the calculation of energy sharing and economic incentives, will be presented in this section, according to the Italian regulations.

The electric energy requested by users is the same in the TS ($E_{el,US}^{TS}$) and in the REC configuration ($E_{el,US}^{REC}$). In the TS, the electric energy is taken from the power grid (PG), where it is produced by using a mix of power plants fed both by fossil fuels and RESs. Thus, the

average national efficiency of the PG for the given year, denoted by η_{PG}, varies across countries. In the REC configuration, the electric energy requested by the users during the specific period can be supplied by the RES community plant, if $E_{el,US}^{REC}$ is less than the energy generated by the RES-based plant ($E_{el,RES}^{REC}$). However, if $E_{el,US}^{REC}$ exceeds the energy generated by the RES-based plant in the same period, the electric energy can be taken both from it and the PG. The energy sharing occurs with a virtual scheme, by means of using the PG as electric energy exchange infrastructure. In the former case, any surplus energy "produced" by the RES-based plant and not shared is fed into the PG (E_{el}^{REC-PG}), while in the latter case, the PG compensates for the shortage of energy (E_{el}^{PG-REC}) not supplied by RES-based plant to meet the users demand. The shared energy ($E_{el,SH}^{REC}$) in the REC configuration is evaluated as the minimum value between the energy taken from the PG, so the $E_{el,US}^{REC}$, and the energy produced by the REC plant and supplied to the PG within a defined time interval, as illustrated in Equation 1.1.

$$E_{el,SH}^{REC} = \min(E_{el,US}^{REC};\ E_{el,RES}^{REC}) \tag{1.1}$$

The primary energy saving (ΔE_p) in a REC configuration compared to the TS, can be evaluated by calculating the difference between the electric energy provided by the PG to satisfy user request in TS ($E_{el,US}^{TS}$) and the electric energy provided by PG to compensate for the energy deficiency from the RES-based plant in the REC configuration (E_{el}^{PG-REC}), considering the average national PG efficiency (η_{PG}), as presented in Equation 1.2. It is worth noting that, in the REC configuration, the energy supplied by the PG is always lower than in the TS, as the community plants are designed to meet as much user demand as possible. E_{el}^{PG-REC} corresponds to the difference between energy demand of REC users and shared energy.

$$\Delta E_p = \frac{(E_{el,US}^{TS} - E_{el}^{PG-REC})}{\eta_{PG}} \tag{1.2}$$

Regarding the environmental analysis, the CO_2 equivalent emissions imputable to the electricity taken from PG, are evaluated by multiplying the electric energy supplied by the PG and the national power grid CO_2 emission factor, represented by the term α_{PG} and measured in g_{CO_2}/kWh_{el}, variable for each country. This evaluation is carried out according to Equations 1.3 and 1.4. The difference between the CO_2 equivalent emissions of TS and REC configurations, as shown in Equation 1.5, represents the avoided GHG emissions (ΔCO_2).

$$CO_2^{TS} = E_{el,US}^{TS} * \alpha_{PG} \tag{1.3}$$

$$CO_2^{REC} = E_{el}^{PG-REC} * \alpha_{PG} \quad (1.4)$$

$$\Delta CO_2 = CO_2^{TS} - CO_2^{REC} \quad (1.5)$$

With reference to the economic analysis, the yearly operating costs (OC) are evaluated for both configurations in Equations 1.6 and 1.7. Yearly operating costs of the TS (OC^{TS}) are obtained by multiplying the electric energy provided by the PG by the unitary electricity average price ($c_{el,PG}$), which is measured in €/kWh and varies for each country. The yearly operating costs of the REC layout (OC^{REC}) are calculated by considering the cost of electricity imported from the grid, maintenance costs (*MC*) associated both with the plants and REC management, and income coming from the economic incentive for the shared energy. The last term is calculated by multiplying the shared energy by the economic incentive (I_{SH}) established by the national authority. The avoiding cost (ΔOC) in a REC configuration compared to the TS can be evaluated as the difference between OC of TS and REC, as shown in Equation 1.8.

$$OC^{TS} = E_{el,US}^{TS} * c_{el,PG} \quad (1.6)$$

$$OC^{REC} = E_{el}^{PG-REC} * c_{el,PG} + MC - E_{el,SH}^{REC} * I_{SH} \quad (1.7)$$

$$\Delta OC = OC^{TS} - OC^{REC} \quad (1.8)$$

Another economic performance indicator that can be evaluated is the number of years necessary to recover the initial investment cost of the RES plant (IC_{RES}) through the annual cash flows of the REC, represented as (OC^{REC}). This indicator, Simple Pay Back (*SPB*), is calculated by comparing the first and the second term, as shown in Equation 1.9. This method is commonly used to evaluate alternative systems, employing the recovery period as a criteria for accepting a project investment. It is typically deemed acceptable if the *SPB* index is within 5 years.

A more thorough economic indicator is the Discounted Pay Back (*DPB*), which accounts for the time variation of the value of money. Consequently, the *DPB* is always higher than the *SPB*. *DBP* is calculated comparing IC_{RES} with the discounted annual cash flows of the REC until year N, as reported in Equation 1.10, where *a* is the discount rate.

$$SPB = \frac{IC_{RES}}{OC^{REC}} \quad (1.9)$$

$$DPB = \frac{IC_{RES}}{\sum_{n=1}^{N} \frac{OC^{REC}}{(1+a)^n}} \quad (1.10)$$

The social purpose of an energy community is primarily realized by addressing the energy poverty of its members, who can be included in the configuration. A quantitative analysis of this condition can be carried out through *10%* indicator. As reported in Equation 1.11, it is the ratio between the energy cost and the income (*IN*) of the considered end-user over a specific period of time [83]. If the end-user spends more than 10% of his overall income on energy services, he is considered to be in energy poverty condition. The indicator must be calculated for the end-users, whether they are members of a REC or not, and the results must be compared.

$$10\% = \frac{OC}{IN} \tag{1.11}$$

Energy, environmental, economic and social assessments conducted during the feasibility study phase are useful for a rough evaluation of the benefits of the REC configuration. However, it is important to repeat the analysis using real consumption and production data.

As mentioned above, the energy, environmental, and economic assessments have been presented exclusively with respect to the electricity sharing scheme. This approach is prevalent in various EU Member States affected by the REC regulation. The electric energy sharing among REC members is often economically incentivized, primarily because it is easier to implement than thermal energy sharing, as the required infrastructure (the PG) is usually already available. Sharing thermal or cooling energy requires dedicated infrastructure, such as district heating and cooling networks that physically connect users, making virtual schemes generally unfeasible and increasing costs, especially in low-density areas. However, thermal/cooling energy sharing may also offer opportunities for user aggregation within a REC, representing a challenge to be explored in future research.

1.2.2 Aggregation

The aggregation phase marks the establishment of the REC, encompassing sub-phases that form an associative link among the participants in the same project with shared interests. These sub-phases include:

- Producer/consumer/prosumer aggregation;
- Legal settlement;
- Evaluation of funding opportunities.

The aggregation of members aims to enhance the RES-based plants efficiency and provide flexibility services to the PG. By optimizing the alignment between actual and planned energy

load profiles, the community gains economic advantages. This optimization not only benefits the community from an economic viewpoint but also from an environmental one, by maximizing the RESs exploitation. Additionally, integrating electric vehicle (EV) charging services as a point of delivery in a REC offers advantages to the end-consumers, who surely use energy from RESs, strengthens the REC by increasing shared energy, and contributes to the territory by promoting the wider adoption of these services. The subsequent subsections will provide a detailed presentation of the sub-phases related to consumer and prosumer aggregation, legal settlement, and the evaluation of available funds.

Producer, consumer and prosumer aggregation

REC participants can belong to different categories. According to RED II, a REC is a legal entity "*based on open and voluntary participation, the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities*" [21]. In some instances, a REC may originate from a group of private individuals pursuing a common project, or by a municipality, which typically issues an expression of interest to identify citizens willing to participate as prosumers or consumers. In this context, the CEU analysis conducted during the feasibility study supports the aggregation of the suitable members, ensuring compliance with legal proximity constraints and enabling the proper design of the RES-based plants. Individuals interested in joining the same REC project can be categorized as:

- Producer: a member who produces energy from its own RES-based plant;
- Consumer: a member who consumes energy supplied by the community;
- Prosumer: a member who both produces energy from its own RES-based plant, consumes the portion aligned with his load curve, and makes any surplus available to the community.

Prosumers play a crucial role in meeting growing electricity demand and promoting RESs adoption. Consumers are expected to shift consumption toward periods of high generation and reduce it when output is low, through Demand Side Management (DSM). Once members are established, they formalize the community and establish its rules..

Legal settlement

Current legislation states the REC is a legal entity that adheres to the principles established by the Directives. While a specific legal form has not been indicated, several studies have identified the most plausible solutions. Among the possibilities considered, there are:

- Cooperatives, which are most diffused in Northern Europe;
- Associations (recognised or unrecognised) or foundations, which are most diffused in Italy [84];
- Social enterprises;
- Benefit companies.

Cooperatives are companies with variable capital set up to manage in common an economic activity aimed at providing members with the desired goods or services. Thus, the essential characteristics concern the mutual purpose and the increase or decrease in capital resulting from the entry or exit of members, who may be natural persons or legal entities. It is the most common legal settlement in Germany and Denmark [85].

Associations are non-profit collective organizations that may perform economic activities only if ancillary to their institutional purpose, without distributing profits [86]. They may have legal personality (recognised) or not (unrecognised). Legal personality is matched by perfect patrimonial autonomy: the members' assets are separate from those of the organisation and the latter is always and only liable for its obligations. In contrast, unrecognised associations have imperfect autonomy, as liabilities may extend to individuals acting on their behalf [87]. The latter can be established without formal requirements, whereas recognised associations require a public deed and formal statutes specifying key elements such as name, purpose, assets, registered office, governance rules, and membership conditions.

Social enterprises address social problems by applying market-based solutions and can be analysed along three analytical dimensions: purpose, ownership and embeddedness. Their use of market mechanisms allows them to sustain operations while advancing a social mission [88]. A notable ownership model is the community-based social enterprise, which supports its mission through democratic or equity-oriented structures [89]. Embeddedness is a key precondition, as responding to social needs requires a local community that expresses and supports those needs [59].

Benefit societies are traditional societies with revised obligations that require management and shareholders to meet higher standards in terms of accountability and transparency. They voluntarily pursue one or more beneficial purposes in the conduct of their business, in addition to the for-profit purpose [90]. These societies, in fact, have a different governance, which pursues both goals, and a more extensive and responsible management which, in addition to

measuring the public value produced [91], assesses the social impact and communicates it transparently [92].

The decision about legal form is often guided by the need for a simple and streamlined structure, as overly complex arrangements may discourage participation and hinder REC implementation. While regulations do not prescribe a specific legal form, they define key principles and requirements that guide the selection. REC must be a collective legal entity, with legal subjectivity and an organisational structure, capable of acting independently from its members, endowed with an organisation and its own organs [93]. In addition, it must not have profit as its main purpose, understood both as the absence of profit distribution and as the prioritisation of benefits such as cost savings for members rather than financial returns [94]. This excludes inherently for-profit entities (partnerships and corporations), limiting suitable options to forms with primarily non-profit objectives. Nevertheless, REC membership can be diverse, involving heterogeneous actors who share energy from RESs within a local market, potentially combining both profit and non-profit elements [95]. During the formation phase, contractual arrangements define relationships among members, including rules, cost-sharing mechanisms for operation and maintenance, and the allocation of incentives. These aspects are formalised in the Constitutive Act, the Statute, and the Operating Regulations, with the Statute being essential for the legal establishment of the REC and required to include specific provisions [96]:

- main objective consisting of the provision of environmental, economic or social benefits at community level to members or local areas where the community operates;
- social purpose;
- right of entry for all those who meet the requirements of the regulations;
- the preservation of end-customer rights and the right of withdrawal at any time, subject to the payment of fair and proportionate charges for co-participation in the investments made;
- economic conditions of entry and participation (membership fees) that are not excessively onerous.

Evaluation of funding opportunities

The economic aspects of establishing a REC should be defined during the initial phases of the project. Funding opportunities can come from different paths, with European and national

programmes often encouraging feasibility studies for their implementation. Assessing these opportunities is particularly relevant when the REC or a local authority economically supports plant installation, although individual members may also contribute to investment costs and receive remuneration as defined in the Constitutive Act. The main financing options typically include equity financing, debt financing and grants, reflecting the complexity of REC activities. Equity financing, in particular, represents a form of self-financing in which each new member contributes capital to the REC [97]. This is a mutualistic situation in which partners incur a long-term debt while gaining control as co-owners [98]. Shareholders may recover their invested capital in accordance with the rules outlined in the contract or the articles of association. Equity financing is common during the aggregation and management phases of a REC. As in all projects, the initial stage carries the highest risks and uncertainties, limiting investor interest and making financing challenging. Early contributions often lead to negative cash flows due to upfront expenses. While shares can facilitate REC participation, they may also hinder inclusion and engagement, particularly when the required funding is high [99]. An alternative to entering equity capital is to apply for funding from a capital fund [100]. Particularly, these financing instruments pool collective investments, while cash flows vary depending on whether the fund is institutional or private. Indeed, the latter typically releases resources gradually, based on set milestones. While this approach can involve time-consuming and potentially costly administrative work, its main advantage is that equity investment allows partners to share ownership [101]. Secondly, the other possibility is debt financing, which differs in the investor's intention [102]. Thus, debt-financing actors examine the REC from a dual perspective: risk and return [103]. Once the debt is repaid, the paths part again and there is no longer any relationship. Debt financing is mainly provided by banks, though citizens can also participate. In the early stages, especially during operations, it can be a quick and accessible source of funding, but collateral requirements may be substantial. While it generates positive cash flows, repayment creates a financial burden on future plans. Banks may also offer short-term financing and connect RECs with qualified companies for equipment installation and administrative support. In contrast, grants do not require repayment, unlike debt or equity financing [104]. Public grants are available at European, national, regional, and municipal levels, typically requiring a project proposal detailing the intended activities. Such funding is widely recognized as important for promoting RECs [105]. In addition, a system could be established to receive donations and keep abreast of the different possibilities [106], though all public support requires time to meet administrative requirements.

The choice of funding can influence REC independence. In a REC fully financed by private citizens, members retain control over activities and strategic decisions [107]. Introducing external investors, especially through debt financing, can reduce citizen control, as lenders may impose conditions. Therefore, selecting the appropriate financing type for each activity is crucial. Grants, while bureaucratic, do not affect ownership.

1.2.3 Operating phase

Once the feasibility study and aggregation phase are completed, the project can progress to the operating phase, which involves implementing the previously simulated plan. This phase follows a technical path aimed at defining the operational parameters. In contrast to the feasibility phase, real end-users consumption data are collected here, subsequent to the aggregation of the members. The operating phase is further divided into sub-phases:

- Design of energy conversion systems;
- Construction of RES-based plants;
- Agreement.

Design of energy conversion systems

It involves considering the evaluation conducted during the feasibility phase, assessing available resources and RESs. Data collected during the preliminary phase, such as installation surfaces, guide the technical design. This phase entails careful planning, including determining plant capacities, selecting RES technologies and module numbers, configuring connections to users and the PG, choosing inverters, and potentially integrating Battery Energy Storage Systems (BESS). An economic plan is also developed.

Construction of RES-based plants

It entails implementing what was established during the design phase. Collaborating with local resources is crucial to promoting employment opportunities within each territory. Constructing a RES plant requires specialized personnel in the sector. The construction phase concludes with the connection and operational launch of the plant. After commissioning, actual production profiles are compared with the expected profiles from the simulation phase.

Agreement

It involves the verification of the REC project by the national competent authority. It ensures compliance with all legal constraints and checks the design and commissioning of the RES

plant. If all requirements are met, the shared energy is calculated, and incentives are disbursed. This process requires providing necessary data about the legal entity, production plants, and all REC members.

Figure 1.4 presents some possible REC configurations based on REC typology, plant size, plant ownership, and RES plant typology, including:

- Residential REC: composed only of residential members, with a private citizen as a possible plant owner;
- Municipality-driven REC: a community comprising private citizens, SMEs, and the local municipality, which acts as the project promoter and may also realize its own plant with public funding;
- Industrial REC: located in an industrial area, with SMEs or factories as community members. In this case, one of the members can be the plant owner, as they may have more investment opportunities to realize a medium or large-sized RES plant;
- Multi-user REC: members can include private citizens, offices, SMEs, religious bodies, and others, each with different energy demand and investment capacity. In this configuration, one of the members can be the plant owner.

PV technology is the most common choice for small and medium-sized installations, whether owned by an individual REC member or the entire REC, due to its relatively lower cost. Large-scale hydroelectric and biomass-based plants, which typically have higher peak power, are often managed by external companies due to significant investment costs.

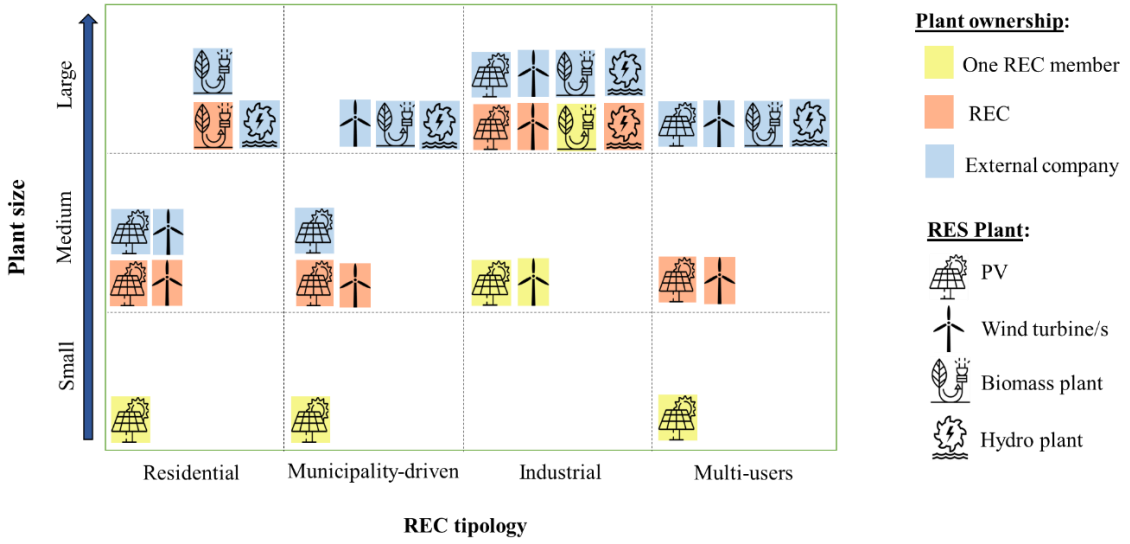

Figure 1.4 Potential REC configurations

1.2.4 Management

The final phase of the roadmap involves managing the REC, throughout the configuration lifespan. The sub-phases encompass the main aspects:

- Monitoring & maintenance of plants: focused on the ongoing monitoring and maintenance of the REC's production plants;
- Economic management: it includes financial planning, budgeting, accounting, and revenue management. Effective economic management ensures that the REC's financial resources are properly allocated, expenses are controlled, and revenue streams are managed efficiently. This sub-phase is crucial for the long-term financial sustainability of the REC;
- Dissemination activities: this sub-phase focuses on raising awareness and promoting the REC within the community and beyond.

By managing these sub-phases, the REC can ensure the continuous operation, financial viability, and visibility of the project. It allows the REC to fulfil its objectives of promoting renewable energy, supporting local energy efficiency, and contributing to a more sustainable and resilient energy system.

Monitoring & maintenance of plants

Monitoring of plant performance involves analysing and evaluating plants are operating efficiently. Monitoring is especially crucial during the early years when the decrease in production rate due to ageing is relatively limited, but it can also extend throughout the plant's entire lifespan. RES-based plants are subject to environmental stress, which can lead to long-term performance and reliability degradation. For example, PV systems are affected by high temperatures and humidity, which impact energy yield [108]. The performance ratio (P_R), ratio between the final and reference yield of a PV system, is the primary index used to assess its energy production. It is expressed as a percentage on an annual basis [109]. Climate conditions in the installation area significantly influence the P_R. A comparison of five crystalline silicon PV modules installed in Singapore (tropical rainforest climate) revealed degradation rates ranging from 0.03 %/year to 0.47 %/year [110]. In contrast, polycrystalline silicon and monocrystalline silicon PV modules installed in the Gobi Desert of Mongolia (cold-dry climate) showed degradation rates of 1.28 %/year and 0.86 %/year, respectively [111]. An investigation of over 2000 PV installations worldwide reported varying degradation rates, with an average of

0.8 %/year [112]. Operating conditions beyond standard parameters also affect the lifespan of wind turbines, typically sets at 20 years. Factors such as wind shear, ambient turbulence, additional wake turbulence, and wind speed significantly affect their durability [113]. The BESS included as a backup system to address the potential unavailability of the considered RES, must also undergo monitoring. Its lifespan is mainly influenced by the number of charge/discharge cycles, discharge depth and operating conditions [114]. Among the various types of BESS associated with RES technologies, Lithium-ion BESS are most prominent due to their excellent dynamic response, high energy density, high efficiency and durability. However, they are sensitive to extreme temperature ranges, which can impact power output, capacity, self-discharge rate, and thermal losses [115]. Nevertheless, BESS play a positive role in enhancing network stability during fault conditions, especially in large-scale plants like wind generators [116]. Estimating the state of health of a BESS in a REC is more complex, as it depends on a broader set of variables. Maintenance, a necessary operation for any industrial plant, is often categorized into ordinary and extraordinary. Ordinary maintenance is typically conducted annually and involves the replacement of accessory components as a preventive measure. Extraordinary maintenance instead, has a ten-year cycle and entails replacing components that require the temporary shutdown of the production plant. This may include replacing the inverter, which has a useful life of around ten years. The allocation of maintenance costs depends on the agreements established during the REC constitution phase. These costs may be borne by the plant owner, the municipality, or the entire REC. Members are free to join or leave REC, but each decision affects energy and economic flows. When users join an established REC, the REC plant's assessments are needed. Depending on the chosen RES technology and the significance of the additional members, repowering the plant may be considered, increasing the energy produced and available for sharing. Therefore, the energy produced and available for sharing increases. Economic benefits have to be recalculated too. From the perspective of the individual member, DSM techniques can be implemented to concentrate energy loads in the hours of maximum producibility of the plants.

Economic management

Economic management of a REC is conducted according to the agreements made among its members. The incentives issued by the authority, calculated on shared energy, are credited to the REC that has the flexibility to determine how to use them, as long as it is specified in a legal agreement signed by all community members. Some possible uses of the incentives include:

- fair division among participants, if the production plant was not financed by any specific member;
- fair division among consumers, with a higher percentage allocated to the prosumers if they funded the production plant themselves;
- allocation of incentives to address social purposes, such as assisting families experiencing energy poverty;
- necessary works within the REC;
- organizing events in the municipality where the REC operates.

In addition to these, a portion of the recognised incentives is typically used to cover REC maintenance and management costs. The social purpose of the REC should be clear from the preliminary phase. The COVID-19 pandemic and energy conflicts have led to an increase of people experiencing energy poverty in Europe. Installing solar PV systems on available surfaces of non-profit associations could contribute to addressing this social issue, providing significant savings on energy bills through self-consumption. Another possibility is to include vulnerable families among the consumers, as they may afford essential energy services like heating and cooling in order to ensure good thermo-hygrometric conditions in environments and reduce health problems. Participation in a REC to address energy poverty is an aspect of the broader energy justice concept, which is still considered marginal in many countries. It has been proven that innovative energy systems have the potential to reduce these phenomena [117]. Municipal administrations may play a crucial role in identifying families facing energy poverty and providing them with necessary information on REC membership, as they might otherwise remain unaware of such opportunities. In the management phase, some specialized organizations usually provide technical assistance through their legal, commercial, financial and technical expertise to reduce costs as well as contractually complex risks, thus creating replicable and financeable business models. These organizations can provide a reduction of transaction costs that would normally be incurred by both the customer and the producer to perform the contract, cost negotiation by facilitating and coordinating transactions and ultimately reduction of information asymmetries between all stakeholders.

Dissemination activities

The dissemination activities carried out by REC promoters, either directly or through third parties, aim to raise awareness of these projects within the territory. It involves implementing various communication and outreach strategies to inform and engage stakeholders, including

members of the REC, local residents, businesses, and other relevant parties. Dissemination activities may include organizing events, conducting educational campaigns, participating in conferences or exhibitions, and utilizing online platforms to share information about the REC's activities and achievements. The objective is to stimulate the conception, development, and participation in governance models of distributed generation and to promote new technologies for the use of RESs. RECs are also considered instruments to address social acceptability issues related to RES plants and to create employment opportunities in the relevant territories. By promoting community activities and publicly disseminating the results, they can inspire others to become potential members of the same project or to create new ones.

1.2.5 Discussion and future development

The presented roadmap includes the main phases required to carry out a community project focusing on energy, environmental, economic and social aspects. Each aspect can have varying importance depending on the members' priorities. The procedure may need to be adjusted to comply with the legal framework of the specific country where the REC is being implemented. Phases can be moved forward or postponed as necessary. The roadmap can also be expanded if the designer deems additional steps necessary, or some steps can be omitted if they are not required by the relevant authority or considered unnecessary in the specific context. While qualitative methods excel in investigating selected research questions, this study has inherent limitations. The qualitative approach falls short in encompassing the complete range of perspectives and experiences, making statistical generalization of results challenging. Concentrating on the roadmap for REC's constitution does not assure specific outcomes but rather indicates potential results. Nonetheless, the presented methods remain applicable to comparable scenarios and hold significance for policymakers and researchers addressing challenges impeding RECs opportunities for an equitable and inclusive energy transition. Furthermore, these findings should be viewed as a catalyst for applying the methodology to extensive real case studies. Having a standardized procedure to follow provides an advantage to stakeholders, public administrators, and citizens interested in REC implementation. The possibility to replicate already realized and successful projects allows for speeding up and streamlining the preliminary phases of the new REC, trying to highlight the strengths and avoid mistakes made in already implemented projects. However, there is a potential disadvantage in following a fixed procedure, as it may lead to the homogenization of projects with predetermined structures, potentially discouraging the emergence of innovative projects with new features compared to existing ones. Each innovative project represents an enrichment and

can draw inspiration for future RECs. These have to use the most RESs in the area, trying to use technologies with a higher rate of national component, and offer as many benefits as possible to members. The research is, in fact, focusing on the study of projects which include the thermal vector, also through the use of geothermal source-based plants. The importance of balancing standardisation with adaptability, allowing for local customization while maintaining core principles and objectives, must always be considered.

The roadmap for implementing a REC can be used to analyse existing cases, providing insights into the processes followed, besides serving as a guide for future RECs. The scientific literature predominantly focuses on studies concerning the already developed RECs. Topics such as the optimization of energy flows influencing members' selection, economic, energy and environmental analyses of case studies, as well as the assessments of cultural factors and end-users' willingness to participate, are extensively discussed in the literature. Management models and business plans are also common subjects of study, but are typically undertaken once the REC is operational. This study, in contrast, commences with generic analyses and endeavours to fill the gap regarding the phase before the birth of the community. It offers a comprehensive guideline covering all the aforementioned aspects and is adaptable to different cases.

1.3 Fundamental aspects of Renewable Energy Communities

RECs play a crucial role in the energy transition process, but addressing the various facets of this topic effectively requires a comprehensive analytical methodology capable of highlighting each aspect to maximise the benefits of their implementation. The methodology employed to structure this paragraph is based on a thorough and critical analysis of the key factors associated with the REC concept. The selection of the ten elements results from an extensive literature review, followed by a detailed evaluation of the main research findings in recent years. Each content has been carefully chosen not only to provide a general overview of the topic but also to delve into key aspects essential to understanding and guiding REC implementation, while also pointing toward future directions. The structure of the paragraph follows a logical and progressive flow, starting with foundational definitions and advancing to more complex topics such as sector coupling, flexibility and upscaling strategies, including economic, environmental and social dimensions. A focus was placed on the issues surrounding

the definition of RECs, including the types of members that can form these communities and the resulting configurations that can be achieved. A crucial factor in this analysis is the level of compliance with each country's regulatory framework, which significantly influences REC implementation, as previously highlighted. The technological dimension of RECs is also crucial, as RES-based installations and established strategies offer key insights for their operation and optimization. To effectively achieve the objectives set at the national, European, and global levels, it is essential for RECs to adopt technical optimization and energy flow management approaches. These objectives can be effectively pursued through the integration of simulation methods and flexibility solutions, supported by tailored tools and strategies. Optimal management of energy-sharing configurations delivers tangible benefits, enabling projects to scale to broader areas and be supported by the policies in place. The analysis of the scientific literature on RECs was instrumental in shaping the responses to the ten proposed subjects. However, only a coherent vision of the topic allowed to effectively integrate the legislative context with the outcomes derived from the case studies examined. This methodological approach enables providing comprehensive and well-rounded responses to each issue, offering the flexibility to explore each aspect in detail or to cluster related topics as needed, depending on the relevance and circumstances of each particular dimension.

1.3.1 Definition and actors

RECs were first legally defined in the European regulatory framework in 2018 as legal entities based on the voluntary participation of stakeholders, who can be natural persons, SMEs or local authorities. However, other member types may also participate in RECs, varying according to the pursued aim and specific circumstances. This diversity is crucial for achieving environmental, energy, and social objectives, with participation shaped by social, economic, technological and policy factors. RECs serve as an instrument for implementing a fair energy transition that involves actors at the local level and actively involves them in decision-making processes, regardless of their individual financial capacity [105]. Individuals are driven by values of sustainability and technical skills, which unite with local identity and social cohesion felt at a community level [118]. Additionally, the potential for economic savings on energy costs remains a significant attraction both for experienced stakeholders and consumers [119]. Despite the strong social drivers, challenges such as high investment costs and operational complexities continue to hinder progress. Addressing these issues requires robust policy support and innovative financial solutions [120]. The social dimension of the energy transition process is mainly emphasized with the participation of residential users as members of the REC [83],

providing concrete opportunities to reduce energy poverty conditions for included low-income households [121]. The participation of residential users allows for load shifting through the implementation of home energy management systems, optimizing energy use from RES-based plants [122]. The community approach also benefits residential buildings with RES installations, especially when retrofitted with upgraded energy conversion systems [123]. Indeed, introducing heat pumps as energy conversion systems to meet space heating demands enhances the thermal sector's flexibility. This approach taps into non-electric loads, enabling maximum energy sharing through the power-to-heat (P2H) approach [124]. Simultaneous control of indoor comfort conditions for residential users of a REC through the air-conditioning systems and batteries associated with the PV system results in economic savings of up to 59 % compared to the case where users act individually [125]. Additional cooperation among community members in demand response events, besides supporting energy balance, results, as a consequence, in economic savings both for individuals and the community [126]. However, due to the current lack of infrastructure for measuring energy loads, non-intrusive techniques are needed to assess them and maximize self-consumption within the community [127]. EVs integrated into a REC add controllable electrical loads, offering opportunities for the transport sector decarbonisation by using primarily RES-generated electricity. Their charging flexibility aligns with appliance load shifting [128], and surplus energy from RES plants can, in some cases, be shared with external EV owners [129]. The advantages of a REC can be enhanced by exploring various user combinations [130]. One important technical factor in selecting members optimally is their energy demand [131]. In fact, the diversity of energy demand profiles, such as residential, industrial, tertiary, and agricultural, can help align energy demand with the community's generation patterns [132]. Incorporating an industrial user positively influences the energy-sharing indicators of a REC that consists of municipal and residential users [133]. The participation of SMEs, indeed, presents great potential for a REC, due to their energy demand and propensity to contribute to decarbonisation. Petrovich & Kubli [134] highlight that SMEs favour local suppliers, supporting the RED II aim of benefiting the territory where the REC operates. Moderate administrative effort and strong interest in DSM and peer-to-peer encourage their participation, while long return-on-investment periods discourage it. On the other hand, matching at the municipal level boosts private citizens' investment in RECs [135]. Public entities included in the REC have a positive effect due to the availability of areas for the installation of RES-based plants on the buildings and the organizational and financial resources, as well as consumption data used for the model's validation [136]. Both public and private energy players recognise that among the main barriers to participating in a REC are the

planning and legal framework, followed by the lack of resources and expertise [44]. The interest in clean energy and new energy production and consumption paradigms has led to important transformations in the communities' sphere, with an increasingly strong focus on energy aspects, including RES projects and energy governance, extending to social, political and economic objectives. In this context, types of energy communities such as municipal, rural or island ones have been implemented [23]. In municipality-driven REC, the local authority promotes the project, engaging other actors to generate local benefits [137]. Rural energy communities attract attention due to technological, economic, and social factors supporting their growth and sustainability. Studies show that key priorities for rural energy advancement encompass community involvement and the integration of agriculture. Current trends reveal a shift from localized solutions to integrated hybrid systems and smart grids [138]. Small islands not connected to the PG are ideal for projects targeting energy independence and self-sufficiency, using RES-based plants and storage solutions [139]. Efficient energy management on these islands requires careful plant design to maximize energy production, optimal use and minimize unnecessary costs [140]. Feasibility of islands' RECs improves by integrating consistent energy loads, not affected by seasonal fluctuations in tourism, such as water desalination unit, which can enhance the economic viability of the project [141]. The RECs can also facilitate the decarbonisation of sectors still heavily dependent on fossil fuels. In this regard, ports are complex and very energy-intensive realities, to which are linked numerous electricity demands for services at the dock, mooring or energy distribution for power boats, which can be partially met by the installation of community RES plants and BESS [142]. The port authority is seen as the primary stakeholder that, as a public body, can promote and facilitate the establishment of one or more RECs, involving maritime stakeholders [143]. *Table 1.2* summarises the main factors which favour or restrict participation in a REC for each of the considered members or organisation types.

Table 1.2 Positive aspects and barriers for the participation in a REC of each member typology

REC member affinity	**Facilitations**	**Barriers**
Residential	Propensity for social aspects, flexibility loads.	Lack of load profile measurement.
SMEs	High and constant energy demand, propensity to decarbonization.	High return time on investment.
Public entities -Municipality-	Area availability for plant installation, organizational and financial resources, energy consumption data.	Legal framework, lack of expertise.

Rural	Technological, economic, and social factors for their growth, propensity to sustainability.	Community involvement and integration of agriculture.
Island	Energy independence.	Not PG connection, seasonal energy loads.
Ports	High energy demand.	Organizational complexity.

1.3.2 The current status of RECs development worldwide

The RECs embody important realities that are recognized worldwide, contributing significantly to the current energy system. Their development has adhered to various operational modalities and regulations, reflecting each country's regulatory environments. The growth of RES-based installations, especially PV systems, and the rise of prosumers have increased the need for energy-sharing models tailored to local requirements. In Japan, this trend has been supported by lower installation costs and RES expansion in previously less favourable areas, underpinned by a robust regulatory framework [144]. Instead, in Russia, microgrids for power supply significantly alleviate rising electricity costs for industrial and commercial consumers, ensuring a reliable, environmentally friendly power supply. Here, the energy community is implemented through these microgrids, and a regulatory framework was developed to govern their operation, focusing on business practices and enhancing efficiency in remote areas [145]. South Korea aims for sustainability by promoting net-zero-energy buildings and decarbonizing existing communities. The maximization of energy from RES is achieved by retrofitting buildings and energy sharing, achieving a positive energy balance [146]. In order to accelerate the energy transition at the national level in the United States, regional and localized entities started the development of focused projects to achieve the target of 100 % renewable energy [147]. In Utah, the *Community Renewable Energy Act* has been enacted, leading to the establishment of the Community Renewable Energy Agency. This initiative will allow up to 23 communities in the state to achieve the goal by 2030 [148]. RECs are crucial to national energy transitions, offering cooperative benefits from renewable generation facilities and opportunities to improve energy efficiency through aggregated consumption [149]. To effectively implement these advantages, a strong legislative framework is necessary to establish clear applications and regulations governing their operation. The EU introduced the CEP as a comprehensive legislative framework to support the energy transition, aiming to reduce GHG emissions, increase the use of RESs, and enhance energy efficiency. It emphasizes the importance of placing citizens at the centre by introducing concepts like active

consumers, individual and collective self-consumers, CECs and RECs [47]. While the EU provided general definitions, each member adapts their application and implementation rules through national legislation [150].

Regarding RECs, the primary distinction is found in how the advantages of collective self-consumption are reflected in the members' energy bills. Specifically, two models have been established in the European setting: virtual and physical. The latter entails a direct energy bill discount for community-shared energy by each member, who pays for the remaining withdrawn energy, while a different internal price valorises the energy traded within the community [151]. Spain and Portugal consider this approach for RECs and employ allocation coefficients to assign shared energy to each member. Portuguese regulation allows the use of dynamic allocation coefficients that can be assigned by REC members or by a designated Management Entity [152], while Spanish regulations involve static ones, fixed over a specific time period [153]. Moreover, in Spain, RECs members have to respect the maximum distance of 2 km from the generation unit [154]. The Belgian regulation also considers a physical scheme, and economic incentives are guaranteed as a discount on members' bills based on shared energy on a sub-hourly basis [155]. In Belgium, the regulation is not uniform across the country and has been developed separately for the Brussels-capital region, Flanders and Wallonia [152]. On the other hand, the virtual scheme provides no energy bill discount for REC members, whereas shared energy results in economic incentives under the country's rules. In accordance with the Italian regulatory framework, RECs receive incentives based on local electricity market prices and plant size, and members must be connected to the same HV/MV electrical substation [156]. Economic revenues can be divided among members or used for sustainability or social purposes. The Netherlands is also considering a virtual scheme for energy communities. The subsidy depends on a fixed and a variable component, accounting for fluctuations in energy prices. However, the incentive is calculated based on the energy produced by community plants, and the shared energy is not measured [157]. Germany also offers economic offsets for RECs through various programs, including incentives, compensation and low-interest loans. Although the country has been a pioneer in developing collective configurations to exploit the energy produced by a RES plant, the regulatory framework does not fully comply with the requirements set out in the RED II [104]. In Germany, indeed, energy communities consist of renewable energy assets owned by individuals, small businesses, or cooperatives. These entities can also sell surplus energy to nearby end-users [137]. The Austrian regulatory contest provides that RECs may produce, consume, store or sell energy from RESs. To encourage participation,

a reduced distribution grid tariff is applied to electricity traded within the REC. Additionally, participants benefit from the elimination of all electricity taxes and green energy charges [158]. The concept of proximity for RECs outlined in the RED II, in Austria results in a connection between members and generating units via LV/MV grids, respectively for local or regional level configurations [159]. In France, the REC provides for energy sharing between producers and consumers following collective self-consumption. The maximum distance among members can be 2 km if they are connected to the LV grid, but it can reach up to 20 km with specific approval for low-density population areas [150]. Not all European member states transposed RED II into national laws, however, projects using renewable sources and energy use are encouraged at the community level. In Ireland, the Renewable Electricity Support Scheme supports energy production from RES and provides priority mechanisms for community-based projects [150], including heat sharing. RECs can access the electricity market and benefit economically by competing with other players [44]. Key features of the RECs for the investigated EU member states are shown in *Figure 1.5*.

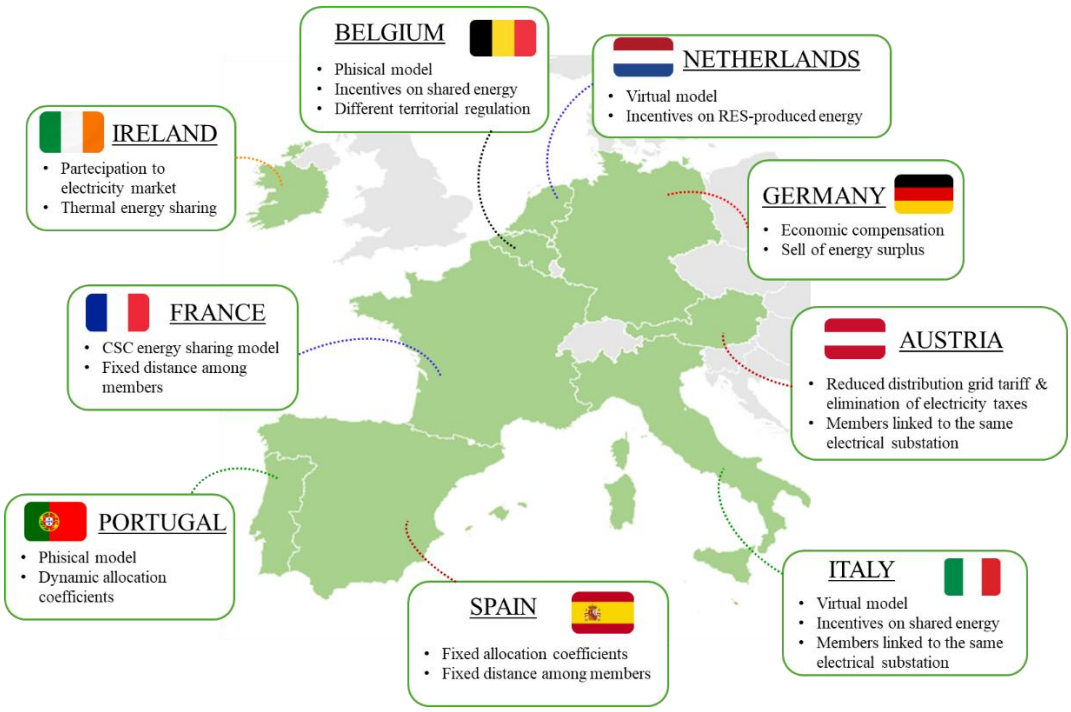

Figure 1.5 Key features of some EU States RECs regulation.

1.3.3 The key renewable technologies

Solar PV plants represent the most widely used RES technology, due to their modularity, ease of installation, and relatively low investment costs compared to other systems [160]. Over the years, the price of solar PV systems has significantly fallen, facilitating the installation of

plants for citizens. In this context, energy sharing configurations have primarily utilized PV technology too, leading to the development of so-called solar energy communities [161]. These installations are typically set up on buildings' rooftops [162] or in dedicated areas, depending on specific project requirements. A multi-tower concentrating solar power plant requires, for example, specific area availability while offering substantial benefits in terms of high electricity generation yields [163]. The exploitation of solar energy can also be used to meet thermal energy needs by installing thermal solar collectors or photovoltaic thermal (PVT) systems, which simultaneously satisfy both electrical and thermal energy demand [164]. Despite their benefits, solar technologies may not suit all regions, especially where other RES are more abundant, such as Denmark, where RECs mainly rely on wind [165].

However, these sources have several limitations due to variable, non-dispatchable output driven by seasonal and daily patterns. More flexibility can be offered by integrating storage systems as BESS to overcome these barriers, despite their significant economic impact [166]. The optimal management of BESS coupled with PV, considering energy prices and weather-based production forecasts to assess the producibility, however, allows for obtaining substantial economic revenues while minimizing associated operating costs [167]. Their use involves a control strategy that has to fit the community's demands [168], which, if optimized, leads to greater independence from the PG and more incentives for energy sharing [169]. On the other hand, hybrid solutions combining multiple RES can offer additional advantages [152], especially when paired with more dispatchable technologies.. These include biomass-fuelled plants that exploit a locally available resource with consequential significant employment impacts on the territory [170]. The combination of a biomass-fuelled CHP unit and existing PV system simultaneously supplies the thermal and electric energy demand of REC members [171]. Specific crops can be exploited for the production of alternative biofuel pellets to cover the thermal demand of a REC [172]. The study in [173] presents a REC where woody products from local activities, such as sawmills, are used to activate a CHP, which covers community demand coupled with a small hydropower plant and PV system. Depending on the specific availability, geothermal or marine renewable energy technologies can also be used, even in conjunction with less complex systems such as PV and wind systems [174]. Adopting hybrid configurations that integrate multiple RES technologies and storage systems offers a promising opportunity to enhance the REC's self-sufficiency while effectively reducing PG withdrawals [175].

Greater flexibility can be achieved in REC that, in addition to BESS, also predisposes thermal energy storage [176], allowing thermal energy sharing among members through a district heating network (DHN) [177]. Additionally, flexible loads such as EVs and heat pumps [178] can be inserted, or RES energy surplus can be stored in green hydrogen, also used for fuel cell EVs [179]. Different Power-to-X (P2X) strategies can be applied within a REC in order to improve self-consumption of energy, including P2H, power-to- vehicle (P2V), power-to-power (P2P) and power-to-gas (P2G) [180]. Finally, hydrogen is an emerging possibility in recent years, whereby RES surplus energy can be used via electrolysers for postponed electricity production [181], promoting Renewable Hydrogen Energy Communities [182]. These systems are also part of the P2P approach. *Figure 1.6* presents the most diffused RESs, in relation to energy carriers and application strategies in the RECs field.

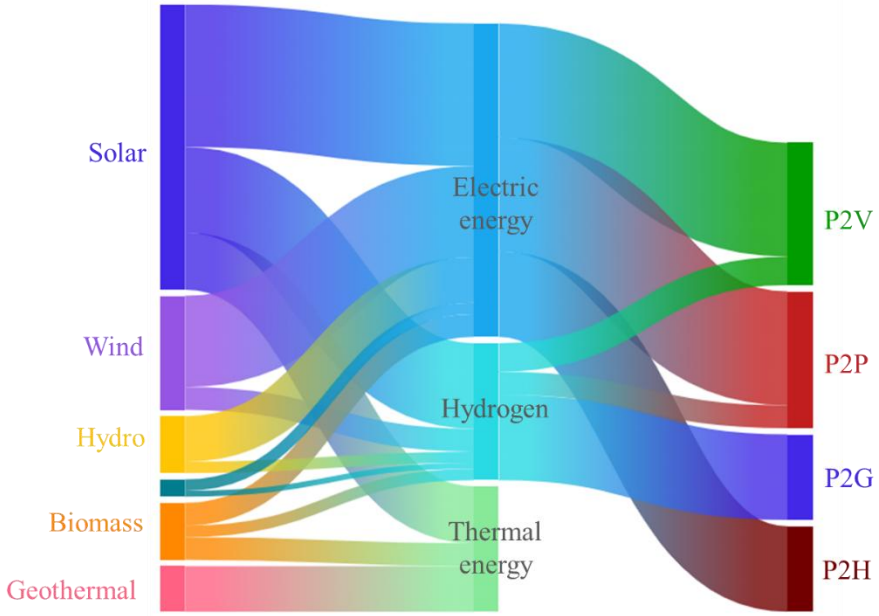

Figure 1.6 Most diffused RESs, energy carriers and application strategies in the RECs

1.3.4 Optimization and simulation approaches for RECs development

As the RED II definition indicates, the operation and development of RECs require tailored modelling frameworks to account for the complexity of energy flows, variable renewable generation, storage integration, and market interactions. To this end, optimization and simulation are essential for REC design, operation, and evaluation. Optimization models identify the most efficient configurations by minimizing costs, emissions, and imports while maximizing self-consumption, efficiency, and returns. In contrast, simulation assesses REC

performance under varying scenarios, conditions, and policy frameworks; thus, the two approaches serve distinct but complementary purposes, with optimization mainly used for efficient design and management. Optimization models are applied for a range of objectives, including energy flow management, e.g., minimizing grid dependency while maximizing self-consumption and local distribution among REC members [121] sizing of renewable generation and storage systems [183], economic optimization, e.g., including tariffs scheme and revenue models [130], energy sharing mechanisms [155], investment and operation costs [184], emission reduction [185], demand-response and other flexibility solutions [186]. In a REC, the optimization problem typically aims to minimize costs, emissions, or energy imports while maximizing self-consumption, flexibility, and sustainability. The most diffused optimization techniques in RECs modelling belong to mathematical programming, such as linear programming [187], mixed-integer linear programming (MILP) [188] quadratic programming [189], and non-linear programming (NLP) [190] commonly used for determining the optimal energy dispatch as well as the financial benefits deriving from energy sharing within the REC, and investment decisions. Meta-heuristic algorithms and approaches [191], such as genetic algorithms (GA) [192], swarm optimization (PSO) [193], ant colony optimization (ACO) [194], or commercial software, such as HOMER or TRNSYS [195] are able to handle complex, non-convex problems. When there is a need to incorporate uncertainty in modelling, such as the one coming from RES generation, demand fluctuations, and market conditions, stochastic optimization techniques are implemented, given their capability to deal with chance-constrained programming [196]. RECs may combine different sectors and aim to achieve opposite objectives. To be able to balance trade-offs between costs, emissions, and energy efficiency, Pareto-based approaches are preferred, with the formulation of a multi-objective function [164]. Recently, AI techniques and deep learning [197] are going to be exploited and implemented, to dynamically optimize energy flows in real-time [198] and to guarantee control mechanisms [199]. These methods can then be combined to obtain hybrid approaches [200], thereby coupling the advantages of different methods. Regarding simulation approaches for RECs, these are employed to assess system behaviour under different scenarios and can also be used to complement optimization methods. In particular, simulations enable performance evaluation in terms of energy, economic and social impacts before implementation [201], sensitivity analysis to understand the impact of variations in demand, generation, and tariffs [202] or impact assessment [203] or future predictions. Among the most implemented simulation methods, agent-based models (ABM) consider REC members as autonomous decision-making entities [204].

Simulation approaches typically do not follow a unified mathematical formulation as they are based on the modelling of the behaviour of systems over time, given a set of input data, decision rules, and system interactions. However, there are some widely adopted mathematical structures, especially for the most common modelling techniques, such as ABM, in which the simulation consists of a set of autonomous agents, e.g. prosumers, grid operators, aggregators, that follow specific decision rules and interact within the REC. Each agent can be characterized by a state and behaviour rules updated at discrete timesteps. Simulation results are often fed into optimization models, enabling model calibration and operational validation and, conversely, optimized results may be used to inform simulations for robustness checks under real-world scenarios [205].

1.3.5 Incorporating flexibility into REC operation

Flexibility is a general term that refers to the ability of an energy system to adjust energy demand and supply in response to specific variations, such as those arising from electricity prices, grid balances, and the seasonality and intermittency of RES. In the context of RECs, flexibility also consists of maximizing self-consumption and sharing, both from the technical and economic viewpoints. Flexibility can be classified into four main dimensions: temporal (adjusting loads or generation in time), spatial (leveraging distributed resources across locations), sectoral (shifting energy use across electricity, heating, cooling, and mobility), and market-based (participating in energy markets). Across the dimensions described, different flexibility mechanisms can be put into place. Demand-side flexibility (DSF) is one of the foundational pillars of REC operation, enabling users to modify their consumption behaviours in response to external variations such as electricity prices [206] or grid constraints [207]. In some cases, this can be achieved through automated demand response, i.e. using controllers to regulate building energy systems, such as HVAC, lighting, and domestic appliances in real-time [208]. When smart appliances, such as heat pumps, washing machines or EVs work as flexible loads, a significant reduction in peak demand, as well as improved grid stability, is usually observed [209]. However, a key challenge for an effective implementation of DSF is properly related to user engagement. As an example, if on one side real-time tariffs and pricing are crucial to access financial incentives, on the other side the implementation of these strategies often relies on the level of interaction between the consumers and the purpose-built mobile applications or platforms as well as on effective awareness of which kind of benefits may be derived from energy savings. In addition, empowering REC members with these digital tools also poses privacy concerns about how this data is effectively handled [210]. This especially

applies to vulnerable users, for whom the access and full use of these technologies can also be considered a barrier. Storage-based flexibility further complements DSF, with batteries acting as a buffer between generation and consumption, storing excess renewable energy for later use. Batteries are particularly effective in handling intra-day variability from solar PV systems [211]. Thermal energy storage adds flexibility by decoupling heating and cooling from generation and is especially effective with solar thermal systems or heat pumps, improving overall efficiency [164]. Another research topic regarding RECs and flexibility is vehicle-to-grid (V2G) solutions, where EVs serve as mobile storage units [212]. V2G enables bidirectional energy flow, allowing EVs to discharge electricity to the grid or to the building. This approach not only supports grid services such as peak shaving and frequency regulation but also offers economic benefits to EV owners participating in flexibility markets [213]. It is worth remarking, however, that V2G implementation faces several barriers including the regulatory authorization, degradation aspects and also technological hurdles, as they need bi-directional chargers [214]. On the other hand, sector coupling represents a more systemic approach to flexibility by integrating electricity from RECs with other energy domains, primarily heating, cooling and transportation [215] with the main aim of increasing self-consumption and reducing waste. For instance, P2H technologies, such as electric boilers or heat pumps, can be activated during periods of excess renewable generation, converting electricity into usable heat. Similarly, P2G systems, while less mature and diffuse, are a promising strategy for long-term storage, such as in the case of hydrogen utilization. Finally, even if they do not fully meet the REC definition, renewable and fuel-based systems are also studied as a hybrid solution to foster the transition toward energy communities, especially in rural areas [216].

1.3.6 Monitoring and energy management

Robust monitoring and energy management tools are essential for real-time performance control of renewable energy assets [217], optimized energy flow management to balance supply and demand [218] predictive maintenance [219] as well as to foster user engagement [220] and demand-side strategies [221]. Effective monitoring systems integrate hardware, software and analytics to establish a consistent operating framework.

Smart meters and IoT sensors are deployed across the REC to collect granular data. In the case of smart meters, data can refer to electricity consumption and production at the single building level or at the community level (as in the case of centralized renewable production plants), enabling net metering and billing. IoT sensors, instead, provide contextual

environmental and technical data, such as temperature, irradiance, occupancy, as well as fault detection and equipment monitoring. This data is transmitted in real time to edge controllers, for a pre-processing stage and implementation of preliminary control actions (e.g., managing battery charge/discharge or operating HVAC systems). Data from the edge controllers flows through gateways or routers, which handle communication with higher-level platforms. These devices manage network traffic and apply security protocols to ensure the integrity and privacy of transmitted data. At this level, data is then transmitted to a centralized cloud platform, where it is aggregated, stored, and processed using data analytics and optimization algorithms. Processed information is visualized through a user interface, typically an energy dashboard accessible via web browsers or mobile apps and in which energy consumption, generation trends, and financial savings, as well as alerts in case of anomalies can be seen. Interfaces are designed for both individual REC members and administrators, with different levels of access and control, to supervise community-level performance, configure optimization routines, and interact with grid operators or markets.

Efficient energy management ensures RECs meet economic, environmental, and social goals, one of the key features of REC included in the definition provided by the RED II Directive [21]. In this context, different strategies can be implemented such as the above-discussed general flexibility mechanisms. In case of demand response (DR) mechanisms, when dealing with energy management, three different programs can be identified. These DR typologies differ in how they influence energy management. Price-based DR shifts consumption through dynamic tariffs, encouraging REC members to adjust their energy behaviour [222]. Incentive-based DR implies direct financial revenues and is usually coordinated by distribution system operator (DSO). Automated DR, instead, adopt AI-techniques without any direct involvement of members [223]: in this case, however, and more than the others, such systems demand secure, interoperable communication networks and raise concerns regarding data protection and user privacy [224]. Regarding the management of the energy flows within a REC, peer- to-peer energy trading enables members to exchange surplus energy locally, promoting decentralization and energy autonomy [196]. These mechanisms could involve in the near future market-based models [225] bidding strategies [226] and decentralized automation platforms with robust IT infrastructure [227]. Each of these approaches contributes to increasing the management and scalability of REC energy markets [228], although they require different levels of technical maturity and regulatory supports [229].

1.3.7 The contribution of RECs to the achievement of SDGs

The United Nations Sustainable Development Goals (SDGs), adopted under the 2030 *Agenda for Sustainable Development*, provide a global framework of targets and indicators to address interconnected economic, social, and environmental challenges [230]. Among these, the energy transition plays a cross-cutting role. RECs, as decentralized urban energy forms in which prosumers and consumers engage in renewable energy production, consumption, and sharing, represent a key innovation to target this transition. Their deployment inherently aligns with several SDGs, particularly those concerning energy poverty (SDG 1 "*End poverty in all its forms everywhere*"), clean energy access (SDG 7 "*Ensure access to affordable, reliable, sustainable and modern energy for all*"), economic growth and decent jobs (SDG 8 "*Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all*"), innovation (SDG 9 "*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*"), reduction of inequality (SDG 10 "*Reduce inequality within and among countries*") sustainable urban development (SDG 11 "*Make cities and human settlements inclusive, safe, resilient and sustainable*"), sustainable consumption and production (SDG 12 "*Ensure sustainable consumption and production patterns*"), and climate action (SDG 13 "*Take urgent action to combat climate change and its impacts*").

A thorough evaluation of RECs within the SDG framework requires translating community-level performance metrics, such as self-consumption rates, grid balances and emission rates, into SDG-relevant indicators. Some literature focused on similar topics [231]. Still, there are open questions on how these indicators can be tailored to specific urban forms.

RECs are strictly connected with SDG 7, as they address energy affordability and sustainability through local generation from RES, typically solar PV, small wind turbines, and biomass. By reducing reliance on centralized grid-supplied electricity, RECs lower retail electricity costs, especially when combined with self-consumption optimization strategies. Various studies indicate that renewable-based systems can reduce household electricity costs compared with conventional supply [232,233]. By facilitating high penetration of RES at the community level, RECs significantly reduce carbon emissions from electricity use, as part of the targets included in SDG 13. Emissions savings from RECs are also significant, especially when coordinated with operational control techniques [234], carbon pricing [235], environmental patents and energy efficiency [236], and the ecological footprint of energy consumption [237]. Given sustainability as part of their definition, RECs directly support the

development of sustainable urban energy infrastructure for cities and communities, as envisaged in SDG 11. By enabling localized production and flexible consumption, RECs reduce the load on central distribution [238]. At the same time, RECs also have an impact on SDG 8 and SDG 9 regarding economic growth and innovation, as their diffusion stimulates local economic activity through the construction, installation, and operation of distributed energy assets [239]. According to IRENA (International Renewable Energy Agency), energy communities may contribute to the creation of direct and indirect jobs, including roles in technical services, data analytics, and customer support [240]. RECs may also act as incubator for innovation, especially in the case of integrating digital technologies for energy trading, AI-based control, digital twin for real-time operation. RECs also contribute to the achievement of SDG 1 and SDG 10, by fostering social equity due to the democratization of access to clean energy and enabling vulnerable populations to participate in the energy transition. Mechanisms such as incentives and cooperative ownership models ensure inclusion of low-income households, renters and marginalized groups [241]. Beyond income considerations, RECs are also relevant to energy poverty, defined as the lack of affordable, reliable, and modern energy services, which affects rural households, elderly individuals, and low-income dwellers [153].

1.3.8 Scalability to city and neighbourhood levels

RECs do not have to respect a standardized size, rather, the specific applications and regulatory frameworks within each country often influence their dimensions. These frameworks may impose certain guidelines that contribute to the variance in extension. For example, in Spain and France, regulations establish a specific maximum distance between REC members and the generation plant. Conversely, in other States, energy sharing is typically confined to the boundaries of the same electrical substation [150]. In this context, a thoughtful analysis of the urban area holds significant importance. It is worth noting that the REC may vary in size relatively to a municipality, reflecting the diverse characteristics of small villages as well as larger cities. In the first case, it could be possible for the entire population to participate, which is likely to respect the established constraints. In the second case, it may verify that a REC has a maximum allowable size of a city neighbourhood. In this instance, specific features can play a crucial role in shaping the project, as investigated in the study [242] that compares three districts within the same city, each exhibiting unique characteristics related to built-up areas and open spaces. To achieve an equivalent size of PV system, the option of utilizing one block of buildings in the district with higher availability of public buildings has been considered, while considering seventeen small houses situated in that one characterized by lower housing

density and fewer public buildings. In order to enhance the benefits for REC members, this analysis has been concentrated on a specific segment of each district for the REC implementation, conveniently accessible by foot or bicycle within approximately 15 to 20 minutes from the district's central location [242]. The exploration of low-density communities is focused on attaining 100 % RES targets, recognizing the considerable space available for renewable energy development and the inherent limitations of energy density in these areas [243].

The limited size of a REC can facilitate effective management by fostering collaboration among its members, which in turn can enhance a collective identity and belonging [95], and simplify the legal management of the configuration. For a REC consisting of a condominium with a rooftop PV plant and a BESS, applying an optimal control strategy becomes more straightforward [125]. The relatively compact dimensions facilitate a more thorough understanding of the technical characteristics and energy consumption of each building involved [121]. However, scaling down the configuration emphasizes the importance of involving individuals with the appropriate expertise in each project to ensure effective energy and economic management. In certain contexts, such as Italy, the regulatory landscape evolved over time, enabling the establishment of RECs at both market-area and national levels. Furthermore, this framework allows for the assessment of shared energy by considering the specific boundaries of each HV/MV electrical substation [244]. The intermediate scale of urban neighbourhoods presents a valuable opportunity to harmonize energy supply and demand while encouraging the development of high-performance buildings and districts [245]. The involvement of people who live in the same district and who constitute a REC also allows for promoting the achievement of social goals that are felt very strongly in that area, such as the fight against energy poverty in a social housing district [246]. In the future, RECs can evolve in city districts or suburban areas. Smart cities resemble smart communities but operate on a larger scale, featuring unique aspects, especially concerning involved stakeholders and their interaction [27]. In this framework, the REC can move towards the concept of positive energy districts (PED). The latter is defined as a mixed-use area that emphasizes high energy efficiency, with the goal of achieving net zero CO_2 emissions and generating a positive energy surplus from RES on an annual basis [34]. Although these entities may not have formal legal recognition, there is a growing interest in them within the research community, since they include interaction among users, building and mobility ensuring sustainability benefits, which thus allows for a broader range of potential applications compared to RECs [247]. The

achievement of the PED targets represents an evolution of what a REC already proposes to do, considering an expansion of energy demands that, in addition to electricity, also considers thermal and cooling energy demand [248]. The inclusion of thermal energy sharing is a key factor that can drive future community projects. In this scenario, members of the same REC need to have a supportive infrastructure, such as a DHN, which enables them to connect physically and utilize thermal energy effectively [177]. This is certainly a significant evolution of configurations, but on the other hand, it leads to greater rigidity as users have less flexibility to alter their settings. Similarly, new users would be barred from joining unless a pre-planned connection is made. Regarding size, the REC here would be much more site-specific, and a reduction or enlargement would not be easy to implement.

1.3.9 Business models framework

Business models are strategies that can be implemented to enhance the profitability of any company or organization. In the case of RECs, it is important to implement the recommendations outlined in the RED II definition, i.e. RECs should not be conceived as urban forms merely dedicated to self-consumption and energy sharing. On the contrary, they should promote environmental, economic and social benefits to their members and, in general, to the urban environment in which they operate. The focus for community-based projects is on creating value through aggregating stakeholders, as well as managing and allocating resources and activities. The REC model, therefore, is not just a vehicle for distributing clean energy, but a broader framework for distributing benefits and responsibilities among community stakeholders [99]. This is a new way of thinking, especially considering the traditional and centralized energy sector, in which the maximization of the profits was at the centre of any decision-making process. Now, REC models must integrate economic viability with social inclusiveness, democratic governance, and environmental performance [83]. However, and also previously discussed with respect to policies and regulations, one of the fundamental challenges in designing REC is the heterogeneity of legal, technical, and economic conditions across Europe as well as the different granularity level [249], and this affect also the definition of business models. Key factors influencing business models include members typology, sharing model, revenues streams, key activities, resources and partners, that can significantly vary case-by-case [250]. For this reason, the operation context of each REC can lead to preferring one model over another. Many RECs are built around a single energy vector, typically solar PV for self-consumption [166], or members' aims, such as electricity bill reduction [251]. However, participation in RECs offers fewer economic benefits than existing social tariffs or general

subsidies, especially for low-income households and, therefore, the participation of members may not be attractive [252]. A promising evolution involves coupling electricity production and sharing with services such as sector coupling [253], energy efficiency retrofits and social impacts of operation [254]. These approaches enable RECs to better align energy supply and demand within their boundaries and generate additional revenue streams. A further extension of the business model involves participation in local flexibility markets, with RECs acting as aggregators of DSF or distributed storage [255]. The way RECs are constituted also impacts the business models. RECs may be initiated by local authorities, citizen cooperatives, energy service companies, or hybrid consortia, thus influencing both cost structures and income potential. In areas with strong municipal involvement, such as in the case of Italian regulations with specific incentives for small cities, RECs often benefit from existing administrative support and infrastructure, facilitating scale and continuity [256]. In contrast, communities relying solely on personal efforts may face limitations in professionalization, maintenance, and growth. To navigate the diversity of business logic, five typologies of REC business models can be identified: PV self-consumption, multi-sector integration, flexibility integration, community investment and social-oriented model. These models differ in terms of revenues, technical requirements, scalability, and vulnerability to policy or market changes. Across these categories, the evolution from a pilot to a fully operational REC entails not only technical readiness but also financial planning, regulatory compliance, and community engagement. Economic considerations are often a priority in various contexts, but they typically support only one of the targets of RECs, which is primarily driven by sustainability. Indeed, the dimensions of sustainability focus more on the environmental and social aspects rather than the economic one. Therefore, the members of the RECs and their effective management aim to create co-value that aligns with the community's complex needs, ensuring that the successful business models must reconcile economic, technical, and social dimensions [257]. They must be adaptable to different local contexts, resilient to changes in energy regulation, and transparent to foster trust among members. The diversity of possible models is not a limitation but a strength, provided there are adequate policy signals, institutional support, and financial mechanisms to ensure that communities can choose and refine the path that best fits their collective vision and capacity [258].

1.3.10 Policy measures supporting the development of RECs

The establishment of RECs in Europe is rooted in the European CEP [15], particularly in the RED II [21]. The Directive formally defines the roles and rights of RECs, legally recognizing

them as non-commercial legal entities with autonomy, voluntary participation, and democratic governance. In addition, the Directive specifies that RECs should have as their primary objectives to bring environmental, economic, and social benefits to members, an element that must also be included in each national transposition. In addition, the Directive obliges Member States to establish enabling frameworks that remove unjustified regulatory and administrative barriers, facilitate access to financing and enable RECs to engage in generation, consumption, storage and energy sharing. Despite these indications, the transposition widely varies across countries [151].

Along with the national regulations, the European Commission supports RECs development also through guidance documents and funding programmes. Notably, the Energy Communities Repository [259] and Rural Energy Community Advisory Hub [260] are platforms launched by the EU to provide technical assistance, facilitate knowledge exchange, and support pilot initiatives. These tools are complemented by structural and investment funds, such as those under the Just Transition Mechanism [261] and Horizon Europe [262]. Moreover, Horizon 2020 and Horizon Europe projects have funded demonstration actions, capacity building and digital innovation in RECs [263]. Financial support for RECs in Europe is anchored in both EU-level and national instruments. At the EU level, the European Regional Development Fund [264] and the Cohesion Fund [265] have been instrumental in co-financing REC infrastructure, particularly in underserved regions. At the national level, Member States have adopted diverse approaches to financial incentivization. Austria is a front-runner in terms of the number of established energy communities [266]. Here, electricity sharing is regulated by the Electricity Act [267] and by the ¨*Okostromgesetz*¨, OSG, referring to RECs [268]. Austrian law recognizes different REC models: local, regional and nationwide communities, depending on the voltage network used for sharing. The regulation recognises a 57 % discount for using the same LV network for local REC, a 28 % discount for regional REC in LV, and a 64 % discount for regional REC in MV.

RECs in Italy were first introduced in 2020 as part of the pilot phase of implementation. Subsequently, ARERA regulated the self-consumption schemes, economic tariff and incentives [269,270], while the GSE (*Gestore Servizi Energetici,* National Energy Services Manager Company) published the technical rules [156]. The Italian Ministerial Decree 414, at the end of 2023, regulates the final incentive and tariff premiums for shared energy in RECs [271]. In addition, a capital contribution of up to 40 % of the plant's investment cost may be covered by available funds from the NextGeneration EU program. In France, RECs are governed under the

framework of collective self-consumption, primarily regulated by the *Code de l'énergie* [272]. The document *Arrêté du* 6 octobre 2021 [273], defines technical and administrative procedures for energy sharing, while the *Arrêté du* 21 November 2019 [274] sets the financial conditions and tariff structures for collective self-consumption operations. Germany's *Erneuerbare-Energien-Gesetz* (EEG) has historically supported energy cooperatives through guaranteed remuneration mechanisms [275]. In Spain, the Royal Decree 244/2019 introduced a regulatory framework enabling collective self-consumption with net metering benefits [38]. The Czech Republic is piloting REC schemes under the Energy Act amendment, also known as *Lex OZE III*, focusing on multi-apartment building collectives[276]. Romania has adopted Law 123/2012 (amended 2022) to facilitate energy sharing and prioritizes vulnerable consumers [277].

RECs also intersect with the EU's goals on social inclusion and energy justice. Article 22 of RED II emphasizes the participatory and equitable nature of RECs, encouraging the inclusion of vulnerable households and municipalities [21]. Despite the indication, equity-based instruments remain inconsistently implemented across Member States. There is a growing consensus among experts that inclusion criteria, governance transparency, and benefit-sharing rules must be codified in national frameworks to prevent elite capture and exclusion. While many policy mechanisms have been launched, a comprehensive assessment of their effectiveness remains lacking. There is a need for EU-wide databases to track REC performance, regulatory maturity, and socio-economic impact, as this would be a powerful tool for any stakeholder involved in the REC design and implementation process [266]. In parallel, there is room for enhanced legal clarity on the interaction between RECs and DSOs, particularly regarding balancing responsibilities and cost allocation.

1.2.11 Future directions

The development of RECs has the potential to significantly reshape the energy landscape. However, to fully harness this capability, there is a necessity to address a series of challenges that can be directly linked to future opportunities in research, policy and practice. From the urban and energy planning perspectives, RECs are expected to evolve into more complex configurations, such as PEDs or contribute to the concept of climate-neutral cities advocated by the EU. This will require a net advancement in energy management and control, especially when dealing with multi-vector energy systems and smart district infrastructure. Future RECs will likely rely on dynamic, real-time data, supported by dedicated analytics and operational models. To this scope, a significant attention, finally, should also be devoted to the digitalization

and exploitation of AI technologies. In this context, digital twins, edge computing and blockchain will increasingly support production, consumption and distribution of energy, as well as predictive maintenance or peer-to-peer optimal transactions. In terms of social innovation and governance models, future RECs will emphasize the role of capacity building and participatory decision-making, especially engaging vulnerable populations and promote energy justice. This can be achieved only with a solid policy harmonization among different legislations, with the possibility for any stakeholder to have access to databases, tools and models to support RECs diffusion from the preparatory design to the effective constitution, operation and monitoring. To achieve this goal, however, common standards for data exchange and systematic integration should also be defined to ensure compatibility across countries, platforms or technologies. Thus, future directions of RECs will depend on the extent to which technological innovation, social inclusion and regulatory aspects will be efficiently integrated into a systemic framework, capable of responding to different challenges of energy transition and generating shared value at both local and European scales.

1.4 Advantages of RECs from case studies analysis

The potential of RECs lies in offering democratic models that enable citizens to have direct involvement in the energy transition process. A REC can be implemented using a bottom-up approach if the venture to create an innovative energy system starts with people who are aware and willing to make a direct contribution to changing the energy sector. Indeed, energy transition requires both direct, increase of RES pervasion in energy production, and indirect actions, citizen energy and environmental behaviour change.

This paragraph highlights potential advantages of RECs by analysing results from case studies based on numerical and experimental investigations.

1.4.1 REC benefits

As introduced above, RECs enable achieving multiple objectives beyond the direct energy benefits for their members. Participation in a REC can enhance control over both final and primary energy consumption and contribute to reducing associated GHG emissions, even when end-users' overall energy demand remains unchanged. Additional economic benefits arise from incentive schemes calculated on the amount of energy shared among community members. To maximize these benefits, DSM strategies can be implemented, providing consumers with

guidance on optimal time periods for increasing or reducing electricity consumption. In a REC configuration, the simultaneity between energy production from RES-based plants and members' consumption profiles is a critical factor. Both production and consumption are inherently variable, depending on the characteristics of the generation technologies adopted and the number and typology of participating end-users. Currently, solar PV systems represent the most widely deployed RES technology, due to their cost-effectiveness and modularity [278]. However, generation depends on location, season, and weather, and forecast uncertainties limit its programmability, despite the predictable daylight production pattern. On the demand side, different consumer categories exhibit distinct load profiles. Residential users typically show peak demand during early morning and evening hours, with significant variations between weekdays and weekends, user typologies, and seasonal daylight conditions. In contrast, office buildings generally concentrate their electricity demand during daytime hours on working days, depending on occupancy schedules, the installed power of electrical equipment, and heating or cooling requirements. In this context, REC optimization approaches commonly focus on identifying the most suitable combinations of generation assets and end-user profiles within the same community, with the aim of maximizing both energy sharing and resulting direct benefits.

Beyond energy and environmental benefits, the implementation of a REC can generate a wide range of additional advantages. The direct involvement of citizens in energy-related decision-making, along with the associated economic impacts, can mitigate social acceptance issues that often hinder the installation of RES-based plants at the local level. Becoming a member of a REC can also be economically advantageous due to incentives for shared energy, as well as potential savings from reduced purchases of other energy carriers. For instance, replacing gas-fired energy conversion systems, such as conventional boilers, with electric technologies like heat pumps allows end-users to exploit electricity generated within the REC. This substitution increases the share of locally shared renewable electricity while simultaneously reducing natural gas consumption and related costs. In this way, sector coupling strategies can further enhance the economic and environmental performance of RECs. According to the RED II, each REC should promote the use of locally available RES, which vary depending on geographical and territorial characteristics. The adoption of technologies with higher national manufacturing content compared to PV systems may also provide strategic advantages by reducing dependence on foreign supply chains. Moreover, the deployment of diverse RES-based plants can stimulate short supply chains, generating employment opportunities for local citizens and fostering economic development in the surrounding area.

These effects are particularly relevant for internal or rural areas that are otherwise at risk of depopulation, as RECs can enhance their attractiveness by offering tangible benefits to residents and businesses through access to renewable energy. The integration of EV charging infrastructure as delivery points within a REC further expands the range of services offered to members. This integration supports the diffusion of sustainable mobility solutions across the territory, providing benefits both to end-users, who can charge vehicles using renewable electricity, and to the REC itself, through increased energy sharing. More broadly, RECs enable the sharing not only of energy but also of resources, equipment, loads, and services, fully embodying the principles of decentralized and collaborative energy systems. Although REC members and generation plants remain connected to the PG, the infrastructure can benefit from the flexibility services provided by RECs. These include a reduction in electricity imports during periods when local renewable generation meets demand, as well as the export of surplus renewable energy during overproduction periods. Such interactions can contribute to improved grid stability and reduced reliance on centralized generation. Finally, one of the most significant social objectives of RECs is their potential contribution to alleviating energy poverty. By encouraging the participation of low-income or vulnerable households, RECs can help ensure access to essential energy services such as heating, cooling, and lighting. In addition to reducing energy poverty, RECs enhance awareness of energy generation, consumption patterns, and sustainable energy systems. Participation in these configurations is also associated with increased environmental consciousness, the adoption of more sustainable behaviours, and a stronger sense of community identity. This social dimension may represent a key factor in achieving higher acceptance of RECs compared to previous energy-sharing schemes, as it is rooted in collective self-determination and local control over energy outcomes.

1.4.2 Biomass-based, multi-purpose, energy poverty-focused and EVs integrated RECs

Four case studies are proposed and examined, each illustrating how variations in system configuration, member compositions, and technology selection influence the types of benefits achieved by a REC and its participants. Collectively, these case studies demonstrate that energy-sharing based configurations can be strategically designed to prioritize specific objectives, highlighting the flexibility of RECs in steering projects toward targeted social, environmental, or economic outcomes in line with their intended focus.

The first case study presents an optimization model for sizing energy systems serving RECs, applied to a REC located in the municipality of Tirano (Northern Italy). The energy conversion systems considered include an organic Rankine cycle biomass-based cogeneration plant, a mini-hydropower plant and a distributed PV system. Several REC scenarios are proposed, and the economic feasibility of a wood-biomass-based REC is demonstrated. Furthermore, the study highlights the importance of promoting renewable technologies based on locally available resources within each territory [279]. A multi-purpose REC is evaluated in the second case study. End-users have been considered in three configurations: simple users, energy close sharing system and REC, in order to evaluate respective advantages. The REC configuration achieves significant reductions in both energy consumption and environmental impacts, while also providing economic benefits through the energy sharing among participants [246]. The mitigation of energy poverty is identified as the key objective of the proposed REC in the third case study. An integrated energy, economic, and environmental analysis is conducted, considering three residential users as members of a REC located in a small town in Southern Italy. Their economic conditions are examined to assess social energy poverty indices. The results indicate that participation in the REC leads to greater mitigation of energy poverty compared to traditional energy supply configurations [83]. Finally, the analysis of the fourth case study focuses on the energy and environmental performance of a REC composed of two office buildings, one of which provides EV charging services. The EV charging load is incorporated into the REC configuration, enabling the provision of an additional service to community members while simultaneously maximizing the amount of shared energy [280].

Biomass-based REC

Ceglia, et al. propose a simulation model for analysing a complex energy conversion system serving a REC in Tirano, Northern Italy [279]. The system is based on a centralized biomass-based system (CBS) designed to meet both thermal and electrical demands of end-users. Thermal energy is distributed through a DHN, while electricity is supplied via multiple generation technologies. The CBS includes a CHP unit based on an organic Rankine cycle (ORC), driven by thermal energy from an 8 MW biomass boiler. In addition, two biomass boilers rated at 6 MW each (with a thermal efficiency of 85%) supply heat to the DHN, while a 6 MW fossil-fuel based boiler (90% thermal efficiency) operates as a backup and integration unit. The biomass boilers are fuelled by locally sourced biomass, including forest maintenance residues, sawmill waste, and pruning materials. Electricity generation is further supported by an 85 kW small hydropower turbine installed along the aqueduct line, which serves the

electricity demand of the Tirano municipality. A syngas-fired internal combustion engine (ICE) cogeneration system injects electricity directly into the local distribution network. Moreover, a solar PV plant supplies the self-consumption needs of plant owners, with surplus electricity exported to the PG. The DHN supplies residential, tertiary, and commercial heating demand throughout the year, including domestic hot water (DHW) needs. During the summer period, a 70 kW absorption chiller, thermally driven by the CBS, provides cooling for a commercial building.

An alternative REC scenario for Tirano was proposed in the study, involving the repowering of existing plants. To address performance degradation, a new ORC-based CHP system (NEW_CHP) was introduced, incorporating a 4.38 MW biomass boiler. The capacity of the NEW_CHP was selected to increase annual operating hours and improve overall system performance. The proposed scenario also includes the installation of a new small hydropower plant and additional PV systems. The PV capacity was determined based on the available rooftop area of public buildings owned by the Tirano municipality. In this scenario, biomass boilers continue to be supplied with biomass derived from local forest maintenance activities. The REC scenario was simulated using a Matlab [281] computational model. A dedicated control strategy was implemented to optimize CBS under different operating conditions:

- Scenario 1 (SC#1): CHP_NEW working at full load;
- Scenario 2 (SC#2): CHP_NEW working in heat-led mode.

Additional PV installations of 500 kW and 1000 kW, as well as a new 77 kW hydropower system, were also evaluated. Finally, an economic analysis of the proposed REC configuration was carried out. In particular, SPB is calculated as a ratio between the investment cost (IC) of new systems and the annual cash flows. The total IC includes the investment costs associated with the new CHP unit, PV systems and hydropower turbine. Revenues from energy sales comprise the income generated from thermal energy supplied by the CHP system to the DHN, as well as revenues from electricity produced by the CHP, PV, and hydropower units and fed into the PG. Additional revenues arise from incentives related to the electricity produced and shared among the members of the Tirano REC, in accordance with the initial Italian regulatory framework. The annual costs related to the management and maintenance of the plants and the REC are considered in reduction to earnings.

In Scenario 1 with a 500 kW PV system (SC#1_PV500), compared with the configuration without a REC, the utilization rate of the new CHP unit increases from 9.92 % to 16.23 % of

the overall demand, while the contribution of RES rises from 39.6 % to 48.6 %. When the PV capacity is increased to 1000 kW (SC#1_PV1000), local RES cover 49.7 % of the total electricity demand. In Scenario 2, RES penetration reaches 44.2 % with a 500 kW PV system (SC#2_PV500) and increases to 45.4 % with a 1000 kW PV system (SC#2_PV1000). The economic analysis identifies SC#1_PV1000 as the most advantageous configuration, yielding an SPB of 6.7 years. Beyond the economic benefits, the proposed REC provides several additional advantages. Biomass sourced from local forest maintenance, sawmill residues, and pruning waste is used to fuel the biomass boilers, fostering the development of a local biomass supply chain while simultaneously ensuring continuous forest management. Moreover, materials that would otherwise be classified as waste and incur disposal costs are instead valorised as locally available energy resources. To further assess the role of biomass within the REC of Tirano, a dedicated indicator, the Biomass Energy Ratio (BER), was developed. The BER quantifies the share of total thermal and electrical energy demand satisfied through biomass utilisation and is defined as the ratio of biomass-based thermal and electrical energy supplied to the total thermal and electrical energy demand. On an annual basis, the BER increases in all REC scenarios compared to the reference configuration without energy sharing. Specifically, the BER rises from 0.650 in the baseline case to 0.681 in SC#1_PV500 and 0.664 in SC#2_PV500. Increasing the PV capacity to 1000 kW does not result in significant changes in BER values [173]. Finally, the proposed REC is based on a relatively uncommon RES technology, namely biomass-based energy systems, which are characterised by a higher share of national components compared to other systems. The implementation of such innovative energy configurations in otherwise less attractive territories contributes to mitigating depopulation trends by enhancing local employment opportunities and supporting regional economic development.

Multi-purpose REC

The analysis about the sharing approach into energy system by including the investigation of past and recent directives about the topic and to present a case study in order to show the potential of the REDII directive and RECs organization is proposed by [246]. In particular, a multi-purpose REC consisting of thirty-six residential apartments and two restaurants located in a social housing district in Benevento (Italian climate zone C) is evaluated. Residential buildings are composed of six buildings with six apartments each (two per store). Restaurants are one-store buildings with a flat roof and a total floor-area of 250 m^2 for each one. Hourly electric loads, for two different typologies of users, is simulated on the basis of input data

(annual electric load and meteorological data) and the typical behaviour of different end-users. The simulation has been performed using Homer Pro [74] software environment. The daily peak electric load is equal to 21.7 and 39.7 kW for restaurants and residential buildings, respectively, and it occurs during evening hours. According to the Italian standard [282], the heating period for climatic zone C is considered from 15th November to 31st March, while the cooling period is assumed to be from 1st June to 30th September. The energy conversion system serving the residential buildings is a reversible air-to-air heat pump in each apartment, and it meets the cooling loads, while a natural gas-fuelled boiler supplies space heating and DHW demands. Three reversible air-to-air heat pumps meet the space cooling load, and a gas-fuelled boiler is used for space heating and DHW energy demand in each restaurant. The case study presents a comparison of three different energy system configurations, which differ how end-users electricity demand is satisfied, *Figure 1.7*:

- Conventional system (CS): the electricity demand of each apartment and restaurant are met by drawing electricity from PG without sharing, so each end-user is assumed to be a single passive consumer;
- System of efficient users (SEU): all end users are allowed to purchase electricity from an external producer through a private grid connection under an off-take contract. Under this arrangement, the producer offers end users a tariff that is lower than the conventional market price while remaining above the producer's minimum acceptable financial return. Both the allocated energy share and the unit electricity price are fixed over a multi-year contractual period. The external producer considered in this work is assumed to own a PV field with a power capacity of 1 MW. Under these conditions, the co-production framework is restricted to a single generation facility and a single plant owner;
- Renewable Energy Community (REC): it is composed of residential buildings and restaurants that are able to share renewable electricity produced by PVs plants installed on each building. In particular, on each residential buildings roof a PV field with a peak power of 15 kW is installed. While, on each restaurants roof a PV plant with a peak power of 22.5 kW is placed. More precisely, in the REC layout, restaurants and residential buildings constitute a legal entity bidirectionally connected to PG. In the hours in which the electricity request of REC is higher than PV fields electricity production, the deficit electricity is taken from PG, while when there is a surplus PV electricity generation, it is sold to PG.

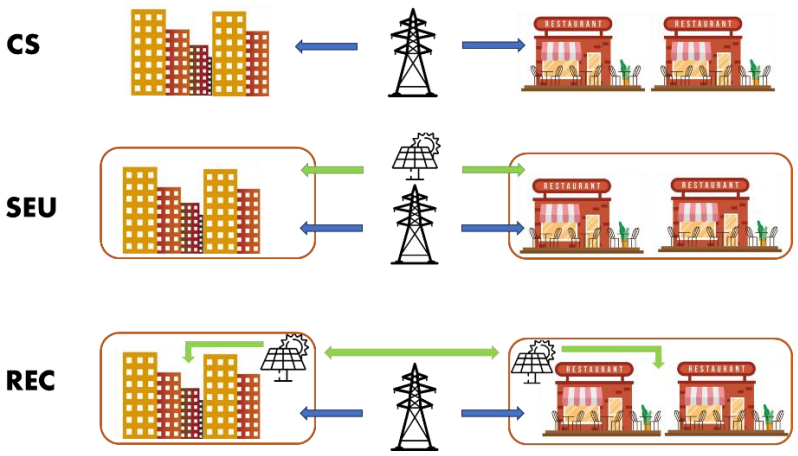

Figure 1.7 Schematic layout of CS, SEU and REC

In CS all the requested electricity is taken from PG, thus the primary energy in this configuration is the highest and it amounts to 436.0 MWh/y. The primary energy need of REC (268.5 MWh/y) is greater than SEU configuration (200.3 MWh/y). This difference arises because it depends only on the electricity drawn from PG and it is greater in the REC case due to the lower installed PV capacity compared to the SEU configuration. Consequently, the difference between the SEU and REC configurations is 68.2 MWh/year, while the difference between SEU and CS is 235.7 MWh/year and that between REC and CS amounts to 167.5 MWh/year.

In order to present an in-depth energy assessment, two specific indices are introduced. Renewable share of electricity index (RSE), amount of electricity demand of all end-users ($E_{el,US}^{REC}$), covered by the PV plants (Equation 1.12), and renewable self-consumption index (RSC), ratio between the PV electricity self-consumed with respect to the total amount of PV electricity produced in each configuration ($E_{el,RES}^{REC}$) (Equation 1.13), are calculated for SEU and REC configurations. θ_n represents the timestep and *N* the total number of timesteps over a year.

$$RSE = \frac{\sum_{n=1}^{N} E_{el,SH}^{REC}(\theta_n)}{\sum_{i=1}^{N} E_{el,US}^{REC}(\theta_n)} \tag{1.12}$$

$$RSC = \frac{\sum_{n=1}^{N} E_{el,SH}^{REC}(\theta_n)}{\sum_{n=1}^{N} E_{el,RES}^{REC}(\theta_n)} \tag{1.13}$$

The RSE index is higher in SEU configuration (54 %) than REC one (12 %) because PV plant installed in SEU has a larger size (1 MW) with respect to total PV capacity installed in the REC configuration (135 kW). The results regarding self-consumption are opposite, indeed the RSC index for SEU is equal to 38 % and to 56 % for the REC.

The environmental analysis has been carried out considering both natural gas CO_2 emission factor (β_{NG}) fixed to 205 g_{CO_2}/kWh for gas boilers primary energy, and the Italian PG CO_2 emission factor (α_{PG}) equal to 360 g_{CO_2}/kWh_{el} for electric energy. SEU ensures the lowest CO_2 emission (47.2 t_{CO_2}/year), while CS layout that emits the highest (102.8 t_{CO_2}/year). The REC CO_2 emissions are equal to 63.3 t_{CO_2}/year. Furthermore, by considering a capacity of PV plant in REC equal to that one installed in SEU configuration (1 MW), it would be possible to create seven energy communities like that one proposed in this study, ensuring a total reduction of CO_2 emission equal to 443.1 t_{CO_2}/year. The REC allows CO_2 equivalent emissions saving of 38 % on a yearly basis with respect to the traditional configuration without the sharing approach. With regards to the economic analysis, the configuration with the highest operating cost is CS (71,402 €/year). By comparing SEU and REC, the economic analysis rewards REC because of the economic incentive for shared energy. In the analysis, the SEU electricity unitary price is fixed to 20 c€/kWh. The avoided operating cost going from REC to SEU configuration is equal to 29,484 €/year, while by comparing REC and CS the reduction amounts to 43,765 €/year. In addition, by comparing REC and SEU, it is important to highlight that REC ensures that the citizens are involved in economic advantages thanks to the economic incentive associated to energy sharing. This could facilitate the participation in the project of vulnerable people, from an energy point of view. REC presents higher social aims than SEU, since the users are to share energy services without economic interest thanks to co-production approach without the definition of single owner.

With regard to the implications of this study, the results suggest that energy policies should promote the innovative valorisation of energy communities by explicitly considering previously defined performance indicators, such as RSE and RSC, while also accounting for the social acceptability of RES by assigning greater weight to avoided emissions. The proposed REC also represents an effective instrument for addressing local opposition to RES-based plants, when they present a shared ownership. Moreover, the integration of PV systems could enable the replacement of natural-gas-fired boilers with electric heat pumps, thereby maximizing on-site electricity utilization and simultaneously reducing expenditures on other energy carriers in the future. Within this multi-purpose REC framework, the two restaurants could additionally provide EV charging services to their customers, fostering the diffusion of EVs at the local level and offering an ancillary service that constitutes a relevant added value for a tertiary-sector entity.

REC addressing energy poverty

Energy poverty, according to the definition provided by the European Commission, is a condition of vulnerable households that can't access essential energy services, such as heating, cooling, and lighting. When energy bills represent a high share of consumers' income, or they must reduce their energy consumption, achieving a discomfort condition, energy poverty occurs [283]. The Covid-19 pandemic and the conflict in Ukrainian territory have had a significant impact on the rise of electricity prices, which caused an increase in the number of people in energy poverty conditions. In this regard, the considered case study focuses on the comparison between end-users as individual customers and in a REC configuration, in order to evaluate the benefits of the second configuration with a focus on socially sustainable advantages. In particular, the mitigation of energy poverty has been carried out through a new social indicator. The REC examined by Ceglia et al. includes three residential users across two buildings in Southern Italy, with a PV plant installed on the rooftop of one of these buildings [83]. The three considered buildings are located in a small town in the South of Italy. The electric load of each building is real and was supplied by the electricity distributor. Dataset has been analysed on a seasonal basis considering weekdays and weekend days. The electricity is used to supply electric appliances, electric-based energy conversion systems to cover the cooling loads for all users, electric-based energy conversion systems to cover the heating loads only for the third user. Two configurations have been investigated:

- Traditional configuration: each building gets from the PG the electricity needs in an independent way;
- REC: a PV rooftop plant with a peak power of 18 kW is installed, so energy is produced on site and shared with other members considering the virtual scheme. In this configuration if energy demand is higher than the produced one, the additional share is supplied by the PG.

Dynamic simulation using Homer Pro [74] and Matlab [281] codes has been developed. Total electricity shared in the REC is equal to 30.48 MWh/year. During winter months (from November to February) the amount of electricity injected into the PG decreases while the share of electricity taken from the PG increases. In this period, the electricity production from the PV plant can cover from 64.3 % of electric loads in December to 80.8 % in November. From March to October the electricity production from PV plant is able to cover higher share of total electric

loads, such as 84.7 % in August and 93.8 % in April. By comparing traditional configuration and REC one, a primary energy saving on a yearly basis of 61.6 % has been evaluated.

Furthermore, REC allows reduction of GHG emissions of 64 % every year. Finally, SPB is equal to 10 years by considering that the RECs members purchase the community's plant. In this study, additional social analysis has been conducted, proposing an evaluation of the energy poverty condition of the three end-users. According to the literature study [284], the most widespread social index is the so called "*10%*" indicator, as reported in Equation 1.11. An end-user is in an energy poverty condition if he spends for energy more than 10% of his overall income. This index is upgraded in this study by considering a more accurate income indicator, the Equivalent economic situation Indicator, ISEE, used in Italy to be eligible to subsidized social benefits, Equation 1.14.

$$10\%_{ISEE} = \frac{OC}{ISEE} \tag{1.14}$$

These two indices are evaluated in both configurations to assess the improvement in the contrast to energy poverty thanks to the participation to the REC. By considering the *10%* index, the results indicate that in traditional configuration only the second end-user is near to the energy poverty condition. Otherwise, if the $10\%_{ISEE}$ index is considered, both second and third end-users are in the energy poverty condition. This result highlights that the ISEE parameters could be more suitable. In the REC layout, by considering both indexes, no end-user is in the energy poverty condition.

Electric Vehicles integrated in a REC

In [280], the authors consider a REC composed of two office buildings located in Naples. The first office (Office1) is occupied by thirteen workers during weekdays, while it is empty on weekends. The second one (Office2) is divided into two apartments intended for office use, and each of them is occupied by a maximum of six employees and six users during working hours, while it is empty on weekends. Both are one store flat roof buildings. Electric load has been determined for each office by considering the occupancy schedule, the lighting and the power of typical electric equipment installed in an office (printers, fax, laptop, copiers, etc.) as defined in [285]. Thus, since the lighting loads can be different from one season to another, a daily electric load for a typical weekday of heating, cooling and intermediate period has been outlined. However, only one type of electric load has been defined for weekends. The allowed heating period for Italian climatic zone C goes from 15th November to 31st March, while the

cooling period is assumed from 1st June to 30th September. Thereby, there is an intermediate period, from 1st April to 31st May, and from 1st October to 14th November, where no space heating and cooling needs to occur, but only electricity requests have to be met. No DHW demand has been accounted since it is significantly lower than the heating and cooling requests for a tertiary building. On the basis of these considerations, the annual heating demand of Office1 is 3.15 MWh/year, while the space cooling needed for the same building amounts to 5.21 MWh/year. The space heating and cooling requirements of Office2 are 3.62 MWh/year and 5.32 MWh/year, respectively. The schematic layout of the REC composed of two office buildings able to share renewable electricity is reported in *Figure 1.8*.

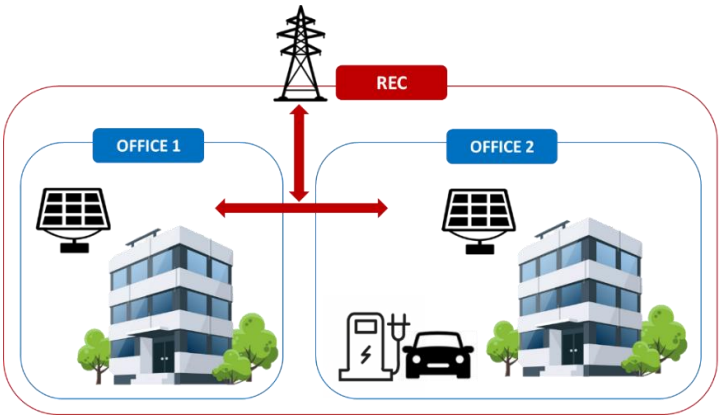

Figure 1.8 Schematic layout of the REC

The main features of energy conversion systems installed in each office are:

- Office 1: a reversible air-to-water heat pump meets the space heating and cooling load. A PV field with a peak power of 9 kW is installed on the roof. The panels are arranged in 3 arrays with 12 units facing south with a tilt angle equal to 30°;
- Office 2: an air-to-water heat pump with the same characteristics of Offfice1 is installed. The PV field has a peak power of 14.25 kW. It faces South with a tilt angle of 30°. At Office2, an EV charging station with a capacity of 3.3 kW is installed. It is able to provide constant charging to a selected EV with a nominal electric storage of 30 kWh [286], a specific consumption of 0.173 kWh/km in direct current [287], and a daily distance covered of 120 km. The electric energy required to charge an EV is equal to 24.41 kWh, while 7.31 h are needed to reach the full charge. Annual electricity requested by the EV amount to 6.84 MWh/year.

Both offices' plants are in parallel with PG, thus PV electricity is used to meet the electricity requested by the heat pump, power equipment, lighting system, plant auxiliaries and EV (in Office2), and the surplus/deficit of electricity could be exchanged with the PG. In the REC

configuration, it is possible to share the electric energy from both PV plants. In particular, if in some instances the PV plant of Office1 cannot cover in whole or in part its electricity load, it is checked the availability of electricity from the PV plant of Office2. Any remainder is balanced by taking electricity from PG. On the contrary, if there is surplus electricity produced by the PV plant of Office1, it finds out whether an electricity request from Office2 occurs; otherwise, it allows the electricity to be exported to PG. The same control strategy is followed for electric energy by the PV plant of Office2. Buildings and plants are modelled and simulated by means of TRNSYS 17 software [75]. Two configurations have been considered in this study in order to evaluate the energy and environmental performances:

- NO SH (No Sharing): the offices cannot share the PV electricity with each other. More precisely, the electric energy from each PV plant can only be used to meet the electricity load of the office where it is installed;
- SH (Sharing): the sharing of PV electricity between two offices is allowed, considering the REC as a single entity that interacts bidirectionally with PG.

Referring to the NO SH case, the electric energy withdrawn from the PG by Office1 and Office2 amounts to 4.93 MWh/year and 5.19 MWh/year respectively, whereas the PV electricity exported to PG by Office2 (9.47 MWh/year) is significantly higher than that exported by Office1 (6.53 MWh/year). This is because the PV electricity available from the Office2 plant is greater due to its larger size, even though the presence of the EV increases the electric load. However, the Office2 PV plant covers 32.7 % of the total EV request. The electricity contribution of the PV plant to the EV electricity request is higher in intermediate months with respect to summer months because in that period, no space heating and cooling demands occur; in addition, in winter months, the low availability of electric energy from the PV plant results in a low contribution to EV electricity demand, too. Referring to whole systems in NO SH cases, self-sufficiency reaches 57.2 % in Office1, while it increases up to 65.8 % in Office2. The self-consumption reaches 50.2 % and 51.2 % respectively, evidencing the opportunity to improve the results. Indeed, by considering sharing approach, RSE and RSC indices within the community increase. The RSE index grows up to 81.3 % and 77.8 %, while RSC index rises up to 74.4 % and 60.7 %, for Office1 and Office2 respectively. Furthermore, the electricity sharing within the community allows a reduction of the amount of electricity exported and imported to/from the PG, reducing grid perturbations. Hereinafter, the primary energy demand and carbon dioxide emissions of the REC have been evaluated by considering fixed and time-varying efficiency and environmental indicators for electricity production. The primary energy

demand of the REC is evaluated 8.76 MWh/year referred to average values and 7.15 MWh/year for hourly-varying indicators, with a percentage decrease of 18 %. With regards to environmental analysis, CO_2 emissions for REC present a 12 % decrease between annual basis values scenario and the use of time-dependent emission factor for electricity. The outcomes highlight the use of average indicators leads to an overestimation of the primary energy demand and CO_2 emissions. Thus, it is necessary to use variable indicators to evaluate the performance of such systems that are based on intermittent and variable sources. To sum up, it is clear that the share of electricity within the community leads to a better PV electricity exploitation. In future development of the research, it could be interesting to evaluate the cases of EV used as "vehicle to building technology" in order to use the EV battery as storage in RECs configurations.

Outcomes discussion

Analysed case studies present results based on the energy, environmental and economic assessment of the proposed REC with respect to the existing energy conversion system. In general, energy analysis is based on the evaluation of the primary energy saving obtained with the REC configuration with respect to the traditional system, the environmental analysis concerns the calculation of the CO_2 equivalent emissions saving, while the economic analysis evaluates SPB, which indicates the number of years to balance the greater investment cost. Not all case studies report numerical values for the considered parameters. In *Table 1.3* these results are reported. In addition, some studies present additional evaluation indices based on specific assessments.

Table 1.3 Energy, environmental and economic results for analysed case studies

Case study	ΔE_p **[%]**	ΔCO_2 **[%]**	**SPB [years]**
Biomass-based REC	-	-	6.7
Multi-purpose REC	62	38	-
REC against energy poverty	62	64	10
EV integrated in a REC	-	-	-

For the case study of biomass-based REC the investigation on the technical features of energy conversion systems serving the thermal, cooling, and electric users of Tirano municipality, as well as the collection of historical data on the existing local DHN was conducted. Different REC scenarios were proposed, including the installation of a new, smaller

biomass-based combined heat and power system based on the ORC. Moreover, in the REC scenarios, different distributed PV capacity, namely 500 kW and 1000 kW, and a new hydropower turbine were considered. In *Table 1.3* only the results related to the best scenario are reported. Multi-purpose REC case study presents a REC composed of six residential buildings and two restaurants located in Benevento. It has been compared with the performance reached by two different aggregations of the same end-users: CS and SEU. The simulation results have been analysed to define the advantage of each layout in terms of the amount of shared electric energy and self-consumption. The reported results are related to the comparison between CS and REC. How RECs can reduce the energy poverty of their members has been analysed in the third case study. REC against energy poverty includes three residential flats located in two buildings, equipped with an 18 kW PV plant installed on the roof of one building. The REC layout is compared with a configuration in which users are individually linked to the PG. The simulation results demonstrate that the REC could achieve primary energy savings of 61 % and a reduction in annual carbon dioxide emissions of up to 64 %, compared to the simple end-user configuration. In addition, the socio-economic indices show an improvement in energy poverty conditions for all users, with some of them moving above the poverty line. With reference to the economic analysis, a 10-year SPB has been evaluated for the considered REC. The integration of EVs in a REC configuration is presented in the last case study. The REC is composed of two office buildings, each one equipped with a PV rooftop plant. The office equipped with the largest size PV plant is furnished with a constant charging station for an EV charged during working hours. The simulation results have been used to compare electricity flows in the case where electricity sharing is allowed and in the case where it is denied. The primary energy demand and CO_2 emissions of the REC have been evaluated by considering fixed and time-varying efficiency and environmental indicators for electricity production. The outcomes reached in two scenarios are very different, and in particular, the use of average indicators leads to an overestimation of the primary energy demand and CO_2 emissions imputable to the REC. No numerical results about the considered parameters are reported.

This review study examined four case studies to highlight the benefits of RECs. As discussed, a REC is not uniquely determined; differences can occur across cases. Different typologies of included members, aims of the project or offered services are only some of the features on which characterisation could be done. In any case, the advantages offered by a REC are numerous and may vary depending on the specific application context. In *Table 1.4*, some advantages have been reported and highlighted in each of the analysed case studies.

Table 1.4 REC advantages from analysed case studies

Case study	Technology with high rate of national component	Development of a local supply chain	Fight against depopulation and impact on employment	Fight against acceptability of RES-based plants	Fight against energy poverty	Saving on the purchase of other energy carriers	Charging services for electric vehicles
Biomass-based REC	X	X	X	X	X	-	-
Multi-purpose REC	-	-	-	X	X	X	X
REC against energy poverty	-	-	-	-	X	X	-
EV integrated in a REC	-	-	X	-	-	X	X

In *Figure 1.9* a radar graph is shown. Each case study has been analysed in terms of the advantages the REC configuration offers. A scale of numerical values has been used, from 0 (the considered case study has no relevance with the advantage taken into account) to 5 (the considered case study has full relevance with the advantage taken into account).

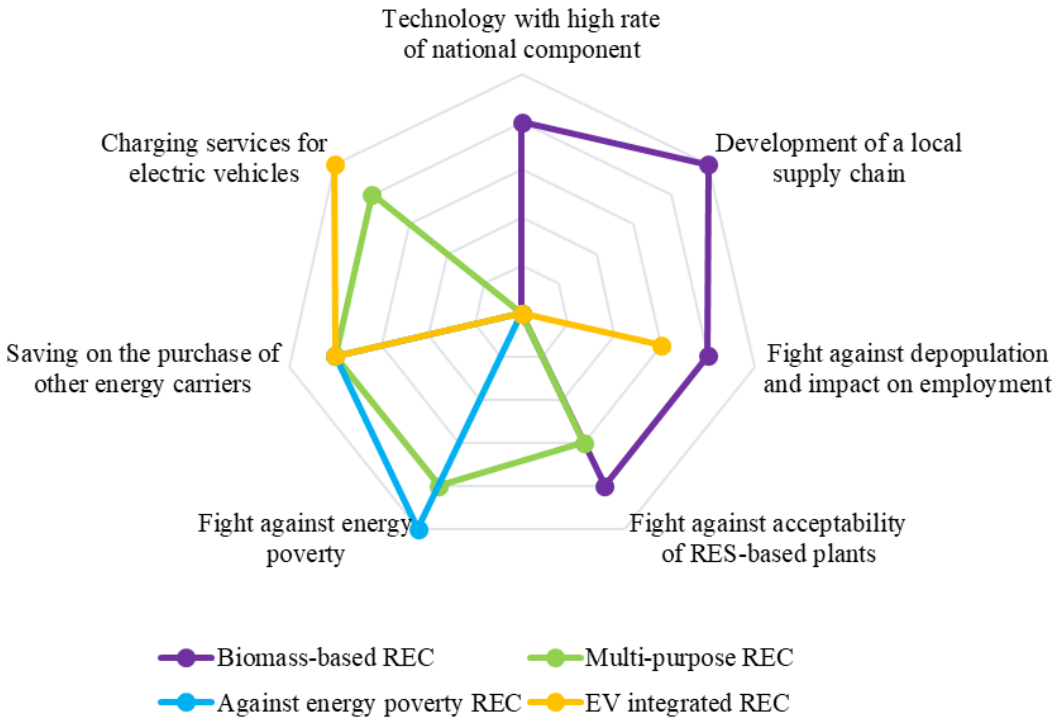

Figure 1.9 Advantages of REC case studies

Biomass-based REC meets energy demands of end-users thanks a technology with higher rate of national component rather than PV plant, using locally available sources that support the development of a local supply chain. All this offer services to the territory through the maintenance of local forest, creating a circular economy which allows to obtain energy values from wastes that should otherwise have to be disposed differently and with an additional cost. REC allows to produce impact on employment, at the same time fighting against depopulation

of otherwise less attractive area. Direct involvement of local population in REC project can also encourage a greater acceptability of RES-based plants on the territory. The case study conducted on the multi-purpose REC highlights that the innovative energy sharing organization may achieve higher acceptance among citizens due to its bottom-up approach, incentive-based mechanisms, and the active involvement of members in management processes. The possibility of including residential users in RECs offers them the opportunity to improve their energy poverty conditions. Moreover, although membership in a REC does not necessarily result in direct savings on final consumers' electricity bills, it can lead to cost reductions in the purchase of other energy carriers when conventional energy conversion systems are replaced with electrically powered alternatives with higher energy efficiency. Moreover, when commercial activities are included in a REC they can offer charging services for EVs to customers as additional services, while simultaneously maximizing shared energy. With respect to energy poverty, RECs deliver social benefits by enhancing the energy access and affordability for all members.

Chapter II: Advancing RECs implementation from multi-sectoral approaches to the regulatory frameworks investigation

RECs occupy a pivotal role within the evolving energy landscape, owing to their inherent versatility in facilitating the integration of diverse application fields. This adaptability is further reinforced by their capacity to engage a broad spectrum of stakeholders, encompassing various user groups and application sectors. The multi-dimensional nature of RECs enables them to address both energy production and consumption challenges simultaneously, thereby fostering a more inclusive and sustainable energy system across different contexts and regions. At the same time, the establishment of RECs is permitted in numerous countries, both within and beyond Europe, albeit under varying procedures and regulatory frameworks. The specific modalities of implementation are not uniform, necessitating careful examination to identify the strengths and limitations of each approach.

This chapter presents studies on the implementation of REC case studies, with a particular focus on multi-sector integration. Electric mobility is included through an EVs car-sharing system integrated within a REC. The potential deployment of storage systems connected to RES-based plants is also evaluated to enhance the flexibility of the configuration and assess the associated benefits. Additionally, the inclusion of industrial users, who have energy load profiles and characteristics typical of this user category, is considered. Finally, a comparative study examines different approaches to energy sharing and economic remuneration for RECs, taking into account the regulatory frameworks of Italy and Spain.

The presented case studies advance the current scientific literature on RECs by addressing a research gap: the integration of non-traditional sectors within energy-sharing configurations. Specifically, the inclusion of the industrial sector in one case and the transport sector in another, is examined. Beyond sectoral novelty, this research distinguishes itself through the empirical

assessment of real-world REC implementations under different existing regulatory frameworks. By systematically evaluating energy-sharing models alongside economic remuneration schemes, the study moves beyond theoretical formulations to quantify the tangible benefits achievable for both communities and individual participants.

This dual contribution, sectoral expansion and real-case comparative regulatory analysis, enables the identification of actionable insights and policy-relevant implications. The findings support the design of more effective and inclusive REC mechanisms, ultimately facilitating scalable and systemic transformations grounded in demonstrated energy and economic outcomes.

2.1 A car-sharing system with EVs integrated into a REC

Achieving European carbon neutrality by 2050 implies involving the most energy- intensive sectors, such as industry and transport [288]. The latter contributes to a quarter of global GHG emissions [289], and road transport is one of the main culprits, accounting for more than 70 % of the whole sector's emissions [290]. Its environmental impact can be reduced through non-technological, promoting public transport, walking or cycling, and technological approaches, adopting new vehicle technologies [291]. In the urban context, the EU instituted the Sustainable Urban Mobility Plan. The promotion of electric mobility, from electric buses [292] to light-duty vehicles [293], is consistent with some of its goals [294]. The transition to EVs is pivotal for the EU, especially when powered by RESs, as it significantly lowers the transportation sector's carbon footprint. This favourable impact can also be reflected in other sectors, as tourism [295]. The diffusion of EVs has increased in recent years: in Europe nearly 22 % of newly registered cars in 2022 were electric [296]. China, the United States, and Australia have made significant policy progress to accelerate EV adoption [297], while developing countries should implement incentive programs [298]. However, even with economic incentives, the costs are still high compared to conventional vehicles, allowing access only to certain population segments [299]. Car-sharing systems with EVs can partly overcome this problem, with the additional benefit of reducing local pollution in urban areas [300]. The sharing economy concept was born to provide opportunities for all socioeconomic levels of the population, embracing the efficient use of resources and non-ownership idea [301,302]. Recently, fashion, cinema, hosting and

transportation sectors have promoted the sharing of products or services through digital platforms [303], promoted by environmental awareness and the use of new technologies [304], in a society striving for sustainable development [305]. Car-sharing systems, widespread worldwide, contribute to reducing car ownership [306] and public space for parking [307]. Nevertheless, the high penetration of EVs in power system, entails technical and stability problems [308], due to numerous charge–discharge cycles [309]. Inefficient management of EV charging, partially overcome with smart charging operations [310], may lead to grid congestion and boost no RES-based generation to satisfy the demand [311], adversely affecting GHG emissions [312]. Local reserve market involving the DSO can integrate EVs flexibility into the overall market to compensate load deviations [313]. Their charging cycles can also be optimized following combined environmental and economic aspects as carbon emissions market prices [314]. Flexibility services for the PG are implemented through load shifting, DR techniques, energy storage integration, and energy sharing-based configurations [315], such as RECs [316]. RECs represent leading models of the new decentralized production, consumption [317], and sharing of energy from local RES-based plants [128]. The scientific literature has extensively investigated the conversion of energy from RESs to other energy carriers. The P2X concept is mainly referred to as P2G or P2H, but then broadens to different applications or energy carriers, including power-to-vehicle or power-to-mobility [180]. Smart grids including EVs, using a V2G technology, offer storage solutions and versatile demand resources [318], through bidirectional power flows during peak load timeslots [319]. The binomial RESs-G2V (grid-to- vehicle) aims to minimize the environmental impact by reducing the withdrawals from the PG only to energy demand excesses or lack of RES availability [320]. The integration of EV charging services as points of delivery (POD) of a REC provides additional services to members, increases the load covered by the RES [280,321], maximises shared energy from the EVs adaptability in coupling to an intermittent RES [129]. Their optimal management leads to reduced energy costs for the community [322] and environmental impact [323]. Though for EVs non-monetary barriers emerge for users, as anxiety factors for the reduced range and limited spread of charging stations [324], advantages of EV car-sharing systems have been demonstrated in literature, considering both different comparing systems and end-user demand evaluation. A comparison between taxicabs and car-sharing system under the same GPS trajectories-based travel scenarios in Beijing (China), highlights the economic advantages of the latter for rentals up to 14 h [325]. Considering real traffic driving conditions, EVs showed the lowest energy consumption compared to gasoline-powered plug-in hybrid vehicles, which

are about 10 % larger, and combustion vehicles, which exceed them by about 30 % [326]. The replacement of different shares of internal combustion engine (ICE) vehicles of a taxi fleet by similar EVs models, presented an energy consumption four times lower and CO_2 emissions production ten times less, with equal daily travel distances [327]. Data collected for car-sharing systems analysis came from online survey [328,329], interviews to drivers and customers (for taxi) [320], highway traffic information [330], national mobility panel [331], or real driving distance for restricted micro-grid [332]. In any case, despite the different methodologies followed, electric mobility shows significant advantages over other types of vehicles, which increase when sharing systems are considered. The sharing of energy resources, equipment, loads, and services fully applies to the REC concept. Numerous studies highlight interest in car-sharing systems [333] and RECs [23], but the combination of these two themes represents a topic that has not yet been studied in depth, offering innovative insights.

In this context, the study presented in this paragraph proposes a car-sharing system based on EVs embedded in a REC. To evaluate the performance of the proposed system, it has been designed for a municipality in southern Italy, assuming that renewable energy is produced by PV panels. Corresponding energy, environmental and economic benefits are evaluated by comparing different layouts, including conventional vehicles and EVs, for the same fleet size and travelled distance.

Some novelty aspects regard:

- real data on traffic flows and mobility demand used to define the car-sharing system;
- EV charging optimized considering the RES availability and technical constraints of the fleet;
- EV car-sharing system integrated into a REC is compared with EV car-sharing system supplied by the PG and fossil fuel-powered car-sharing system, which meet the same end-users transport demand;
- energy, economic, and environmental (3-E) analysis is evaluated using both hourly and daily time intervals.

2.1.1 Urban mobility car-sharing layouts

Recently, high interest in decarbonising the transportation sector and achieving energy targets has led to a strong acceleration towards electrification, involving the RES sector too. In this study, the implementation of a car-sharing system is proposed, and different layouts are

considered to evaluate the benefits of each from several viewpoints. The car-sharing configurations mainly differ in the type of vehicles: traditional ICE vehicles or EVs, changing only, in the second case, how the energy is produced. The utilization rate, distance travelled and fleet size are assumed to be the same for all configurations examined. Three mobility car-sharing layouts have been proposed (*Figure 2.1*):

- EVs integrated into a REC (EV-REC): the EV car-sharing system is included in a REC. A RES-based plant meets electric energy demand of EVs (E_{el}^{EV-REC}) and maximises the configuration benefits. A virtual sharing scheme is considered;
- EVs fed by the PG (EV-PG): an equal sized EV fleet is considered. The electric energy for charging service (E_{el}^{EV-PG}) is taken from the PG considering the mix of power plants fed both by fossil fuels and RESs to produce it;
- Traditional system (TS): the system is characterized by a fossil- fuelled vehicle fleet. The car typologies included are evaluated in detail below.

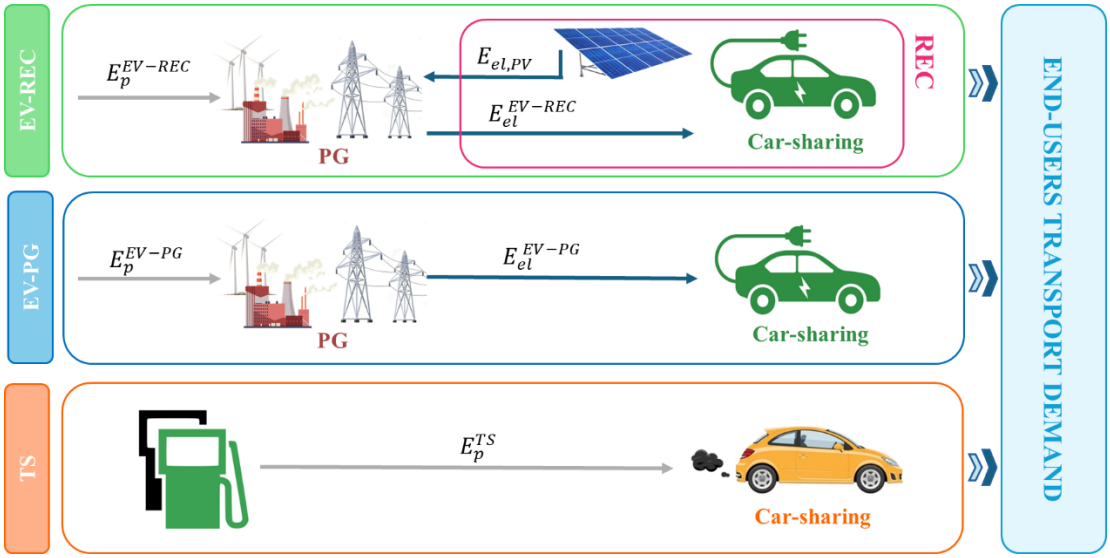

Figure 2.1 Investigated layouts

In *Figure 2.1* the primary energy associated with the electric energy withdrawn from the PG in the first (E_p^{EV-REC}) and second layout (E_p^{EV-PG}) considers the mix of plants of the PG production subsystem. In the REC, the electric energy from the PV plant ($E_{el,PV}$) is virtually shared with the configuration POD. E_p^{TS} represents the energy provided by fossil fuels to satisfy the energy demand for car-sharing systems in TS.

Car-sharing is a widespread transportation mode in many medium and large-sized cities and is a significant component of the mobility-as-a-service systems, central to future urban mobility

[334]. The car-sharing user pays only for the use of the car, owned by the service provider, based on time of use and/or kilometres driven. The annual cost that an average car-sharing user incurs is usually much less than the fixed costs of owning a car if occasionally used. In contrast, the costs would be much higher in the case of continuous use. Indeed, car-sharing is not seen as a substitute for owning a car as it is for a second car in the family when this is used not habitually [335]. Car-sharing services can be station-based or, conversely, free-floating [336]. EV-based systems are usually station-based, constraining the user to park the vehicle in parking areas where electric charging stations are available. Station-based systems can be either bi-directional or mono-directional; the former requires the vehicle to be returned to the same station where it was picked up, while the latter allows the vehicle to be returned to any other charging station. In this study, the three one-way station-based urban mobility car-sharing layouts have been designed for the municipality of Lioni, a town in southern Italy (Avellino province). Lioni has about 6,000 inhabitants and a territory of about 46.5 square kilometres; the central area houses two-thirds of the population. The economy is mainly driven by industry, which can attract labour from neighbouring municipalities. The tertiary sector has also been developed, including qualified services and a rich distribution network. Characteristics of the considered area make it interesting to propose a car-sharing system. For Lioni, a fleet of 12 cars has been considered. Sizing has been conducted in a proportional way to the population, starting from other car-sharing systems in the country. Indeed, there are no codified methodologies for sizing car-sharing systems. Usually, it starts with an experimental type of service, with a certain number of vehicles and stations, and then it is extended or reduced according to users' response to the service. An initial sizing can be obtained based on systems already operating in other cities that have thus passed the experimental start-up phase, depending on the number of inhabitants.

For the sizing of the car-sharing system in Lioni, the service in Bologna (Italy) was used as a starting point, adapting the number of vehicles to the inhabitants of the city under study, considering the absence of a scaling factor. The city of Bologna has a fleet of 455 vehicles [337] for about 390,000 inhabitants, thus 1.17 vehicles per 1000 inhabitants. Considering the different population of Lioni, which does not allow for economies of scale, it is assumed 2 vehicles per 1000 inhabitants, therefore, a fleet of 12 cars. The evaluation of the charging stations was conducted considering a station-based car-sharing system for all layouts, providing a predefined number of vehicle pick-up and drop-off points. For station-based systems, it is necessary to provide more than double the number of parking stalls and charging stations than the average

number of vehicles expected at each station to avoid the user not finding a free parking space at the destination; therefore, 25 parking stalls and charging facilities have been considered, 5 for each station. *Figure 2.2* shows the stations location.

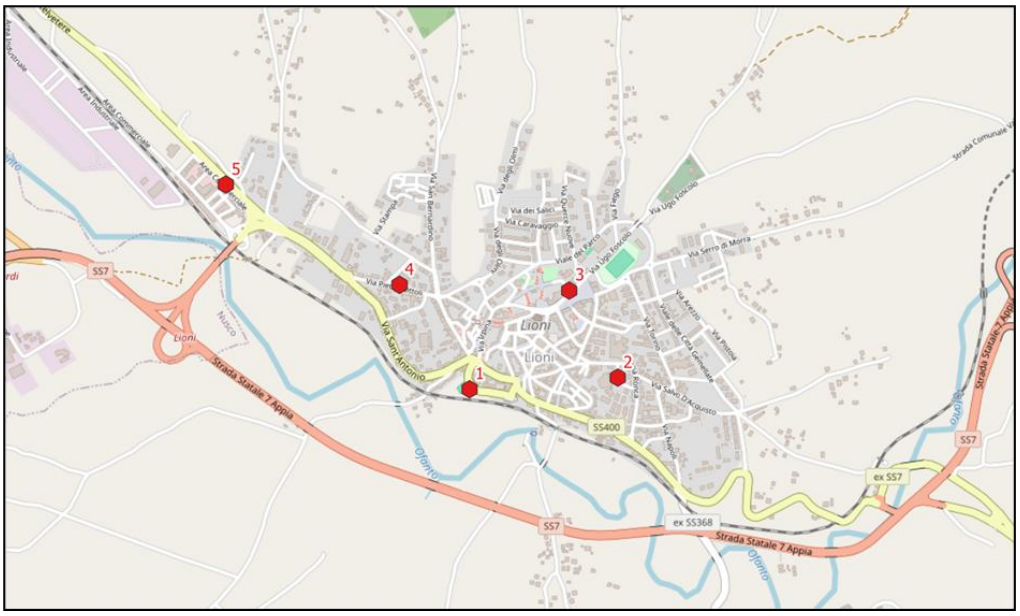

Figure 2.2 Location of car-sharing stations

All charging stations have been located in the central area of Lioni, where the population density makes it useful, taking int account travel attraction points: station 1 is located next to the suburban bus terminal, station 2 in an area where there are 2 schools, as well as commercial and residential activities, station 3 in a very central area of the municipality, station 4 along the route to the industrial and commercial area and near recreational activities, and station 5 in the main industrial and commercial area.

In this analysis, the proposed car-sharing system is compared only with a similar system based on traditional vehicles; given the small size of the municipality, there are no conventional urban public transport services (buses, trams, etc.) and it would not be possible to implement them. For small municipalities, car-sharing can also be seen as a contribution by the local administration to the mobility of citizens, particularly if it is financed or co-financed with public money.

EVs car-sharing system integrated into a REC

The EV-REC layout consists of a car-sharing system with a fleet of 12 EVs included in a REC, where a RES-based plant meets electricity needs. The REC is proposed in accordance with regulatory and technical constraints.

In Italy, the initial transposition of RED II legislated RECs with specific limits, but the final transposition updated the maximum power of the REC's single plant to 1 MW and the possibility of including a wider typology of members underlying the same HV/MV electric substation. According to Italian regulations, the Lioni REC only includes the northern section of the municipal territory, underlying the respective electrical substation, as shown in *Figure 2.3*. The REC is implemented (red area) by verifying the required constraints. This is where most of the inhabitants reside and the proposed location of charging stations is included. In Italy, an economic incentive is provided for shared energy [271], according to the virtual self-consumption scheme: all electric energy supplied by the RES plant is injected into the primary substation, and REC members take electric energy to meet their needs. Sharing takes place when injection and adsorption occur at the same time.

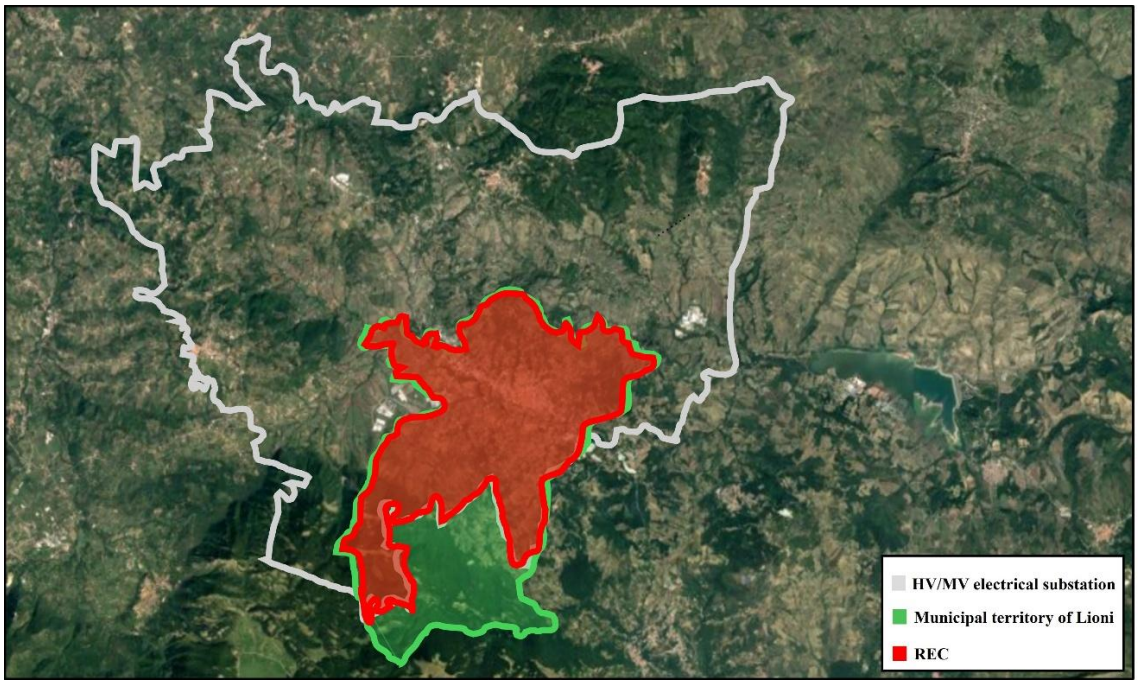

Figure 2.3 Boundaries of HV/MV electric substations (grey line), municipality of Lioni (green area), REC (red area).

The economic incentive varies with the REC plant's peak power (P) and the unit price of the electricity (P_z), depending on the market zone where the plant is located, as reported in *Table 2.1*. Additional POD consisting of EV charging services increase the REC's shared energy since a bigger exploitation of the installed power plants is achieved.

Table 2.1 Economic incentives for the shared energy in a REC

P [kW]	**Economic incentive [€/MWh]**	**Max value [€/MWh]**
$P \leq 200$ kW	$80 + \max(0; 180 - P_z)$	120

200 kW < P ≤ 600 kW	70 + max (0; 180 - P_z)	110
600 kW < P ≤ 1000 kW	60 + max (0; 180 - P_z)	100

The proposed REC implementation, as in some other countries such as Austria, places limits on proximity according to the area below the same electric substation [338]. In Croatia, members should be located near the RES project of the REC [339], while for some other EU Member States, the limits are based on fixed distance, as for Spain [153]. For Lioni car-sharing system, a 5-seat car type of small/medium size has been chosen. Respective characteristics are reported in *Table 2.2* [340]. Regarding the range, a value lower than the maximum stated by the manufacturer was used to consider "non-ideal" operating conditions. The EV provided for the system is recharged from 20 % to 80 % of the charge level with a standard charging power of 11 kW in 2 h 50 min.

Table 2.2 Characteristics of the selected EV

Battery size [kWh]	**Range [km]**	**Efficiency [kWh/km]**	**Price [€]**
44	256	166	24,000

In the EV-REC scenario, a solar PV plant has been considered. Solar PV is nowadays the third largest RES technology for electricity, covering 4.5 % of the world's production [341]. In 2022, power generation from PV increased by 26 % compared to the previous year, favoured by the modularity of the technology, investment cost reduction [342] and government incentive policies. In particular, the decentralized structure of solar PV plants has supported implementation in RECs, despite its intermittency [343] and source dependence on location [140]. A specific recharging methodology has been defined to comply with the selected RES type and the vehicle's characteristics. EV recharge is allowed only when:

- energy is produced directly from REC's PV panels, that is, during daylight hours;
- the charge level of EVs is less than 40 %.

The performance of PV systems depends on season, weather conditions and geographical parameters (latitude and longitude) [344]. Accordingly, each parked EV, with a charging duration of one hour, recharges in a different time interval depending on the month, if all imposed constraints are satisfied.

PG-powered EVs car-sharing system

For the EV-PG layout, a fleet of 12 EVs is considered. The type of cars and location of the stations in Lioni are the same as in EV-REC. In this case, the charging service uses the electricity of the PG, taking into account the combination of RES and fossil fuel power plants. This system is assessed by considering the same distance travelled by the fleet on an annual basis.

Traditional system

The TS is characterised by a fleet of fossil-fuel powered vehicles. Considering the percentage distribution of car typologies in the province of Avellino [345], the vehicle fleet of the TS car-sharing system has been modelled, as shown in *Table 2.3*.

Table 2.3 Features of circulating vehicle fleet in the Province of Avellino

Fuel	**Percentage distribution [%]**	**C_{FF} [l/km]**	**LHV [MJ/kg]**	**c_{FF} [€/l]**	**β_{FF} [kg_{CO_2}/kg_{fuel}]**	**$\beta_{FF,dis}$ [kg_{CO_2}/km]**
Diesel	48.20	0.067	42.70	1.79	3.17	0.177
Petrol	41.30	0.094	43.77	1.87	3.17	0.223
LPG	10.50	0.110	46.56	0.75	3.02	0.166

The vehicles considered are only diesel, petrol and LPG (liquefied petroleum gas) since the spread of other types is marginal in the considered area. For each type of vehicle, the corresponding fuel consumption (C_{FF}), lower heating value (LHV) [346], average fuel cost (c_{FF}) based on Italian Ministry of the Environment (MASE) data for 2023 [347] and the CO_2 emissions factor (β_{FF}) are also reported. Estimates of fuel consumption and GHG emissions are based on Corinair [346] data, according to the distribution of car categories in the selected location. In addition, the CO_2 emission factor for km ($\beta_{FF,dis}$) is calculated for each vehicle. Based on the percentage distribution data, the TS fleet comprises 6 diesel, 5 petrol and 1 LPG vehicle. A medium- sized 5-seater car model, similar to the one chosen as EV, has been taken into account for TS [348]. The covered distance by the fleet on a yearly basis is considered equal to the EV-REC car-sharing system.

2.1.2 Model of urban mobility car-sharing system

The design of the system is based on the characteristics of the area considered and the corresponding traffic flow analysis. The traffic flows on the network are estimated using the simulation software Omnitrans [349]. Then, the processing of input data based on probabilistic

functions for the number of daily rentals and the covered distance for each rental has been realized through codes written in the dedicated programming software Matlab [281]. One of the analysed configurations involves RES-based plants, modelled and simulated through the dynamic simulation software Homer Pro [74]. Microsoft Excel [350] has been used for the post-processing and evaluation of 3-E analyses results. The number of daily rentals has been evaluated by analogy with implemented car-sharing systems in other cities [351]. In the Lioni case study an average value of 6 rentals per day, on an annual basis, is assumed for each vehicle. For the purposes of experimentation, a probability density law was used on the number of daily rentals, as shown in *Table 2.4*.

Table 2.4 Probability density of rentals for a day on a yearly basis.

Number of rentals a day [rentals/day]	**Probability density [%]**	**Days per year [days/year]**
2	5	18
4	20	73
6	50	183
8	20	73
10	5	18

The average distance covered for each rental was calculated by analysing the transport demand, using an origin–destination matrix estimated for the Lioni municipality and the distance matrix, origin–destination pairs, obtained by building a graph of the city's road network. Taking into account the data obtained from the road network model, it is possible to estimate the average distance of 4.2 km, with a variance of 4.1, calculated from the distance matrix and increased by 10 % to account for possible extra-urban trips. Thus, each distance covered in one hour can vary from 0.1 km to 8.3 km, with a 0.1 km step. Using a probabilistic function, a value of the covered distance, included in the range, is associated with the hours the vehicle is not stopped at the stall. The variation of daily rentals, carried out randomly in compliance with the set constraints, and the distance covered by one vehicle yearly are respectively presented in *Figure 2.4* and *Figure 2.5*. It can be assumed that each vehicle covers an average of 25.2 km/day and 9,198 km/year. In total, the 12 cars would travel 110,376 km/year.

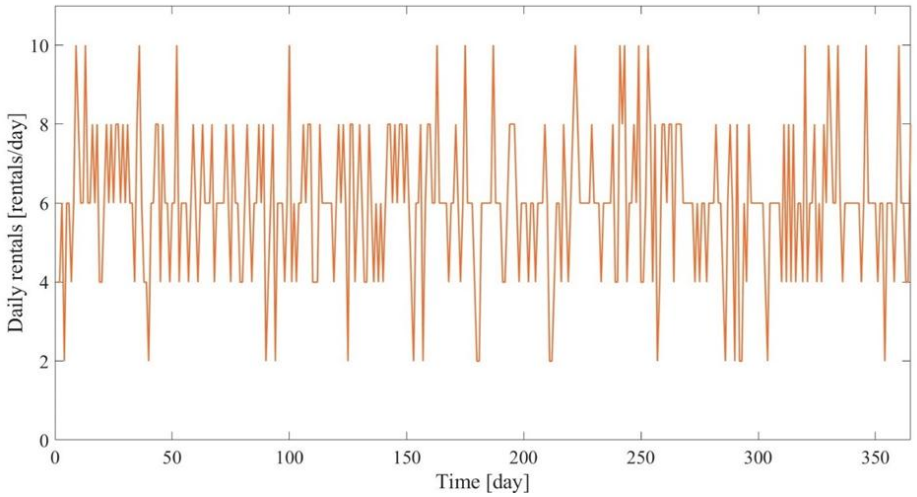

Figure 2.4 Number of daily rentals on a yearly basis for one vehicle.

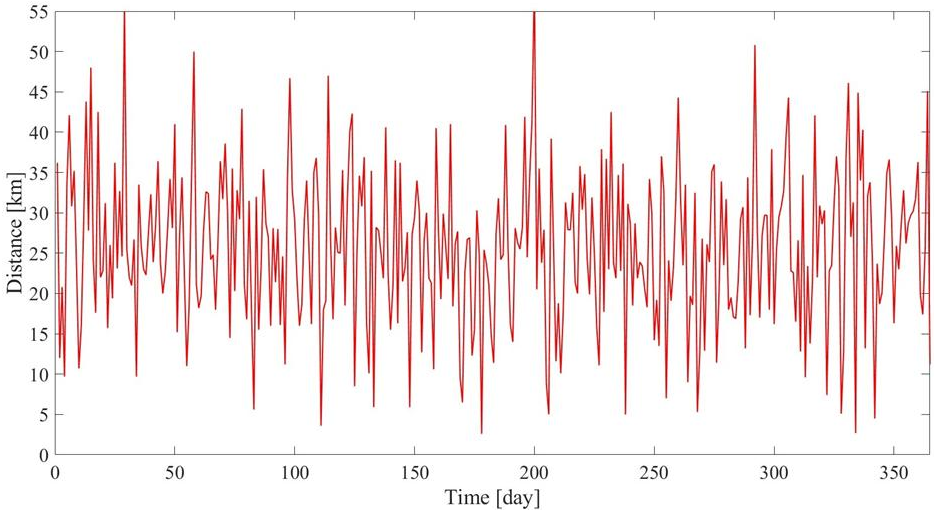

Figure 2.5 Daily covered distance on a yearly basis by one vehicle.

Energy, environmental and economic analysis

The purpose of e-mobility and REC configuration may not be unique, but more benefits may be offered to members and territory. The benefits of implementing different urban mobility car-sharing systems are evaluated by comparing EV car-sharing systems (EV-REC/EV-PG) with the system equipped with ICE cars. The same number of vehicles and daily travelled distance have been considered for all layouts. Considering the consumption data of EVs, a proportional consumption value was associated with each distance. For this case study, 3-E assessments have been carried out to quantify e-mobility benefits compared to the TS. Different timesteps (θ), entailing different outcomes for EV-REC layout, have been considered:

- Scenario 1 (EV-REC#1): assessment on an hourly basis (θ =1 h);
- Scenario 2 (EV-REC#2): assessment on a daily basis (θ =1 day).

Based on the energy needs of EVs, a sensitivity analysis was conducted to optimize the PV size. For each size of the PV plant, the electric energy shared ($E_{el,SH}^{REC}$) within the car-sharing system in the REC configuration has been considered. It is calculated as the minimum between the energy produced ($E_{el,RES}$) by the RES plant and the energy needs of the car-sharing system ($E_{el,US}$) on the same time interval, as reported in Equation 1.1. Being θ_n the timestep and N the total number of timesteps over a year, subscript n ranges from 1 to 8,760 for hourly, 365 for daily analysis. Moreover, two indices have been assessed for each PV size. The first is the RSE, also called the REC self-sufficiency index in the literature, and expresses the ratio of shared electricity to total electric energy needs, as reported in Equation 1.12 [173]. The second, the RSC, expresses the ratio of shared electricity to the total electric energy produced by the RES plant, Equation 1.13. In addition, the Community Grid Perturbation (CGP) index, Equation 2.1, is considered [352]. It is the ratio between the sum of annual electric energy taken from the PG (E_{el}^{PG-REC}) and annual electric energy exported (E_{el}^{REC-PG}) and the total yearly load of the car-sharing system ($E_{el,US}^{REC}$).

$$CGP = \frac{\sum_{n=1}^{N} E_{el}^{PG-REC}(\theta_n) + \sum_{n=1}^{N} E_{el}^{REC-PG}(\theta_n)}{\sum_{n=1}^{N} E_{el,US}^{REC}(\theta_n)} \quad (2.1)$$

Regarding the energy analysis, the primary energy saving (ΔE_p) is evaluated as the difference between the primary energy provided by fossil fuels to satisfy car-sharing system energy demand in TS (E_p^{TS}) and the primary energy (E_p^{EV-REC}/E_p^{EV-PG}) associated with the electric energy provided by the PG in the sharing (E_{el}^{EV-REC}) or no-sharing layout (E_{el}^{EV-PG}), Equations 2.2 and 2.3. E_p^{TS} depends by *dis*, C_{fuel} and LHV, for each type of vehicle (6 diesel, 5 petrol and 1 LPG vehicles), Equation 2.4. E_p^{EV-PG}, as reported in Equation 2.5, is the ratio of the electric energy taken by the users from the PG ($E_{el,US}^{REC}$) to the national PG average efficiency (η_{PG}) for Italy. Considering the EV-REC layout, the primary energy related to the energy taken from the grid is the ratio between $E_{el,US}^{REC}$ decreased by the $E_{el,SH}^{REC}$, according to the virtual sharing scheme, and η_{PG}. The surplus energy produced by the PV and fed into the grid is the ratio between the electric energy exported to the PG, thus the difference between $E_{el,RES}^{REC}$ and $E_{el,SH}^{REC}$, and the average PG national efficiency not accounting primary energy request for RES (η_{PG}^{**}) for Italy, Equation 2.6. The approach used to calculate η_{PG}^{*} considers the primary energy related to RESs

feeding no-fuel-based plants to be equal to zero, thus the primary energy accounted is only related to fossil fuels.

$$\Delta E_p^{EV-PG} = E_p^{TS} - E_p^{EV-PG} \tag{2.2}$$

$$\Delta E_p^{EV-REC} = E_p^{TS} - E_p^{EV-REC} \tag{2.3}$$

$$E_p^{TS} = C_{fuel} * dis * LHV \tag{2.4}$$

$$E_p^{EV-PG} = \frac{E_{el,US}^{REC}}{\eta_{PG}} \tag{2.5}$$

$$E_p^{EV-REC} = \left(\frac{E_{el,US}^{REC} - E_{el,SH}^{REC}}{\eta_{PG}}\right) - \left(\frac{E_{el,RES}^{REC} - E_{el,SH}^{REC}}{\eta_{PG}^{**}}\right) \tag{2.6}$$

With reference to the environmental analysis, the avoided CO_2 equivalent emissions (ΔCO_2) between TS (CO_2^{TS}) and EV-PG/EV-REC (CO_2^{EV-PG}/CO_2^{EV-REC}) configurations are considered, Equations 2.7 and 2.8. CO_2 emissions imputable to the TS depend on the corresponding fuel consumption (C_{FF}), the covered distance (*dis*) and the CO_2 emission factor of the respective fuel (β_{FF}), Equation 2.9. For EV-PG, they are evaluated considering the electricity taken from the PG, Equation 2.10. In EV-REC, the same, calculated as difference between $E_{el,US}^{REC}$ and $E_{el,SH}^{REC}$, is reduced by the difference between the total energy produced by PV ($E_{el,RES}^{REC}$) and the shared energy, Equation 2.11. In this analysis, the electric energy produced by the PV plant and fed into the PG is considered as a credit. The contribution is in terms of primary energy saved and CO_2 emissions avoided. The corresponding efficiency factors of the PG and equivalent CO_2 emissions, for this share, are only linked to production from fossil fuel plants, because the PG does not produce energy from the traditional mix of technologies, as the energy fed into the PG comes from a RES-based plant [353].

$$\Delta CO_2^{EV-PG} = CO_2^{TS} - CO_2^{EV-PG} \tag{2.7}$$

$$\Delta CO_2^{EV-REC} = CO_2^{TS} - CO_2^{EV-REC} \tag{2.8}$$

$$CO_2^{TS} = C_{fuel} * dis * \beta_{FF} \tag{2.9}$$

$$CO_2^{EV-PG} = E_{el,US}^{REC} * \alpha_{PG} \tag{2.10}$$

$$CO_2^{EV-REC} = (E_{el,US}^{REC} - E_{el,SH}^{REC}) * \alpha_{PG} - (E_{el,RES}^{REC} - E_{el,SH}^{REC}) * \alpha_{PG}^{**} \tag{2.11}$$

The energy and environmental benefits have been calculated for the whole system in order to emphasize the convenience of car-sharing with EVs compared to conventional cars. The economic analysis, instead, is presented from the investor's point of view to evaluate the feasibility of initial investments in car-sharing systems including EVs. It may also be of interest to a car-sharing company or any other stakeholder with a public partnership.

Regarding the economic analysis, the avoided yearly operating costs (ΔOC) in EV-PG and EV-REC configurations, compared to TS, are evaluated as the difference between the corresponding OCs, Equation 2.12 and 2.13. Yearly operating costs of the TS (OC^{TS}) consider the income from rental and the expenses for fossil fuel consumption and ICE maintenance costs, which are about the same for all types of considered vehicles [354], Equation 2.14. The yearly operating costs of the EV-PG ($OC^{EV\text{-}PG}$) consider the EV rental cost per distance, the cost of electric energy provided by the PG [355] and the maintenance cost of EV (MC_{EV}) [354], which is lower than for traditional cars, as reported in Equation 2.15. In the REC layout, the EV rental cost per km travelled is considered as income for the investor, while the electric energy taken from the PG ($E_{el,US}^{REC}$) and MC^{EV} are borne by the investor. In addition, PV maintenance costs (proportional to the size and equal to 1.5 % of the investment cost (IC) [356]), revenues from the sale of electric energy fed into the PG, according to the national energy sales mechanism, and economic incentives (I_{SH}) on shared energy are considered, Equation 2.16. The latter is evaluated as reported in *Table 2.1*, where the P_z is considered for the electricity market zone '*SOUTH*' [357], where Lioni municipality is included. The rental cost (c_{rent}) for the car-sharing system, both for ICE vehicles and EVs, has been evaluated starting from the most common car-sharing companies in Italy, considering for the case under study that the rental always has a duration of 1 h and a distance travelled between 0.1 and 8.3 km. Thus, c_{rent} has been evaluated by matching hourly and per km rates [358]. The feasibility of an investment is often evaluated by considering the years required to recover it, with the economic performance indicator SPB. For each layouts the IC differs (Equations 2.17, 2.18, 2.19): in the TS only the IC of corresponding fossil fuel vehicles (IC_{ICE}) is considered [348], in EV- PG and EV-REC configurations, the IC for the 12 EVs fleet (IC_{EV}) [340] and the IC of the 11 kW recharging stations (IC_{st}) [359] are included. IC of the PV plant (IC_{PV}), size-variable [347,360], is also considered in the REC layout.

$$\Delta OC^{EV-PG} = OC^{TS} - OC^{EV-PG} \tag{2.12}$$

$$\Delta OC^{EV-REC} = OC^{TS} - OC^{EV-REC} \tag{2.13}$$

$$OC^{TS} = (c_{rent,FF} * dis) - (C_{FF} * dis * c_{fuel}) - (MC_{ICE} * dis) \quad (2.14)$$

$$OC^{EV-PG} = (c_{rent,EV} * dis) - (E^{REC}_{el,US} * c_{el,PG}) - (MC_{EV} * dis) \quad (2.15)$$

$$OC^{EV-REC} = (c_{rent,EV} * dis) - \left(E^{REC}_{el,US} * c_{el,PG}\right) - (MC_{EV} * dis) - MC_{PV} + (E^{REC}_{el,RES} * Pz) + (E^{REC}_{el,SH} * I_{SH}) \quad (2.16)$$

$$IC^{TS} = IC_{ICE} \quad (2.17)$$

$$IC^{EV-PG} = IC_{EV} + IC_{st} \quad (2.18)$$

$$IC^{EV-REC} = IC_{EV} + IC_{st} + IC_{PV} \quad (2.19)$$

The main assumptions of TS, EV-PG and EV-REC are reported in *Table 2.3* and *Table 2.5*.

Table 2.5 Energy, environmental and economic assumptions of TS, EV-PG and EV-REC.

Parameter	Description	Value	Unit	Reference
C_{FF}	Fuel consumption of diesel vehicle Fuel consumption of petrol vehicle Fuel consumption of LGP vehicle	0.067 0.094 0.110	[l/km]	[347]
LHV	Diesel Lower heating value Petrol Lower heating value LGP Lower heating value	9.876 9.093 6.449	[kWh/l]	[347]
$c_{rent,FF}$	Rental cost of ICE vehicle	0.38	[€/km]	[358]
MC_{ICE}	Maintenance cost of ICE vehicle	0.016	[€/km]	[354]
IC_{ICE}	Diesel vehicle Investment cost Petrol vehicle Investment cost LGP vehicle Investment cost	18,500 15,000 17,000	[€/vehicle]	[348]
η_{PG}	PG efficiency	0.509	[-]	[361]
η^{**}_{PG}	PG efficiency (no RES)	0.471	[-]	[353]
α_{PG}	PG CO_2 emission factor	0.286	[kg_{CO_2}/kWh_{el}]	[361]
α^{**}_{PG}	PG CO_2 emission factor (no RES)	0.508	[kg_{CO_2}/kWh_{el}]	[353]
$c_{rent,EV}$	Rental cost of EV	0.38	[€/km]	[358]
$c_{el,PG}$	Unitary electricity average price from PG	0.23	[€/kWh]	[355]
MC_{EV}	Maintenance cost of EV	0.007	[€/km]	[354]
MC_{PV}	Maintenance cost of PV plant	1.5% * IC_{PV}	[€/y]	[320]
IC_{st}	Investment cost of recharging station	1568	[€/station]	[359]
IC_{EV}	EV Investment cost	24,000	[€/vehicle]	[340]
IC_{PV}	PV 15 kW Investment cost PV 20 kW Investment cost PV 25 kW Investment cost PV 30 kW Investment cost	22,046 24,298 26,549 28,800	[€/plant]	[360]

2.1.3 Results and discussion

Following imposed constraints on the availability of charging services, the hourly load profile of the EV fleet has been evaluated. The initial charging level of each EV is set to 100 % at the beginning of the yearly dynamic simulations. The initial condition does not significantly affect the final results, which are on an annual basis. This assumption implies no recharging during the first year's days. As reported, the threshold value below which the EV can recharge has been set at 40 % of the charge level, which implies that the vehicle has a range of at least 102.4 km. In this way, an EV can still be used in the time slot when no charging service is available, such as at night. As shown by the overall hour-by-hour electric load profile (*Figure 2.6*), the maximum hourly consumption for a single vehicle is 11 kWh, corresponding to the energy required in one hour, considering the selected standard recharging of 11 kW. This recharging cycle increases the EV charge level by 20 %, by the technical features of the EV model. The overall hourly load profile of the whole fleet reaches higher energy demand values. In 63 % of the hours the peak value is 11 kWh, that is, in the selected time slot only one vehicle is in charge, while in 0.05 % of the time there is a peak energy demand of 77 kWh, which is the highest value recorded. In this case, seven vehicles meet all constraints simultaneously. Since the data processing is based on a random distribution, the probability that EVs meet all the required conditions at the same time, and therefore are in charge, decreases as the number of vehicles increases.

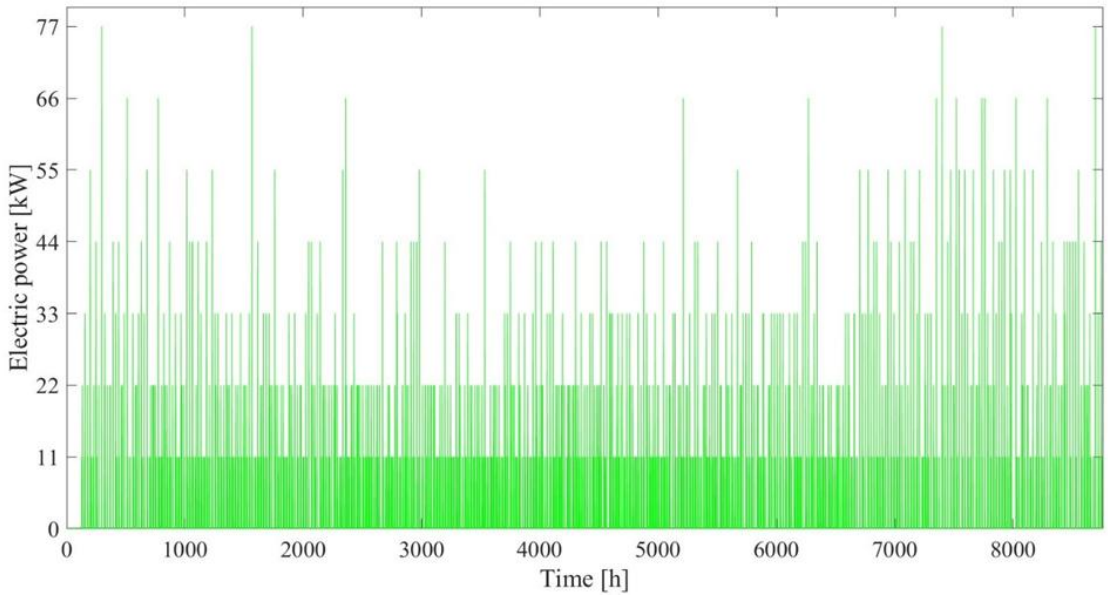

Figure 2.6 Overall hourly load profile of EVs on a yearly basis.

Figure 2.7 shows the overall electric load profile of the EV fleet with a 1-day time step. In this case, the maximum energy consumption value is 121 kWh/day, meaning eleven recharges have been carried out in 24 h, each with a 1-hour duration and 11 kWh required. This condition is verified on 0.82 % of days. On the first 6 days, the electric energy consumption is zero, due to the initial conditions set. The value that occurs most frequently, at 19.2 % of the days, is 55 kWh/day, corresponding to five recharges per day. The average value of the overall daily load profile is 65.67 kWh/day.

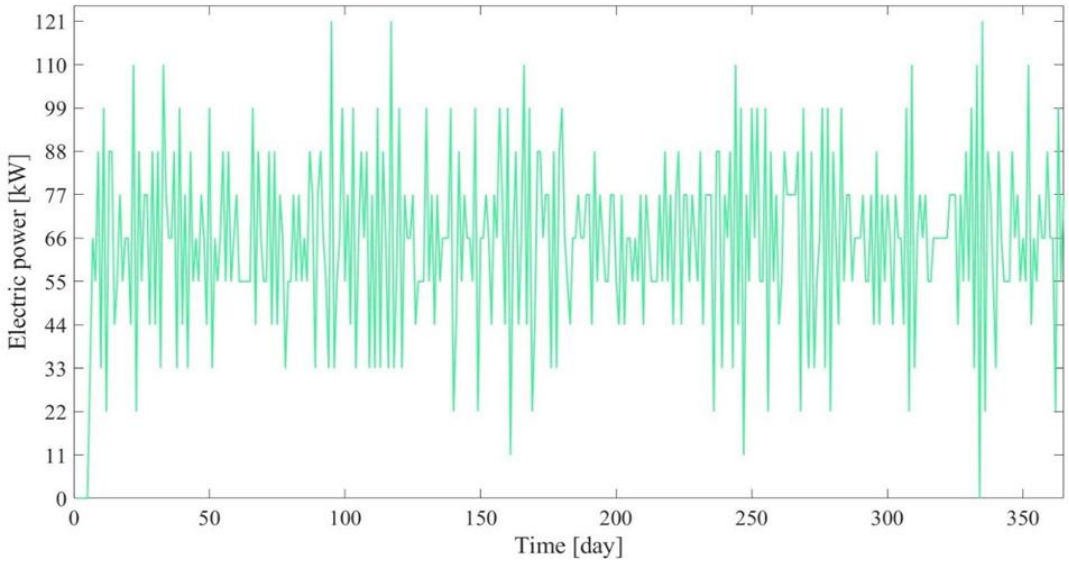

Figure 2.7 Overall daily load profile of EVs on a yearly basis.

The electric energy load is the same for EV-REC and EV-PG systems. The EV-REC layout includes, in addition to the EV-PG, the implementation of a PV plant, for which four different sizes have been considered: 15 kW, 20 kW, 25 kW, 30 kW. Dynamic simulations of PV have been carried out for one year with an hourly timestep; the optimal azimuth and tilt angle were considered, respectively equal to 30° and 0° (South direction). The assessment of the REC configuration varies with the size of the RES-based plant, in particular, the corresponding shared energy, despite the energy demand of the car-sharing system being the same, depends on the energy produced by PV panels, and so on the met energy needs of the car-sharing system. The results of PV size sensitivity analysis are presented for EV- REC#1 and EV-REC#2 in *Figure 2.8*. Different timesteps imply different values of $E_{el,SH}^{REC}$, which is calculated as the minimum between $E_{el,RES}^{REC}$ and $E_{el,US}^{REC}$, hour by hour in the former case, day by day in the latter. Additionally, the RSE trend is presented. Shared energy substantially varies from EV-REC#1 to EV-REC#2 scenario. In both cases, considering the same energy demand, $E_{el,SH}^{REC}$ increases

with PV size. For the hourly analysis, the RSE index has a positive variation of 12.5 % from PV 15 kW to PV 30 kW. In each case, no more than 33.2 % (PV 30 kW) of energy demand is reached. In the second case, the RSE index varies from a minimum of 73.3 % (PV 15 kW) to a maximum of 87.2 % (PV 30 kW). The implemented optimization method on an hourly basis does not reach interesting values, mainly due to very high energy demand values in some hours requiring a substantial energy import from the PG. In the other case, evaluations on a daily basis present the best possible results, which take into account the contemporaneity of load and production on a daily basis. This scenario is only feasible through the association of storage systems with the PV plant.

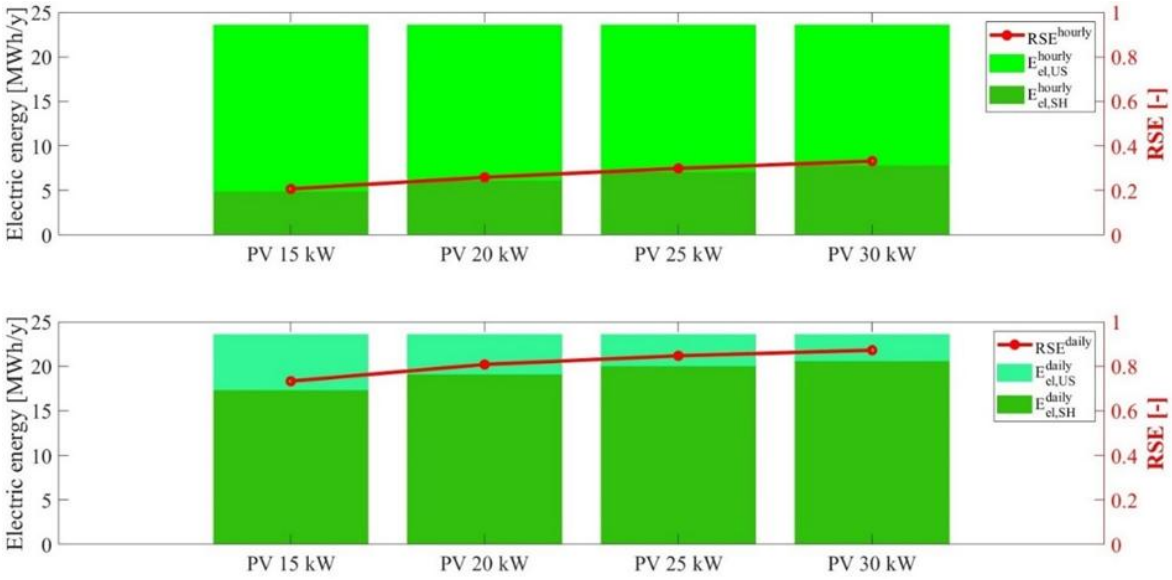

Figure 2.8 Electricity needs, shared energy and RSE index for different PV sizes in the REC configuration (EV-REC#1 and EV-REC#2).

Figure 2.9 shows the electric energy shared in the REC configuration, compared to the electricity produced by the PV plant, for EV-REC#1 and EV-REC#2. On a yearly basis, EVs' electric load is always equal to 23.6 MWh/y. Both $E_{el,SH}^{REC}$and $E_{el,RES}^{REC}$ increase with plant size. Moreover, the RSC variation for the different PV sizes is presented. The index decreases with the increase in plant size, with a variation of 4.6 % from PV 15 kW (23.1 %) to 30 kW (18.5 %) for EV-REC#1. While for EV-REC#2, the RSC index varies respectively from 67.8 % to 48.7 %, achieving a variation of 19 %. Considering the daily data assessment, more significant shares of the PV production are used to supply the car-sharing system load. *Table 2.6* reports EV-REC#1 and EV-REC#2 energy outcomes for different PV plant sizes.

Table 2.6 Results on an hourly and daily basis considering different PV sizes.

Scenario		$E_{el,US}^{REC}$ [kWh]	$E_{el,RES}^{REC}$ [kWh]	$E_{el,SH}^{REC}$ [kWh]	E_{el}^{PG-REC} [kWh]	E_{el}^{REC-PG} [kWh]	*RSE* [-]	*RSC* [-]	*CGP* [-]
EV-REC#1	PV 15 kW	23,606	21,123	4,878	18,727	16,244	0.207	0.231	1.48
	PV 20 kW	23,606	28,164	6,111	17,494	22,053	0.259	0.217	1.67
	PV 25 kW	23,606	35,206	7,069	16,536	28,136	0.299	0.201	1.89
	PV 30 kW	23,606	42,247	7,827	15,778	34,420	0.332	0.185	2.12
EV-REC#2	PV 15 kW	23,606	21,123	17,314	6,291	3,809	0.733	0.820	0.42
	PV 20 kW	23,606	28,164	19,085	4,520	9,079	0.808	0.678	0.58
	PV 25 kW	23,606	35,206	20,002	3,603	15,203	0.847	0.568	0.80
	PV 30 kW	23,606	42,247	20,583	3,022	21,664	0.872	0.487	1.05

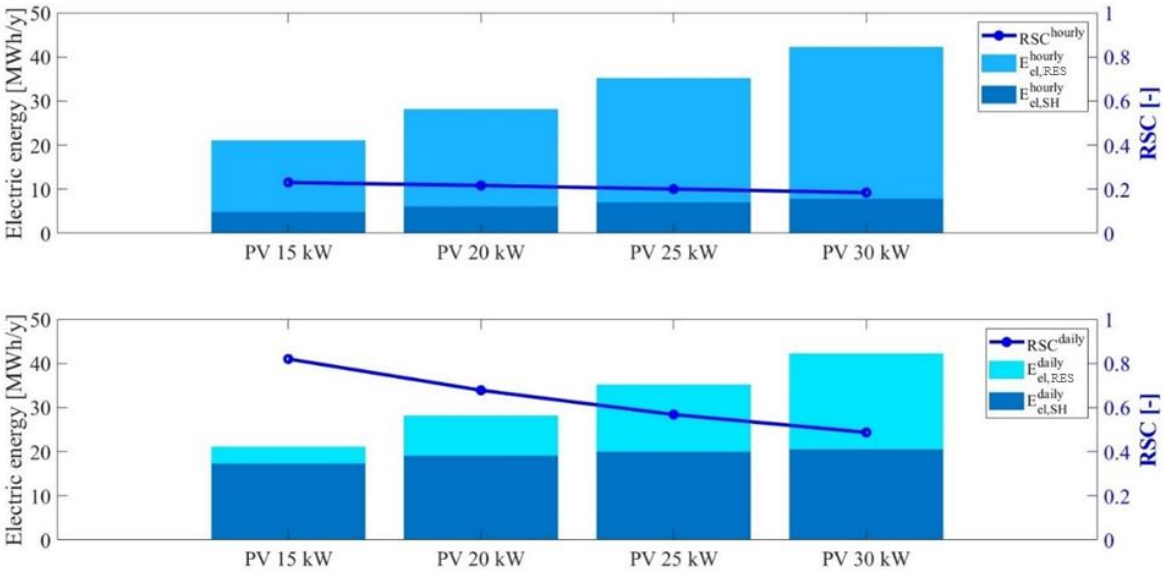

Figure 2.9 Electricity produced by PV plant, shared energy and RSC index for different PV sizes in the REC configuration (EV-REC#1 and EV-REC#2)

Numerical results of the 3-E analyses are presented to show the benefits of EVs layouts, compared to the TS. *Figure 2.10* shows primary energy results. TS is the most energy-intensive: primary energy is associated with the consumption of the corresponding fossil fuel, according to the vehicle type selection. Being equal the yearly distance covered by the fleet, the primary energy decreases in layouts including EVs. In EV-PG the primary energy saving is equal to 44.5 % with respect to TS. In the REC layout, as the peak power of the plant increases, the corresponding primary energy decreases because a more significant load share is satisfied by the PV plant and, at the same time, electric energy exported to the PG increases. In particular, from EV-REC#2 to EV-REC#1 the corresponding E_p decreases; indeed, on one hand the $E_{el,SH}^{REC}$ increases, on the other hand E_{el}^{REC-PG} decreases. The ΔE_p between EV-REC#2 and EV-REC#1 is around 2000 kWh/year for each PV size. Despite this, the *CGP* varies from 1.48 to 2.12 for

EV-REC#1 and from 0.42 to 1.05 for EV-REC#2. Thus, the grid perturbation is more relevant when a lower E_p is estimated, mainly due to the high surplus exported to the PG.

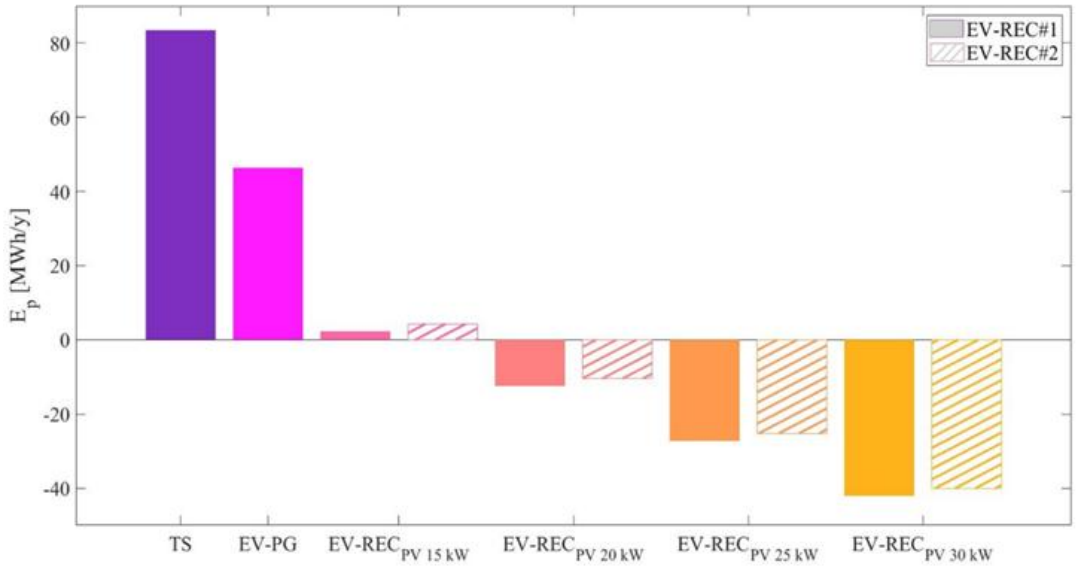

Figure 2.10 Primary energy per year in the TS, EV-PG, EV-REC#1 and EV-REC#2 (PV 15 kW, PV 20 kW, PV 25 kW, PV 30 kW).

The reduction of CO_2 equivalent emissions from TS to e-mobility systems is significant, *Figure 2.11*. A reduction of 69.2 % is achieved by switching from ICE vehicles to EVs. Even higher values are obtained when considering REC implementation, where energy sharing minimizes CO_2 emissions. The avoided CO_2 equivalent emissions between TS and REC increase as the PV size increases for both EV-REC#1 and EV- REC# 2. Being equal the PV size, CO_2 is higher for daily scenarios with respect to hourly ones. In the latter case, $E_{el,SH}^{REC}$ is less relevant and consequently an important share of $E_{el,RES}^{REC}$ is fed into the PG, increasing the CO_2 credits of the whole system.

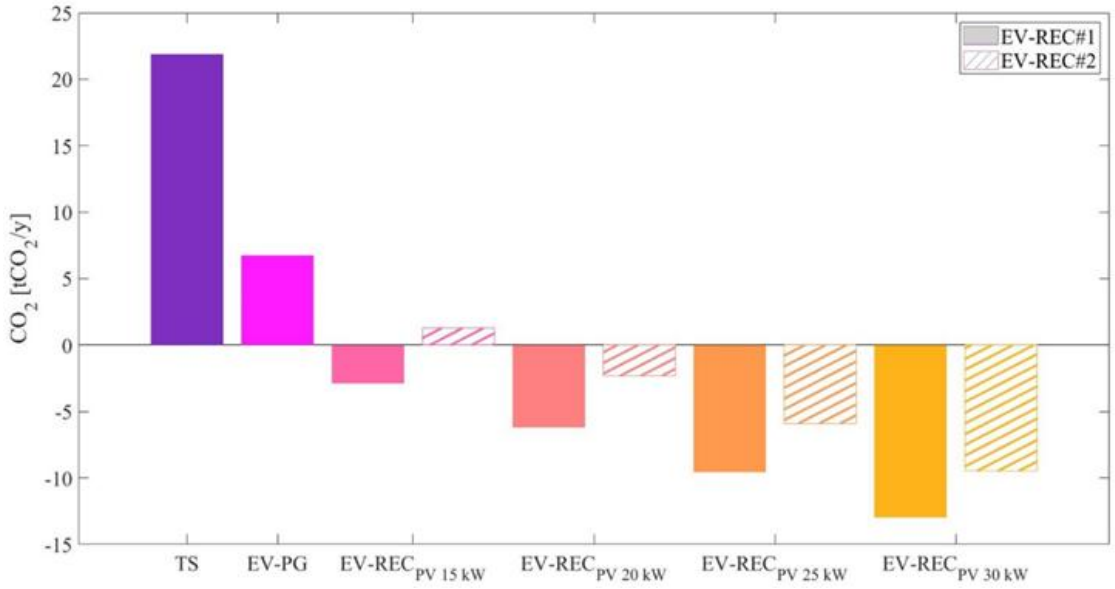

Figure 2.11 CO_2 emissions per year in the TS, EV-PG, EV-REC#1 and EV-REC#2 (PV 15 kW, PV 20 kW, PV 25 kW, PV 30 kW).

In *Figure 2.12*, the results of the economic analysis are shown. In particular, the yearly OC^{TS} is 25.0 k€, considering the corresponding average fuel cost [347], MC_{ICE}, and income from the rental of the car-sharing system vehicles. For EVs layouts, the corresponding cost of electric energy taken from the PG, MC_{EV} and the income from rental are considered. In the EV-REC layout also MC_{PV}, income from the economic remuneration of the $E_{el,SH}^{REC}$ and $E_{el,RES}^{REC}$ fed into the PG, are evaluated. As shown, OC, which represent the investor's profits, are the lowest for TS, increasing for EV-PG and EV-REC. The difference between TS and EV-PG is mainly due to the lower cost of electricity compared to fossil fuels and the reduction of *MC*. Annual benefits for the investor for EV-REC increase with the PV size, due to the increase of $E_{el,SH}^{REC}$and $E_{el,RES}^{REC}$. The comparison between EV-REC#1 and EV-REC#2 for the same PV size highlights the economic advantage of the second scenario, where the $E_{el,SH}^{REC}$ increases, even though the producibility of the PV plant is the same. SPB trends are also presented in *Figure 2.12*. The TS achieves the lowest number of years to recover the IC of the whole car-sharing system, which is less than compared systems. Indeed, IC_{EV} instead of IC_{ICE}, and IC_{st} is considered for EV-PG and also ICPV is added for EV-REC. SPB reduces as the PV size increases for both scenarios. Considering the e-mobility car-sharing systems, the lowest SPB value (8.22 years) is achieved for EV- REC with PV 30 kW and daily estimation. In this case, the highest value of $E_{el,SH}^{REC}$ entails significant economic remuneration, which contributes to the corresponding OC. For EV-PG, SPB is the highest (9.01 years), because no income other than user rent is considered,

despite IC does not take IC_{PV} into account. Changes in car-sharing prices can also be applied to reduce the SPB to acceptable values.

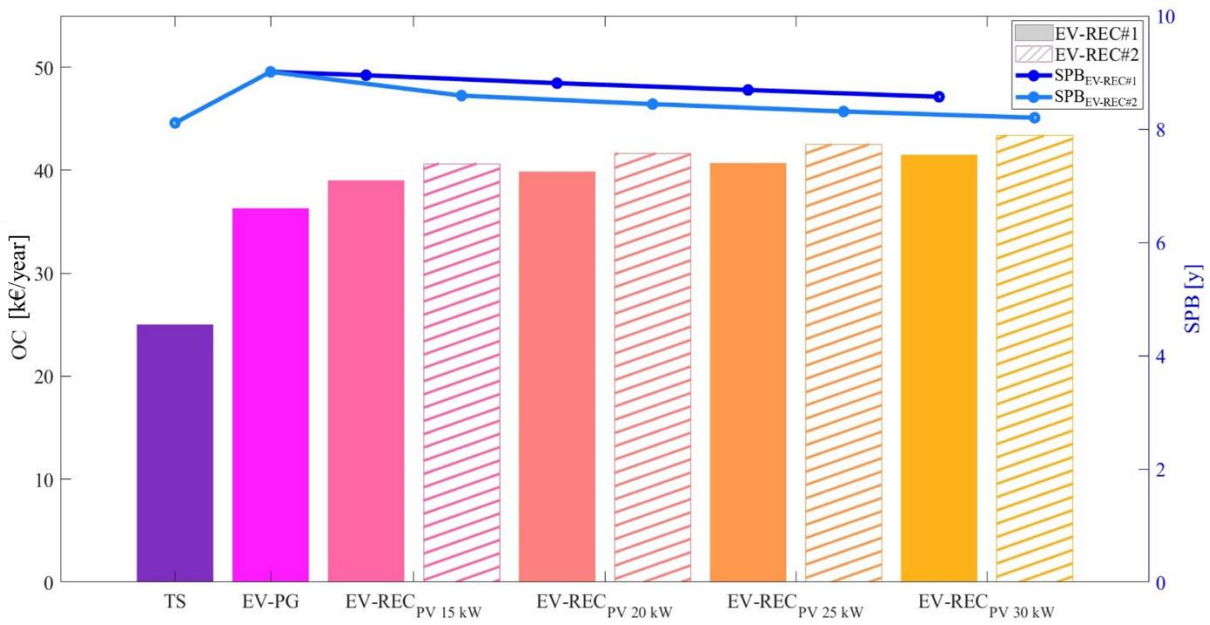

Figure 2.12 Operating costs per year and corresponding SPB for the TS, EV-PG, EV-REC#1 and EV-REC#2 (PV 15 kW, PV 20 kW, PV 25 kW, PV 30 kW).

In *Figure 2.13* a sensitivity analysis on the rental cost of vehicles in the car-sharing system is proposed. As shown, to achieve SPB equal to 5 years, $c_{rent,ICE}$ should be increased from the considered value of 0.38 to 0.52 €/km for TS, while for EV-REC it should vary from a minimum of 0.63 €/ km (EV-REC#2-PV 30 kW) to a maximum of 0.66 €/km (EV-REC#1- PV 15 kW).

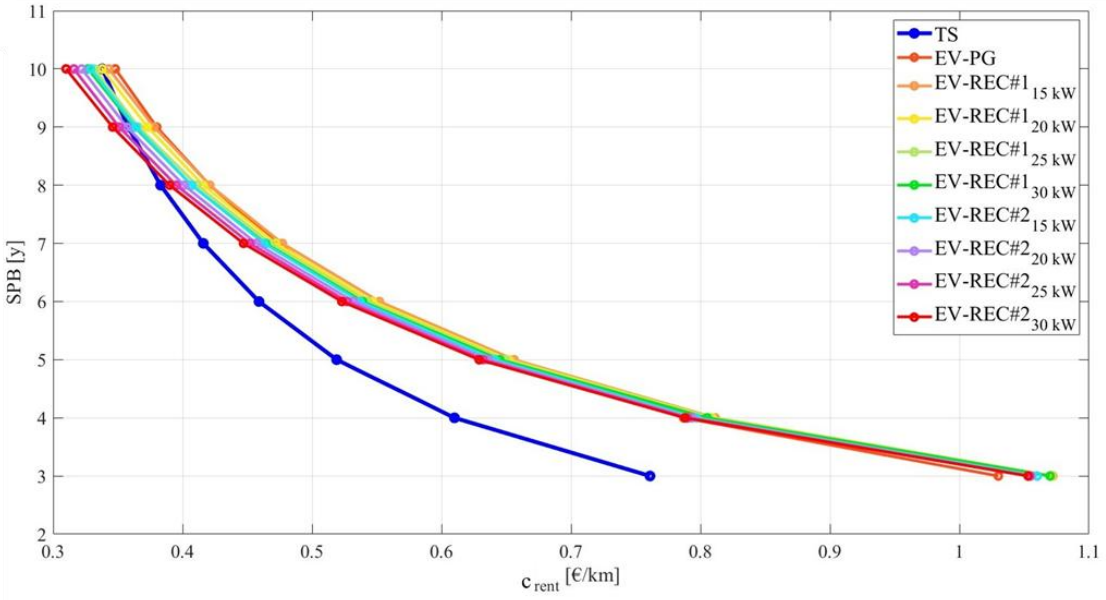

Figure 2.13 SPB variation in function of the rental cost for the TS, EV-PG, EV-REC#1 and EV-REC#2 (PV 15 kW, PV 20 kW, PV 25 kW, PV 30 kW).

Innovative systems usually have higher IC than traditional ones, indeed, for the selected vehicle type for the Lioni case study, IC_{EV}, exceeds IC_{ICE} by an average of 7,000 €. Therefore, European Countries, in line with EU targets in the transport sector and energy transition, propose national economic incentives for EVs purchase. In this way, the payback period for EVs is comparable to that of ICE vehicles. Europe offers a variety of financial incentive options for EVs, such as rebates, special depreciation, reduced purchase and circulation taxes and fee waivers [362]. In addition, nonmonetary incentives, such as access to high-priority lanes, are offered [363]. In Italy, purchase incentives are recognized, depending on vehicle characteristics, and the share rises with old vehicles scrapping [364]. According to current national law, a purchase incentive equal to 6,000 € can be applied to each new EV (with no strapping) [365]. SPB has been evaluated for each of the investigated scenarios, both with and without IC_{EV} incentives. *Figure 2.14* shows that EV scenarios present a substantially reduced recovery period if incentives are considered, even compared to TS. The sharing of cars, together with automation and electrification, is considered the most significant transformation of the transport sector in the last decades [366].

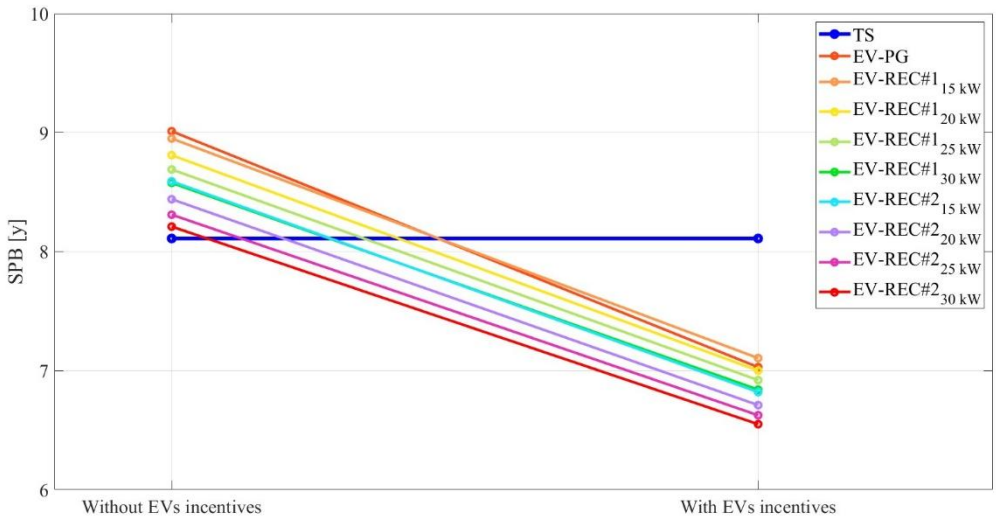

Figure 2.14 SPB variation considering and not EVs incentives for the TS, EV-PG, EV-REC#1 and EV-REC#2 (PV 15 kW, PV 20 kW, PV 25 kW, PV 30 kW).

Despite e-mobility's environmental and energy advantages, a comparison with fossil-fuelled vehicles highlights its disadvantages. The battery is the core of EVs constraints: charging time, limited mileage and lifetime are some associated aspects [367] to the most expensive component [368]. However, in large cities, end-users prefer to rent EVs instead of using their traditional cars to access ever more diffused low-emissions zones [369]. Life cycle assessment

(LCA) of EVs and ICE vehicles shows the adoption of the former results in GHG emissions reduction but an increase in human toxicity due to the use of metals and chemicals [370]. However, environmental results can be affected by the used battery type: lithium-ion batteries present a higher impact than lead-acid batteries in the production but lower in the use phase [371]. During the recycling phase, reusing and remanufacturing batteries enhances the environmental impact of EVs [372]. On the other hand, ICE cars can cover longer distances, and the refuelling time is less, but having significant energy, environmental and social impact. Trans port noise annoys about 18 million people worldwide and about 5 million suffer from sleep disturbances due to this phenomenon [289]. Car-sharing systems promote more efficient mobility, contributing in fewer vehicles per capita, lower demand for parking space, reduced fixed costs, and serving as a complement to public transportation [373]. The main factors affecting car-sharing users concern parking availability and reduced costs with respect to owning vehicles [374]. Nevertheless, the technological expertise these systems require is a barrier for some citizens, so youngers result as primary users. High income, education level and living in the city centre are some of the characteristics associated with those who hase a greater propensity to use these opportunities [375]. Car-sharing system may also redirect users away from public transport solutions [376].

2.2 Dynamic simulation model of a REC for small municipalities

This paragraph presents the dynamic simulation model developed to predict the real time operation of a REC based on PV panels coupled with electric energy storage systems. The dynamic model is able to evaluate the self-consumed energy of the community as well as the energy delivered to the PG, considering a real electric load of the community. The model is able to evaluate in detail the economic feasibility of the plant, according to a comprehensive economic analysis, based on the Italian REC regulation.

2.2.1 Methodology and system layout

The layout of the investigated REC is based on a PV field connected to a system inverter/regulator, managing the load of the community and the power production of the solar

PV field. However, in order to better understand the performance of such a REC, several scenarios were investigated, namely:

- scenario A1: PV field without electric energy storage system (ESS);
- scenario A2: PV field with ESS.

TRNSYS 18, a reference and valid tool for the academic community [377], was adopted to develop the dynamic simulation model of the examined REC layouts. The software is based on built in components, experimentally validated [378–381], providing high accuracy and reliability of the returned results in terms of dynamic energy performance of solar systems. The energy components of TRNSYS are defined as Types and are based on detailed and comprehensive models. In this work, in order to simulate the presented scenarios, the Type 94 was adopted to simulate the PV field of the REC using the so-called "four parameters" model [382]. The lithium-ion battery model was simulated by using the Type 47 according to the Shepherd model. Note that his model is natively designed for mimicking the performance of a lead acid battery. However, in this case the main parameters of the type are customized in order to fit the performance of a lithium-ion battery [320]. The model evaluates the discharging efficiency according to battery conditions. Finally, Type 48 models the regulator/inverter for the optimal management of the current exchanged among PV arrays, ESS, inverter and community. Type 48 is used to mimic the performance of a regulator/inverter converting the DC into AC, before providing it to the PG when the state of charge reaches the maximum value or to the charging stations.

In the A1 and A2 scenarios, two distinct models have been developed. These dynamic models are designed to mimic the performance of the PV field and storage system. They also assess the energy shared within the community and the PV energy production in relation to the energy demand of the REC. For both scenarios, an economic analysis was developed. In order to perform the analysis, the scenarios were compared with the traditional system (TS), where the load is totally balanced by the electric energy withdrawn from the PG.

Concerning the proposed systems (A1 and A2), according to REC policy, only a virtual electricity self-consumption is considered [383]. This means that the total PV energy production is delivered to the PG, and the load of the REC is balanced by withdrawing the electricity from the PG. Then the shared energy is assessed as the difference between the PV energy production and the community energy demand. The main economic factors considered were:

- the unit cost of electricity withdrawn from the grid ($c_{el,PG}$);
- the REC ordinary management, maintenance and administration costs (MC_{REC});
- the selling of the renewable electricity (P_z);
- the feed in tariff (*TIP*) according to the Italian regulation, as detailed in *Table 2.1*, and the feed in tariff due to ARERA (*AR*) [383].

Note that for both scenarios, the economic analysis is developed by means of a suitable cash flow able to evaluate the following economic indices: the SPB and the net present value (NPV), assuming a lifetime of 20 years and a discount rate of 5 %. To evaluate the economic feasibility of the considered scenarios, the capital costs of the PV field (scenario A1 and A2) and ESS (scenario A2) are evaluated considering the nominal capacity of the components.

For each year, the yearly economic saving ΔOC, is the difference between the operating cost of the TS and proposed system (*REC*), Equation 2.20. The latter is evaluated according to two incentive regulations, as reported in Equations 2.22. In the first case the TIP is considered in full, because no reduction on investment cost are taken into account. In the second case (*INC*), the TIP is reduced by half, because an incentive according to the REC regulation, equal to 40 % of the capital cost, is expected.

$$\Delta OC = OC^{TS} - OC^{REC} \tag{2.20}$$

$$OC^{TS} = c_{el,PG} * E_{el,US} \tag{2.21}$$

$$OC^{REC} = \begin{cases} (c_{el,PG} * E^{REC}_{el,US}) + MC_{PV} - (P_z * E^{REC}_{el,RES}) - (E^{REC}_{el,SH} * (TIP + AR)) & if\ IC = IC_{PV} \\ (c_{el,PG} * E^{REC}_{el,US}) + MC_{PV} - (P_z * E^{REC}_{el,RES}) - \left(E^{REC}_{el,SH} * \left(\frac{TIP}{2} + AR\right)\right) & if\ IC = IC_{INC} \end{cases} \tag{2.22}$$

The case study selected for this research consists of the municipality of Foiano di Val Fortore located in the south of Italy. In particular, such small municipality includes 1,325 inhabitants. *Figure 2.15* and *Figure 2.16* displays the assumed load of the whole municipality for a typical summer and winter day respectively, ranging around 24 kW.

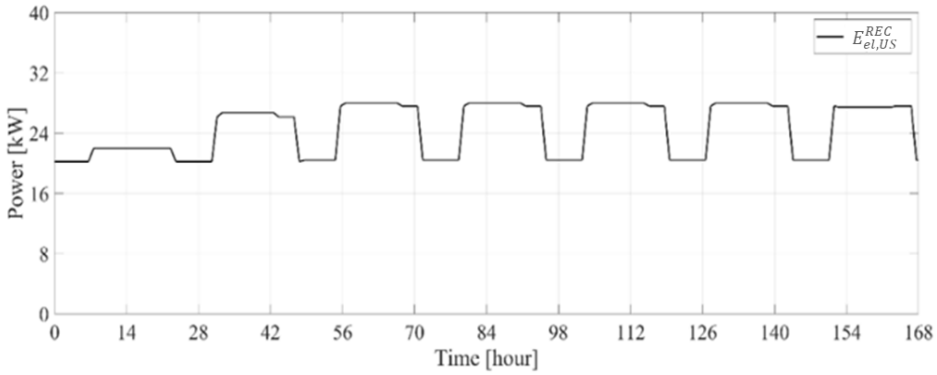

Figure 2.15 Daily load for a typical summer day.

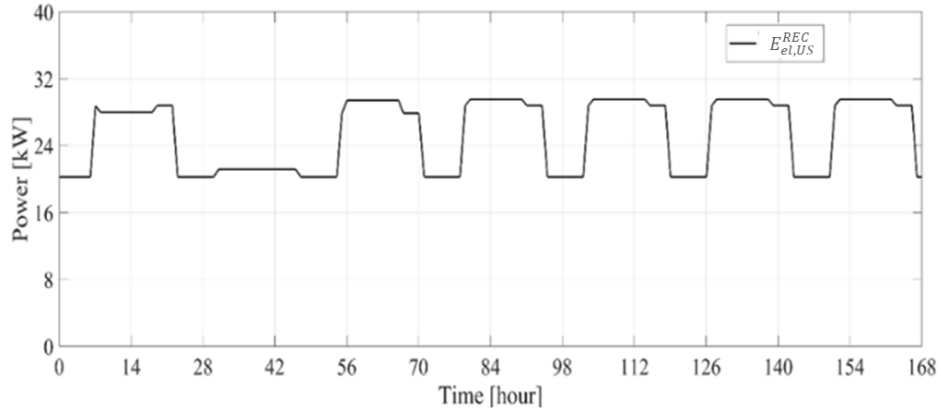

Figure 2.16 Daily load for a typical winter day

In the reference system the municipality load is balanced by means of the electricity withdrawn from the PG. The first proposed system (scenario A1) relies on the foundation of a REC, where a diffuse PV installation is performed. In particular, an overall PV capacity of 50 kW is installed. The second proposed system (scenario A2) is equal to first, i.e. it is considered a REC relying on diffuse PV field installation (overall PV capacity of 50 kW). Moreover, such arrangement also includes a district electricity energy lithium-ion battery of 20 kWh. Also, in this case the virtual electricity self-consumption is considered.

Table 2.7 summarizes the main cost figures and assumptions regarding the economic analysis. The PV plant is shutdown two days per month, due to maintenance. This assumption is performed for both the proposed systems. Note that an yearly degradation by 2% through the whole lifetime of the PV field is considered. For the considered case study the extraordinary maintenance cost of the REC (MC_{extr}) is considered in correspondence of the tenth year. For the electricity exporting ($c_{el,PG}$) and purchasing price (P_z) average values are considered.

Table 2.7 Main economic assumptions.

Parameter	Description	Value	Unit
IC_{PV}	PV specific cost	1400*(P)	[€]
IC_{ESS}	Lithium-ion battery specific cost	200.0	[€/kWh]
MC_{REC}	Ordinary maintenance cost of the REC	3.0	[%/year]
MC_{extr}	Extraordinary maintenance cost of the REC	20.0	[%]
P_z	Electricity exporting price	0.060	[€/kWh]
$c_{el,PG}$	Electricity purchasing cost	0.210	[€/kWh]
TIP	Feed in tariff due to REC policy	0.120	[€/kWh]
AR	Feed in tariff due to ARERA	0.008	[€/kWh]
IC_{INC}	Incentive due to REC policy (related to capital cost)	40 % * IC_{PV}	[€]

2.2.2 Results and discussion

This section deals with the results achieved by this study. *Table 2.8* summarizes the yearly results. As expected, the installation of the PV fields leads to a significant reduction of the primary energy consumption of the municipality. In particular, a reduction by 27 % of the primary energy of the municipality is achieved for Scenario A1.

Table 2.8 Yearly results for scenario A1.

Parameter	Value (REC)	Unit
$E_{el,RES}^{REC}$	71.42	[MWh/year]
$E_{el,SH}^{REC}$	58.38	[MWh/year]
ΔE_p	26.96	[%]
RSE	0.269	[-]
RSC	0.817	[-]
SPB	5.30	[years]
NPV	56.10	[k€]
$SPB\ (INC)$	4.00	[years]
$NPV\ (INC)$	52.20	[k€]

Note that the shared energy balances almost 27 % of the load of the municipality. This result is due to the fact that the power production occurs only during the central part of the day balancing only a limited part of the district daily load, as shown in *Figure 2.17* with respect to

a specific day. Note that the community is able to self-consume the majority of the PV production, indeed RSC index is almost equal to 82 %. From the economic point of view, the REC policy is able to make this investment profitable. The scenario, where only the feed in tariffs are considered, leads to SPB of 5.30 years, with a NPV of 56.1 k€. The scenario, where both the feed in tariff and the capital cost incentives are considered, achieve the better results with a limited payback period of 4.0 years and NPV of 52.2 k€. Then, the policy combining the reduced feed in tariff with the capital cost incentive is the better solution.

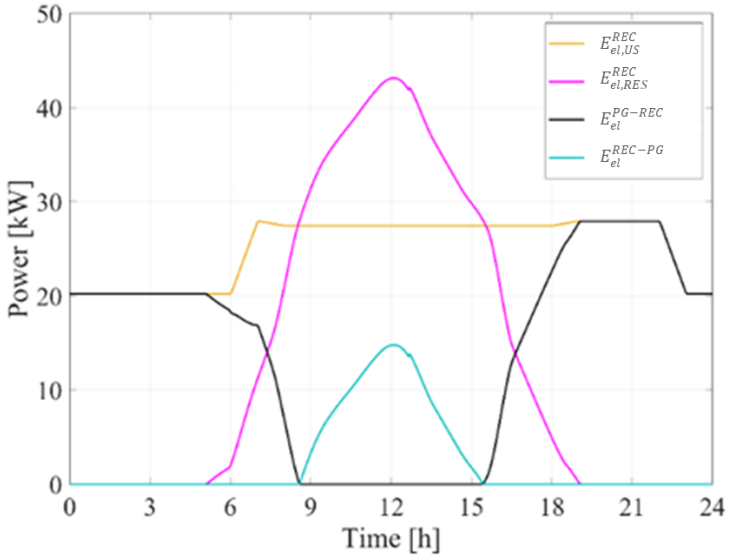

Figure 2.17 Dynamic energy results for scenario A1.

The proposed system 2 (scenario A2) is able to reduce the primary energy consumption of the REC due to the electric energy storage system. In fact, for A2 the REC is able to reduce the primary energy consumption by 31%, as presented in *Table 2.9.* Note that the battery increases by 3 % the self-consumed energy ratio, RSE index, which passes from 27 % in scenario A1 to 29 % in A2. This slight enhancement is mainly due to the battery limited capacity. In fact, because of the high capital cost of such technology, a small battery is installed.

Table 2.9 Yearly results for scenario A2.

Parameter	Value (REC)	Unit
$E_{el,RES}^{REC}$	71.42	[MWh/year]
$E_{el,SH}^{REC}$	62.85	[MWh/year]
$E_{el,fromEES}$	6.96	[MWh/year]
$E_{el,toEES}$	4.84	[MWh/year]
ΔE_p	29.01	[%]
RSE	0.290	[-]

RSC	0.880	[-]
SPB	12.40	[years]
NPV	2.97	[k€]
SPB (INC)	13.50	[years]
NPV (INC)	0.01	[k€]

The result is furtherly confirmed by Figure 2.1*Figure 2.18*. In fact, the battery is able to handle only a limited amount of excess renewable electricity, i.e. 4.22 kW out of 10.91 kW.

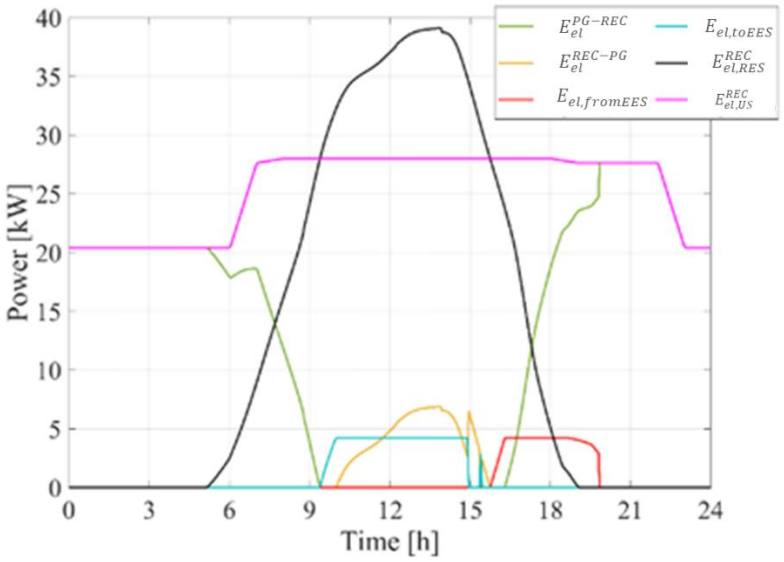

Figure 2.18 Dynamic results for scenario A2.

The battery adoption leads to a worsening of the economic performance if compared with A1 (i.e. the layout without the battery). This result is related to the fact that the battery has a very high specific cost, leading to average economic results. In other words, the increase in the capital cost is not balanced by the reduction of the operative cost due to the increased self-consumed energy. As for A2, the better policy relies on the full feed in tariffs policy without any incentive on the investment. This result is mainly due to the fact that the policy regarding the feed in tariff is able to maximize the revenue due to the increase in the self-consumed energy because the battery adoption.

The main findings of this research concerns:

- the PV adoption leads to a reduction of the primary energy consumption of the REC by 29 %;

- the self-consumed energy balances 27 % of municipality load for the scenario relying only on PV. The shared energy matches almost 29 % of the load of the municipality for the scenario adopting PV and battery;
- the REC policy is useful in making such investments very profitable. In fact, due to incentives the achieved SPB is extremely limited. The first scenario achieves a SPB of 4.0 years and the second scenario reaches a SPB of 13.5 years. In the case of a PV plant without EES, the use of incentives is preferable to the case without them.

2.3 Towards the decarbonization of industrial districts through RECs: techno-economic feasibility of an Italian case study

The European *Green Deal Industrial Plan* [13] reaffirms the commitment of the EU towards the 55% reduction of GHG emissions compared to the 1990 levels by 2030 [384] and carbon neutrality by 2050 [385] by supporting the roll-out of RESs in the industrial sector. In 2021, the industrial sector's global CO_2 emissions amounted to 9.4 Gt_{CO_2} and represented one-quarter of the total (except for indirect emissions due to electricity production for industrial processes) [386]. As such, the industry is nowadays not on track to achieve either the Net Zero Emissions goal by 2050, or the objectives introduced by the Paris Agreement of the United Nations Framework Convention on Climate Change [387]. Although industrial companies are making increasing investments, improvements in energy efficiency, the uptake of low-carbon technologies, and the deployment of RES-based plants are advancing more slowly than needed [388,389]. Hence, they would require additional support and incentivization by single countries' policies [390]. Techno-economic issues especially discourage single SMEs from investing in energy efficiency and RESs, thus hindering the potentialities of these interventions. For instance, the valorization of large unused surfaces often available in industrial areas through RES-based plants would open up the opportunity to reinforce the provision of renewable energy in urban centres [391].

RECs, as defined in the RED II, can involve different end-user types. In this regard, these configurations are open to voluntary participation, not only of natural persons and local authorities, including municipalities, but also micro, small or medium-sized enterprises. The

co-participation of different user types is beneficial to the performance of RECs [392], since it provides positive outcomes from the energy, economic and environmental viewpoint. The combination of different load curves increases the generation plants' operating hours [393] and results in a smoother aggregated load profile, which typically lowers the mismatch between energy demand and supply from RES-based plants.

As regards industrial areas, they can take advantage of the complementarity of loads as well, being characterized by energy requests relating to different end-use types, such as the activation of production processes, service facilities, safety and transportation systems, as well as the lighting, heating and cooling of office buildings [394]. Hence, the implementation of RECs in industrial areas may combine the potentialities offered by the growing integration of RES-based plants with the opportunities relating to the aggregation of complementary loads.

The study presented in this paragraph aims to investigate the constitution of a REC in the industrial area of Benevento (Italy). The REC under examination involves two different kinds of users, namely a mixed-use building and the consortium wastewater treatment plant (WWTP). Their choice is expected to take advantage of the diversity of users' load profiles due to electric energy demand linked to different end-uses in a real case study. The ultimate goal is to demonstrate the feasibility of RECs in industrial areas without restraining the scope of interest to the boundaries of the industrial site being analyzed, but rather to stimulate the replication of the analysis performed in this study within the literature in order to foster real applications. The users under examination have been equipped with a PV plant. Within the REC boundaries, energy sharing has been implemented according to the Italian regulation, that is, under the virtual self-consumption scheme. In addition to this proposed scenario, the alternative single end-users' configuration where energy sharing has been neglected has been investigated too. Both examined scenarios have been compared with the current status, where the users' electric energy demand is covered by the PG

2.3.1 Industrial REC development

The industrial area of Benevento covers a surface of 3,179,357 m^2 and it is divided into seven zones, including several micro, small, medium, as well as internationally renowned enterprises. The collective services center (CSC) building and the consortium WWTP have been considered as users in this study (Us#1 and Us#2, respectively). The CSC building is the setting of the Consortium Centre for Management, which is responsible for the management of the

industrial area and common services, and four companies operating in the services sector. The WTTP is deputed to the treatment of the wastewater produced from the office building, the enterprises located in the area and urban wastewater produced in one of the districts of the municipality nearby. The data about users' electric energy demand in 2021 have been gathered from their electricity bills. They are referred to nine POD, seven serving Us#1 and two serving Us#2. In the case of two POD (one serving Us#1 and one serving Us#2), the 2021 electric load curves with a quarter-hour time step have been made available by the Italian electricity distributor [395]. For the remaining seven PODs, the load curves on a quarter-hourly basis have been constructed, manipulating the aggregated monthly data known from the bills. Namely, the monthly electric energy demand has been split into hours, depending on the day of the week and distinguishing between peak hours (belonging to the F1 band, from Monday to Friday from 8:00 a.m. to 7:00 p.m.), intermediate hours (belonging to the F2 band, from Monday to Friday from 7:00 a.m. to 8:00 a.m., from 7:00 p.m. to 11:00 p.m. and on Saturady from 7:00 a.m. to 11:00 p.m.) and evening and weekend hours (belonging to the F3 band, from Monday to Saturday from 11:00 p.m. to 7:00 a.m., and on Sunday and public holidays all-day) [396].

The Us#1 and Us#2 total load profiles on a quarter-hourly basis are shown in *Figure 2.19* and *Figure 2.20* respectively. The graphs have been constructed by varying the colour of indicators depending on the time in order to emphasise the distribution of the electric load during the day. In the case of Us#1, the electric load is clearly higher during morning hours, and minimum load values are detected in the evening. By contrast, in the case of Us#2, the distinction between morning and evening loads is not straightforward. As it can be seen, the loads of the two users are characterised by different orders of magnitude. Indeed, the load of Us#1 is at most equal to 46.5 kWh in January. By contrast, Us#2 has significantly higher requests, and its maximum load amounts to 186.0 kWh in July. Moreover, the workload profiles are differently distributed throughout the year. Starting from January, the maximum electric energy requests of Us#1 decreased during spring until June. In June, an arising trend can be found, which stops in July, and restarts from August onwards. Conversely, the electric energy requests of Us#2 are characterised by a rising trend in the spring months until the end of June, when the maximum load is found. From July onwards, maximum load values start decreasing.

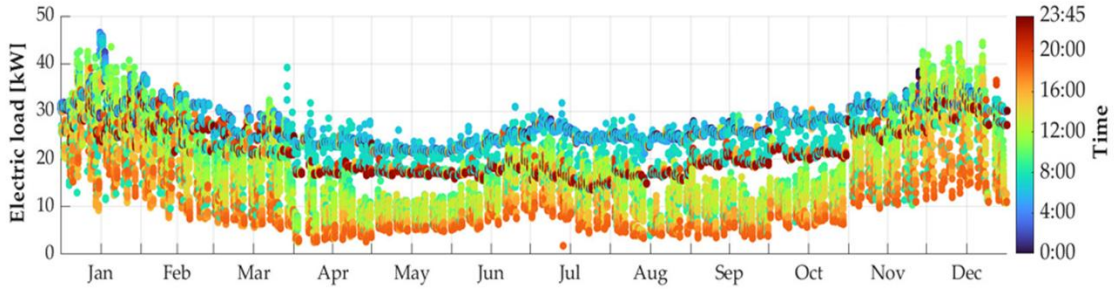

Figure 2.19 Electric load profile on a quarter-hourly basis of Us#1.

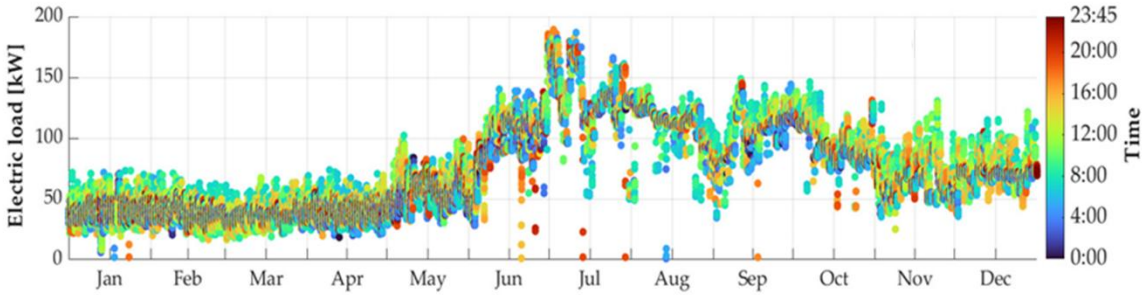

Figure 2.20 Electric load profile on a quarter-hourly basis of Us#2.

The users' electric energy demand ($E_{el,US}$) is quantified on a monthly basis in *Table 2.10*, where, in addition, their loads have been considered as a whole in the last column. As shown, in all months, $E_{el,Us\#2}$ is higher than $E_{el,Us\#1}$, especially in summer and autumn months. Overall, the yearly electric energy demand of Us#1 is equal to 190 MWh/y, whereas it amounts to 655 MWh/y regarding Us#2. Hence, on a yearly basis, the two users require in total 846 MWh/y.

Table 2.10 Users' monthly electric energy demand

Month	**$E_{el,Us\#1}$ [MWh/month]**	**$E_{el,Us\#2}$ [MWh/month]**	**$E_{el,US}$ [MWh/month]**
January	21.6	29.9	51.5
February	17.0	25.9	42.9
March	15.7	26.9	42.6
April	12.4	28.1	40.6
May	12.2	42.0	54.2
June	13.3	71.0	84.4
July	14.5	100.2	114.7
August	13.3	83.6	96.9
September	13.4	74.7	88.2
October	15.8	71.6	87.4
November	19.0	47.9	66.9

December	22.1	53.5	75.5
Total [MWh/year]	190	655	846

The surfaces selected for installing the PV panels have been highlighted in *Figure 2.21*. Specifically, the PV panels belonging to Us#1 have been assumed to be placed on the rooftop of the CSC building, on unused land nearby, and on PV canopies in the parking area, whereas those belonging to Us#2 are on the horizontal rooftop of seven establishments. Monocrystalline cell PV panels with 327 W of peak power have been chosen for installation [397].

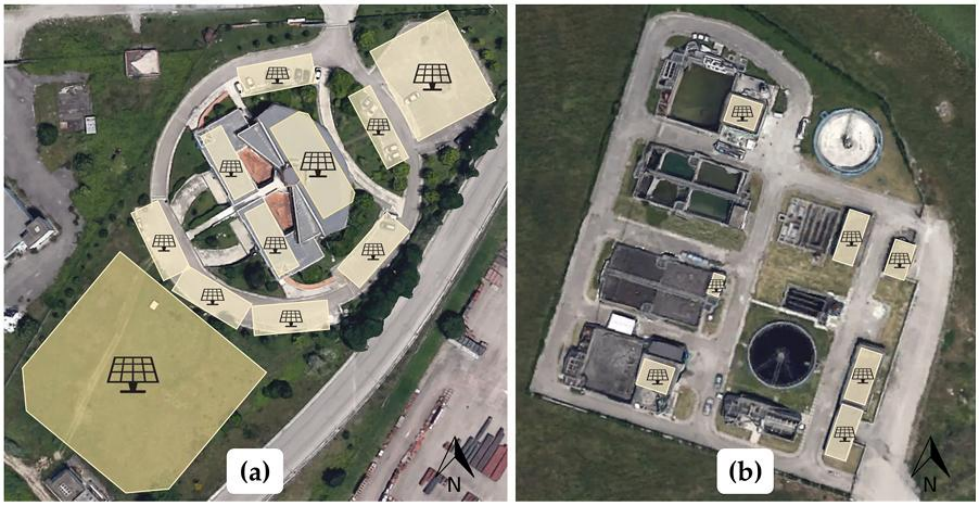

Figure 2.21 Aerial view of the surfaces selected for installing the PV plant, belonging to Us#1 (a) and Us#2 (b).

The area of each surface has been measured by excluding the portions subjected to shading phenomena and considering a 15 % reduction in order to ensure enough service spaces. Optimal installation conditions for the PV panels have been chosen in order to maximise the PV plant productivity by maximising the solar radiation captured by each module [398]. Overall, the total number of PV panels installable is equal to 1424, and the PV plant peak power is equal to 466 kW, of which 431 and 35 kW are installed in sites pertaining to Us#1 and to Us#2, respectively. The results obtained are detailed in *Table 2.11*.

Table 2.11 Characterisation of surfaces available for the installation of the PV panels.

User	Installation site	Type of surface	Exposure	Area [m^2]	Number of panels	Peak power [kW]
Us#1	CSC building's rooftop	Horizontal	South	486	154	50
	CSC building's rooftop	Tilted	South-West	170	104	34

			South	200	64	21
	Parking area	Horizontal	South-West	475	152	50
			South-East	112	36	12
	Unused land	Horizontal	South	2550	807	264
Us#2	Building's rooftop	Horizontal	South	340	107	35
Total	-	-	-	4333	1424	466

The electric energy production profile of each portion of the PV plant, distinguished by the installation site and exposure, has been evaluated on a quarter-hourly basis using the software Homer Pro [74]. The dynamic simulation has been carried out over one year. Hourly meteorological data about global solar radiation and air temperature, evaluated as hourly average values of the data collected by one of the weather control units in Benevento during 2021 with a ten-minute timestep, have been provided as input to the software. The PV generation curves resulting from the simulation carried out in Homer Pro have been post-processed in Microsoft Excel [350] for evaluating, with a one-hour time step (θ), the electric energy consumed on-site by the users ($E_{el,SC}$), the surplus fed into the PG ($E_{el,exp}$) and the residual electric load drawn from the grid ($E_{el,imp}$). $E_{el,SC}$ has been evaluated on an hourly basis as the minimum between the electric energy hourly supplied by the PV plant ($E_{el,RES}$), evaluated starting from the quarter-hour data resulting from the dynamic simulation, and the users' hourly electric energy demand ($E_{el,US}$).

The profitability of the PV plant has been investigated under two different scenarios, shown in *Figure 2.22*, along with the reference traditional case (TS), where the users' electric energy demand is fully met by the PG. The two alternative solutions have been outlined as follows:

- in the single end users' scenario (hereinafter recalled as noREC scenario), the PV plant has been divided into two portions, each owned by one user, and the sharing of electric energy has been neglected. Thus, the PV panels installed in the sites pertaining to Us#1 (the rooftop of the CSC building, the parking area and the unused land) have been assumed to supply renewable electricity only to Us#1 itself. Likewise, those installed on the rooftop of the WWTP buildings only to Us#2. Hence, each user has the opportunity to self-consume the renewable electricity supplied by his own plant and inject into the PG the potential surplus;

- in the REC scenario, the PV plant has been treated as a whole and supplies electricity both to Us#1 and Us#2, which are involved in the REC. Electricity sharing has been implemented in compliance with the Italian regulation about RECs, that is, according to the virtual self-consumption scheme for users under the same primary electric substation. On the one hand, all the electric energy supplied by the PV plant is injected into the primary substation; on the other, the users draw electric energy from the primary substation to meet their requests since no physical self-consumption takes place. Electric energy virtual sharing is realized when the absorption from and injection to the primary substation occur simultaneously. The energy balance on the primary substation is evaluated on an hourly basis [156].

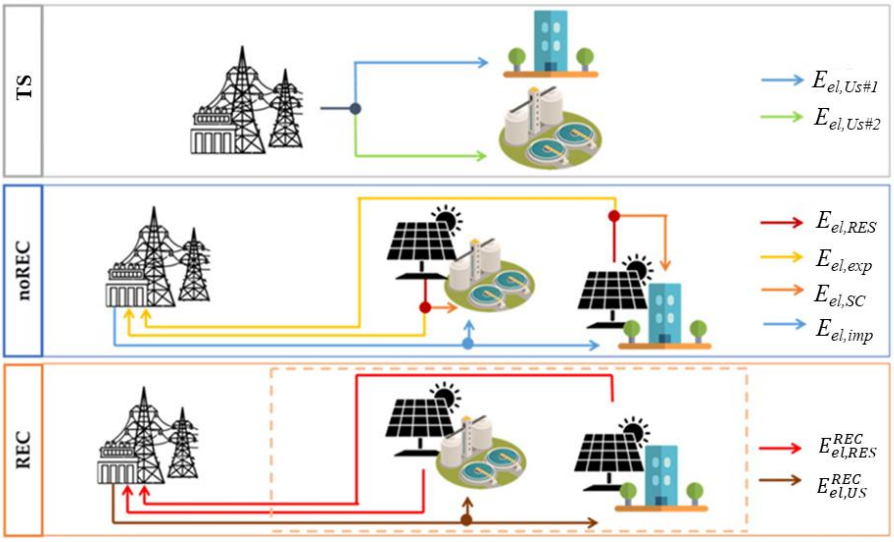

Figure 2.22 Layout of investigated scenarios.

No-REC and REC scenarios have been compared with the TS case from the energy, environmental, and economic points of view. As for the energy analysis, the RSC and RSE indexes have been evaluated on a monthly basis, both in No-REC scenario considering the $E_{el,SC}$ of each user separately, evaluated by using the electric energy supplied on a monthly basis by the portion of the PV plant serving him and the respective electric load. Conversely, in the REC scenario, overall values have been considered both from the production and consumption sides. Shared energy has been evaluated according to the rules of the Italian regulation on RECs.

Referring to the energy, environmental and economic analysis, the primary energy saving (ΔE_p), the CO_2 emissions reduction (ΔCO_2) and the variation in operating costs (ΔOC) respectively, compared to the TS has been evaluated on a monthly basis according to Equations reported in Section 1.2.1 in the no-REC and REC scenario. The electric energy injected into the

PG has been supposed to be sold according to the Dedicated Withdrawn scheme [399]. In this framework, the hourly electricity selling price (P_z) has been assumed to be equal to the 2021 hourly zonal price of electricity in the Central-South bidding zone of the Italian electricity market. With regards to the economic incentive recognized on the shared energy of the REC, a fixed value is taken into account, according to the normative context of RECs for 2021. This contribute combines the 110.0 €/MWh incentive by the Italian GSE [400] and a network charge restoration due to avoided transit on the PG, which accounts for 8.6 €/MWh in 2021, resulting in a total incentive (I_{SH}) equal to 118.6 €/MWh.

2.3.2 Results and discussion

In the *Figure 2.23 a)* and *b)*, the results obtained in the no-REC scenario are reported by distinguishing between Us#1 and Us#2. The stacked bars in *Figure 2.23a* represent to $E_{el,RES}$, considering the green bars equal to $E_{el,SC}$ and the orange bars equal to the share of energy fed to the PG, that is, $E_{el,exp}$. In addition, the blue line plots the trend of RSC in 2021 with respect to the secondary axis. As shown, Us#1 self-consumes at most 34.8 % of $E_{el,RES}$ in December, equal to 4.1 MWh. In the months of highest producibility, such as May and July, when $E_{el,RES}$ is equal to 70.3 and to 68.8 MWh, RSC reduces to 7.9 and 10.4 %, respectively. In particular, RSC in May is the minimum value detected in 2021. In *Figure 2.23b*, the stacked bars amount in total to $E_{el,Us\#1}$. The green bars keep being equal to $E_{el,SC}$, whereas the blue bars equal the energy withdrawn from the PG, $E_{el,imp}$. As shown by the orange indicator plotting the time trend of RSE during 2021 with respect to the secondary axis, the maximum self-sufficiency is measured in June, being RSE equal to 49.8 %. Conversely, RSE reaches its minimum value in December, when it is equal to 18.6 %. In fact, December is the month characterized by the highest $E_{el,US}$ but the minimum $E_{el,RES}$.

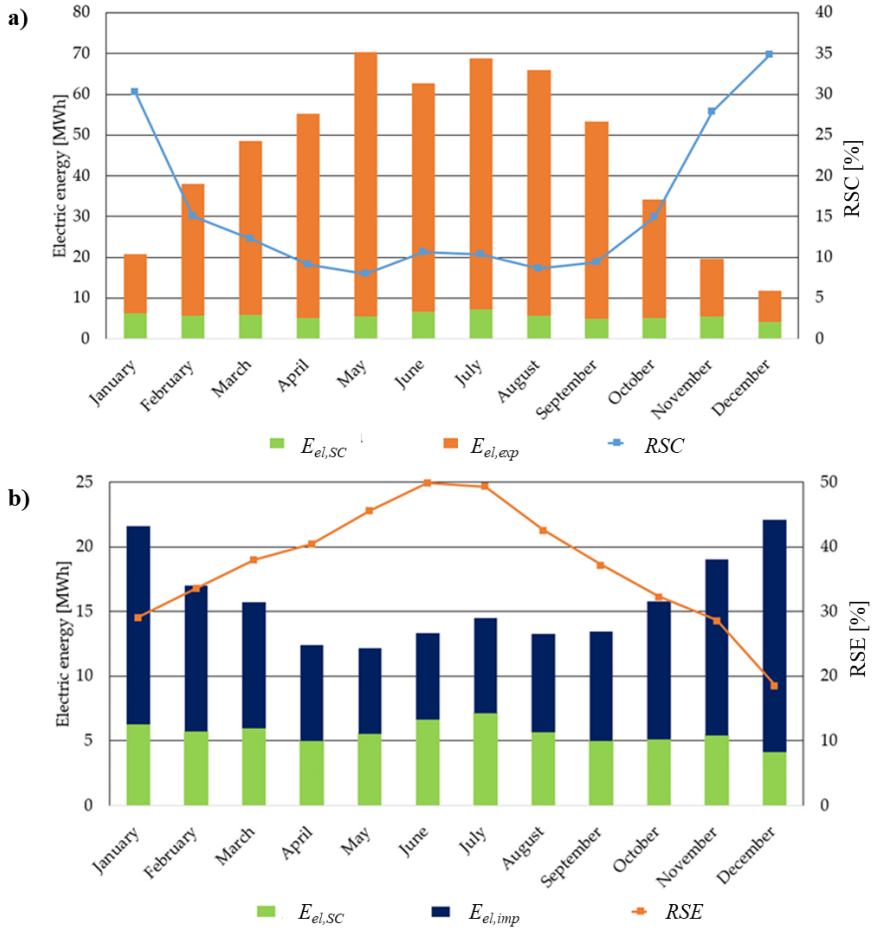

Figure 2.23 a) Producibility of the PV plant serving Us#1 in the noREC scenario. Electric energy consumed on-site and fed to the grid and RSC index on a monthly basis. b) Load of Us#1 in the noREC scenario. Load covered by the PV plant, the grid and RSE index on a monthly basis.

Still referring to the no REC scenario, *Figure 2.24 a)* and *b)* characterise the results obtained in regard to Us#2, as the same for the previous one. As shown in the *Figure 2.24a*, in almost all the months, the electric energy supplied by the PV plant belonging to Us#2 is fully consumed on-site. Indeed, the lowest value of RSC is detected in January and is equal to 99.5 %. Nevertheless, the results shown in *Figure 2.24b* highlight that the high on-site consumption rates do not imply high energy self-sufficiency. The maximum RSE for Us#2 is measured in April, and it is equal to 16.1 %. By contrast, the minimum RSE occurs in December, when it is equal to 1.9 %.

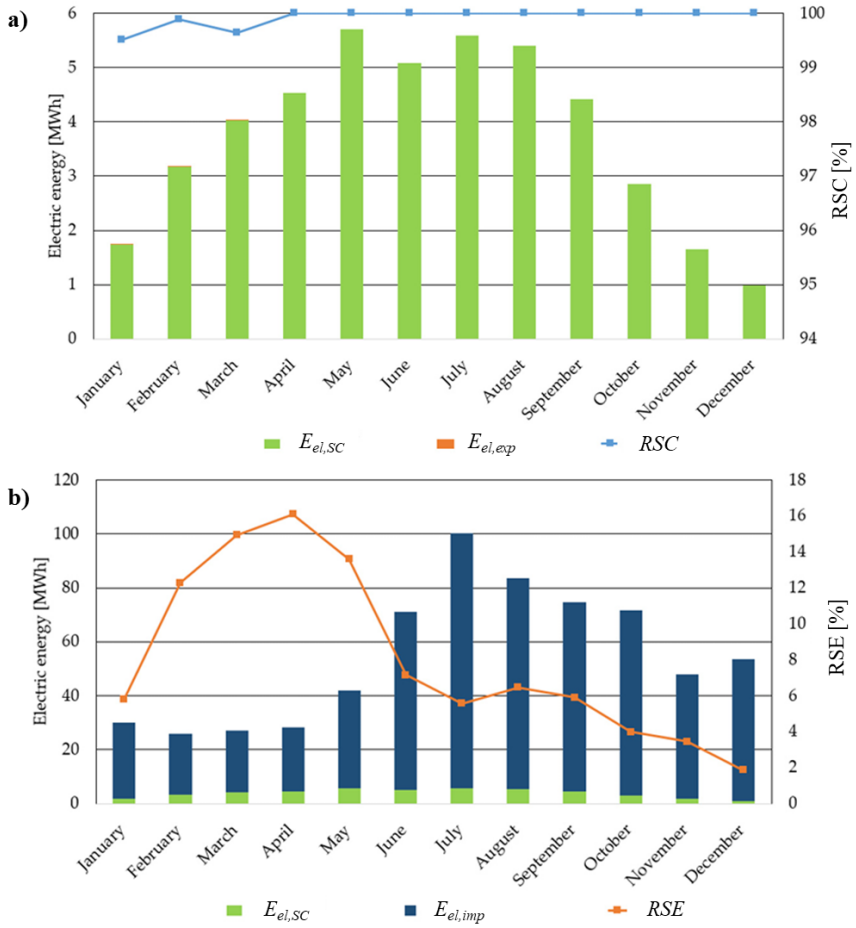

Figure 2.24 a) Producibility of the PV plant serving Us#2 in the noREC scenario. Electric energy consumed on-site and fed to the grid and RSC index on a monthly basis. b) Load of Us#2 in the noREC scenario. Load covered by the PV plant, the grid and RSE index on a monthly basis.

The reason for the outcomes shown so far relies on the under-sizing which characterizes the portion of the PV plant serving Us#2 compared to its electric load. As a matter of fact, the PV plant supplies at most 5.7 MWh in May, whereas the maximum load is equal to 100 MWh in July. On the other hand, the results regarding Us#1 emphasize a significative mismatch between demand and supply. The summer months are characterized by high self-sufficiency but low self-consumption rates, as it happens in May, which is characterized by the highest supply of electric energy from the PV plant (70.3 MWh), but the load is much lower, being equal to 12.2 MWh. By contrast, the load is maximum in December (22.1 MWh), when the producibility of the PV plant reaches its minimum value (11.8 MWh).

By analogy with the previous cases, *Figure 2.25 a)* and *b)* present results for the REC scenario. The sharing of energy between Us#1 and Us#2 increases both the energy self-consumption (RSC index) and the self-sufficiency of users (RSE index).

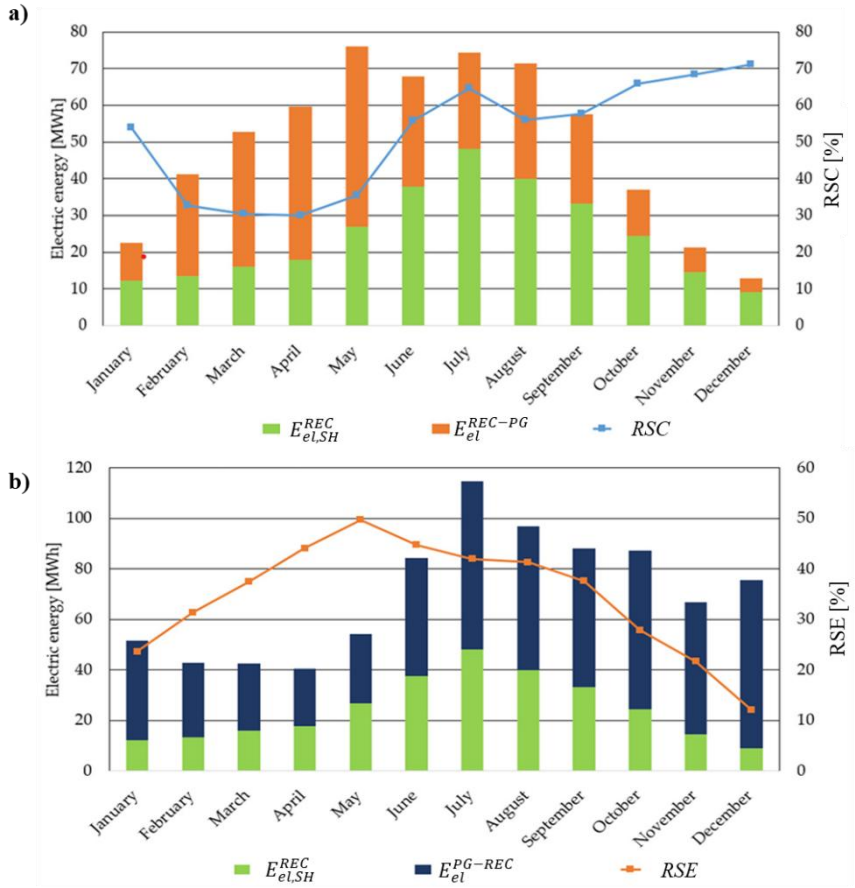

Figure 2.25 a) Producibility of the PV plant serving Us#1 and Us#2 in the REC scenario. Electric energy virtually shared and fed to the grid and RSC index on a monthly basis. b) Load of Us#1 and Us#2 in the REC scenario. Electric energy virtually shared and load covered by the grid and RSE index on a monthly basis.

Considering the month of May, which is the month of maximum productivity of the PV plant, $E_{el,SH}^{REC}$ is equal to 26.9 MWh and is higher than the sum self-consumed energy values determined in the no-REC scenario. As a result, in May RSE is the maximum, being equal to 49.7 %. The amount of electric energy in total fed to the grid and not shared (E_{el}^{REC-PG}) reduces accordingly. Similar considerations apply to July, which is the month characterised by the highest total load. In particular, $E_{el,SH}^{REC}$ is equal to 49.1 MWh, while $E_{el,SC}$ is equal to 7.1 MWh and 5.6 MWh, respectively for Us#1 and Us#2 for the same month. As a consequence of increased self-consumption, the amount of electric energy import from the grid, exceeding shared energy, reduces compared to the no-REC scenario. As a matter of fact, E_{el}^{PG-REC} is equal to 66.6 MWh, whereas $E_{el,imp}$ is equal to 7.3 and 94.6 MWh, respectively for Us#1 and Us#2 for the same month. Regarding the minimum value of RSC, it is found in April and is equal to 29.9 %. Hence, it is more than tripled compared to RSC of Us#1, equal to 9.1 % in the same month.

The increased energy self-consumption and self-sufficiency, owing to the energy sharing and characterizing the REC scenario, results in a reduction of the primary energy demand higher than in the noREC scenario, as shown in *Figure 2.26*. Indeed, ΔE_p for noREC is, at most, equal to 25.0 MWh, whereas for REC scenario equal to 94.5 MWh. Overall, the primary energy demand in 2021 is equal to 1.1 GWh in the REC scenario and to 1.4 GWh in the no-REC. In the TS, the annual primary energy demand is equal to 1.7 GWh/y. The constitution of the REC allows a 34.7 % primary energy saving on a yearly basis, whereas it is limited to 13.3 % in the noREC scenario.

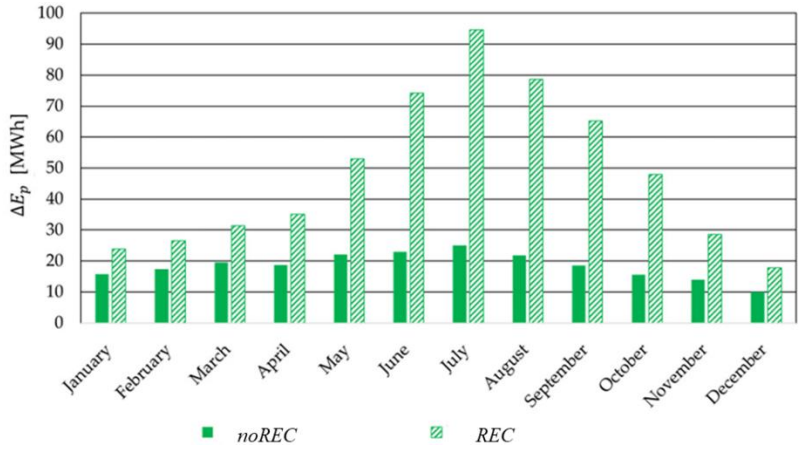

Figure 2.26 Primary energy saving in the noREC and REC scenario.

Environmental analysis further supports the mitigation of CO_2 emissions compared to the noREC scenario; the emissions are equal to 242.3 t_{CO_2}/year in the TS, 210.0 t_{CO_2}/year in the noREC scenario and 158.2 t_{CO_2}/year in the REC scenario. Hence, the 13.3 % reduction in CO_2 emissions characterizing the noREC scenario increases to 34.7 % in the REC scenario. As shown in *Figure 2.27*, the best reduction on a monthly basis is found in July, and it is equal to 3.6 t_{CO_2} in the noREC and to 13.8 t_{CO_2} in the REC.

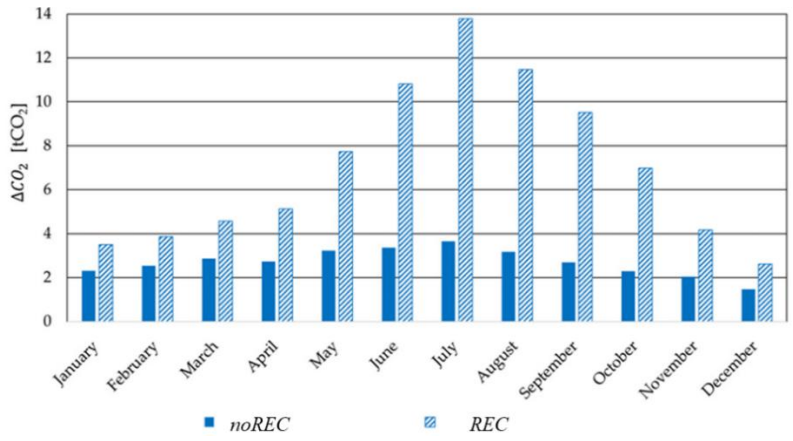

Figure 2.27 CO_2 emissions avoided in the noREC and REC scenarios.

In *Figure 2.28*, the operating costs relating to the first year of the investment horizon are shown. In particular, the values of OC for TS are compared with noREC and REC, showing that the constitution of the REC is profitable from the economic point of view since it ensures increased economic savings. As a matter of fact, OC of the REC are always lower than noREC case. On a yearly basis, the reduction for the REC is by 24.6 k€ compared to noREC and by 100.8 k€ compared to TS. Hence, the annual 31.9 % economic saving characterizing the noREC scenario increases to 42.3 % in the REC scenario.

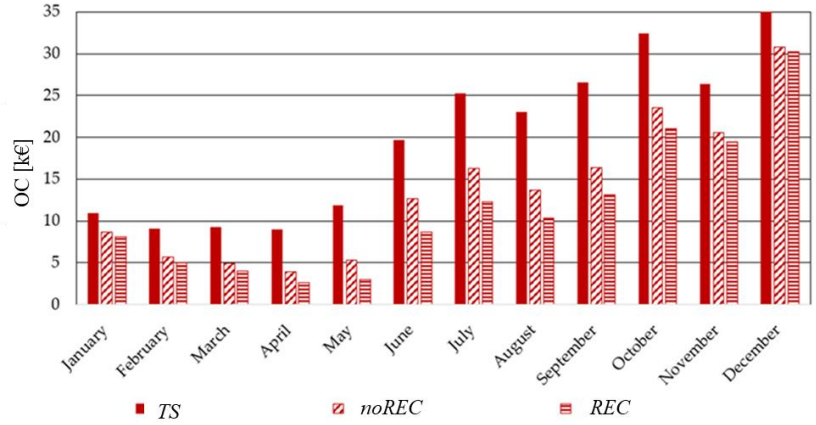

Figure 2.28 Operative costs in the TS, noREC and REC scenarios.

These results encourage the implementation of the RECs in industrial parks. In future works, the installation of an EES in order to further increase the users' energy self-sufficiency and renewable energy self-consumption, according to the Italian regulation on RECs could be additionally investigated. Moreover, other renewable energy technologies (such as biomethane-based cogeneration plants or wind turbines) able to meet the community's loads can be investigated as solutions to reduce carbon dioxide emissions. Yet, their economic feasibility must be verified as they are less mature technologies compared to PV plants. In addition, the possibility of including other industrial members in energy sharing will be addressed, also to promote the constitution of such configurations within the industrial sector considering their many positive effects.

2.4 Assessments of energy sharing models and economic remuneration schemes for RECs

In recent years, the global energy sector has witnessed a substantial increase in electricity demand, surpassing the overall growth rate of total energy demand [401]. This trend is indicative of the ongoing electrification process of end-users' energy consumption, representing a fundamental pillar of a broader decarbonisation strategy. In order to sustainably meet the increasing demand, the integration of RES in electricity generation is progressing at a steady and appropriate pace. The RES-based technologies have become competitive with the fossil fuel sector, largely due to the policies enacted for energy security and climate change [402]. The transformation of the energy system also required significant investments in enabling RES systems, including BESS, hybrid systems and advancements in digitalization [403]. Effective policy measures also occur for the success of the transformation process. The *National Energy and Climate Plans* represent a strategic plan implemented by the EU to direct the necessary investments in the pursuit of energy and climate transition, involving the public and private sectors [404]. Current policies target the reduction of GHG emissions by at least 55% by 2030 and the achievement of climate neutrality by 2050 [13].

Among the strategies implemented by the EU, the RECs, introduced by RED II as part of the CEP, act as key configurations for maximizing the use of energy from RES to meet the energy demand of end-users [37]. Through the direct involvement of citizens, RECs promote a new energy sector paradigm. Community engagement fosters social cohesion and supports more democratic governance practices [22]. The opportunity to also capture non-economic benefits represents the core strength of such configurations. Although RECs may involve legal complexity and can be less competitive than individual installations, they are supported by financial remuneration schemes and energy-sharing mechanisms that enable the effective pursuit of non-economic benefits.

However, forms of participation, sharing mechanisms, and economic reward schemes vary depending on the regulatory environment of the country implementing them. In the context of the EU, RED II has introduced pivotal concepts related to energy-sharing configurations, including RECs. Each member state has thoughtfully integrated these into its national legislation, creating an implementation system that aligns with the existing regulatory framework [137].

The sharing systems currently in force on European territory involve, as previously presented, either a physical or virtual model. Indeed, the shared energy is evaluated on the overall REC consumption, as in the case of Italy, or through allocation coefficients assigned to each community member, as implemented in Portugal and Spain. Economic remuneration schemes may consist of reductions on the electricity bill proportional to the energy exchanged within the community, or dedicated incentive mechanisms [151]. At the territorial level, specific proximity conditions must be met, depending on national regulations.

The adoption of one sharing system over another significantly influences the benefits associated with RECs implementation, particularly in terms of the amount of shared energy and the economic returns for community members. To better understand these differences, the study presented in this section compares the sharing mechanisms and remuneration structures based on those adopted in two European countries, Italy and Spain, by applying them to a case study, with the aim of assessing the actual benefits that can be achieved under specific aspects of these regulatory frameworks.

2.4.1 Literature review and research context

An overview of some key similarities and differences between the regulatory frameworks governing RECs in Italy and Spain contributes to evaluating the strengths and implementation challenges of each system. The analysis focuses on national transpositions of EU directives, incentive schemes, and technical requirements.

The implementation of policies supporting REC projects in Italy predates the 2018 European RED II directive. The transposition process into the national legislative framework underwent a transitional phase, during which initial rules and constraints for RECs were defined and subsequently revised, leading to the current framework established by Decree 414/2023 [271]. In Italy, electricity sharing within a REC is based on a virtual model that operates through the national PG. Shared energy is estimated on an hourly basis as the minimum between the energy injected into the PG by all community RES-based plants and the total energy drawn by all its members, as established by the GSE, National Energy Services Manager Company [156]. Economic incentives are recognized for shared energy, with the amount varying according to the plant size, bidding market zone, and the type of RES technology employed. REC projects do not benefit from priority grid access [405]. Energy sharing is allowed within the same electricity market zone; however, eligibility for incentives requires that either consumers and generation plants, not exceeding 1 MW installed capacity, be connected to the same HV/MV

electrical substation. The regulatory framework offers NextGeneration EU co-financing for municipalities with fewer than 50,000 inhabitants, covering up to 40 % of the REC installation investment. Normally, this reduces the shared energy incentive, but RECs including local authorities, private individuals, or third-sector entities are exempt [383].

The Royal Decree 15/2018 introduced an important shift in the Spanish energy sector by promoting participation in self-consumption activities and simplifying procedures for RES installations [406]. This was followed by the Royal Decree 244/2019, which established the administrative, technical, and economic conditions governing electricity self-consumption [38]. Subsequently, Royal Decree-Law 23/2020 formally introduced RECs in line with the European framework [40]. Spanish regulation requires REC members to be located within a specified distance from the generation plant, extended to 2 km under the Royal Decree 20/2022 [154]. Within RECs, generated energy from RES-based plants is distributed among members employing allocation coefficients, which can either be fixed annually, based on each member's energy consumption, or vary on an hourly basis, defined in advance (*ex-ante*) the energy sharing consumption [407]. Allocation coefficients defined after the moment of consumption (*ex-post*) are not allowed according to the Spanish regulation. A simplified compensation mechanism ensures that the shared energy allocated and consumed by each member is deducted from their electricity bill. Any surplus energy fed into the PG is economically compensated by the Transmission System Operator [408]. However, compensation cannot exceed the total billed amount, ensuring that the net electricity bill remains non-negative.

State of art

The operation of a REC is significantly affected by both internal factors, such as the type of members involved and their energy assets, and external factors, including the regulatory framework governing energy sharing schemes and economic compensation mechanisms. Maximizing the associated benefits can be achieved by focusing on the optimal management of the community and its composition. Various optimization model, as reported in the literature, are employed to enhance the performance of RECs.

A bilevel optimization approach for REC management developed in [409] maximizes the shared energy as the objective function of the model and considers constraints related to minimizing members' individual costs. Di Somma, et al., [125] presents an innovative stochastic program model to optimize energy sharing in RECs in order to maximize revenues associated with incentives for shared energy as established by the Italian regulation. A multi-

objective optimization model for the allocation of energy from the community plant is associated with a combinatorial method for selecting participants to obtain high-performance configurations [410]. Optimization models applied to RECs present as their objective the management of energy flows, also in accordance with flexibility solutions, for the reduction of costs or environmental impact related to users' energy consumption [411].

The impact of the optimized management of the REC has direct consequences on members also depending on the economic benefit-sharing techniques, which can follow project specifications to pursue dedicated purposes, or be selected by the REC based on different logics that seek to reward users in proportion to their contribution. Minuto & Lanzini [155] evaluated sharing algorithm mechanisms to allocate the community net profit among members, based on the ownership of the plant, the contribution to self-consumption or both factors. Monchecchi, et al., [412] propose a cooperative solution to allocate the costs and profits of shared infrastructures to each member of the community, considering a similarity and a utilization factor. The use of a Nash bargaining problem to achieve a fair division of incentives between members of a REC, specifically a residential user and a biogas producer, indicates that a centralized sharing rule should always be assumed, to maintain the vitality of the configuration [413]. However, the proposed mechanisms involve complex systems that are challenging to implement in practice. Furthermore, the benefits that the community can obtain can be particularly influenced by the regulated charges of the country in which the configuration is located. The analysis of regulated tariffs for energy sharing in different European countries highlights how the economic advantages, which can have repercussions on reducing the cost of users' bills, depend both on the choice of dedicated fiscal support mechanisms and on the specific arrangement of the REC [414].

In order to maximize the benefits for the REC, and therefore for individual users, studies have been conducted in the literature to analyze the variation of numerous factors based on a specific reference regulatory context. For Italy, the impact of composition (cooperative, non-cooperative and traditional approach), electricity market prices, geographical location on the national territory, type of prosumer and consumer, and plant size were analyzed to maximize the economic indices of the community [252]. Economic assessments were also conducted for a public-driven REC with the same plant peak power, in different Italian cities, varying the number of consumers, along with investment and operating costs [415]. A multi-source biomass and PV plant-based REC in central Italy has been examined by varying the sizes of the systems and the configuration of the members involved [170]. In accordance with the Spanish regulatory

context on energy sharing, various approaches were compared, including static, variable and dynamic allocation coefficients, also providing for the inclusion of BESS [416]. Different capacities and ownership options for BESS were evaluated in REC scenarios, taking into account two types of allocation coefficients and varying the number of consumption points associated with the configuration [417]. The implementation of the REC, aimed at addressing energy poverty in a specific area of the Spanish capital, was instead based on the evaluation of different installation conditions of the PV plant [418]. However, the variations in the conditions considered for a REC do not compare the different sharing strategies proposed by various countries. Concerning this point, the studies present in the literature review focus on theoretical comparisons of the different sharing mechanisms and the major implications related to legislative frameworks, such as the most widespread legal forms, assessments of access to the PG, public subsidies, geographical proximity constraints and regulatory barriers [405]. The legal aspect and market conditions of some European and non-European countries have been analyzed in order to highlight the main differences and similarities [406].

The literature gap, therefore, concerns the applicability to case studies of the different mechanisms established by the regulatory conditions to carry out more detailed comparison evaluations. Only Barbaro & Napoli [419] compare energy sharing case studies, analyzing REC, self-consumers of renewable energy and individual self-consumption scenarios for Italy and RES-based incentivazed configuration for Spain. However, this study does not directly compare REC configurations or assess individual benefits, focusing only on aggregate community results also within an outdated regulatory framework. Thus, there is a need to provide a comparison of the results obtained for different frameworks. These should be carried out under systematic conditions and assessments, implementing the real and more current rules envisaged for the same energy sharing configuration implemented by the various regulatory contexts. This would allow to establish the real advantages achievable with the application of each mechanism, drawing conclusion, and identifying implications that offer the possibility of making systematic changes.

Aim of the study

The literature analysis reveals a gap mainly concerning the comparison between the specific application of sharing models provided by different regulatory frameworks and the assessment of the direct economic impact on individual members of the REC. This study presents a numerical evaluation based on the comparison of REC to which four different sharing schemes

are applied, starting from the model proposed by the Italian and Spanish normative contexts. In the latter case, different methodologies for evaluating allocation coefficients are considered, also based on previously published and validated models [420]. The economic remuneration is calculated based on the incentives scheme or electricity bill reduction, and is presented at both community and individual user levels. In order to highlight the strengths of these sharing models, mixed cases are also taken into account. In particular, the proposed study examines how the energy and economic benefits of REC vary according to the energy-sharing mechanisms, economic remuneration schemes, and the size of RES–based plants. It also analyses how these benefits differ among individual REC members from both energy and economic perspectives.

2.4.2 Methodology

The methodology proposed in this study is based on the analysis and comparison of REC layouts that consider different energy sharing models and economic remuneration schemes. As shown in *Figure 2.29*, the energy sharing within the REC occurs following the Italian virtual sharing model (a), static (b) or dynamic (c) allocation coefficients, based on the Spanish regulatory context. Even in scenarios where energy sharing is envisaged using allocation coefficients, the energy generated by the community's RES plant is not physically self-consumed by users, but the exchange takes place through the PG.

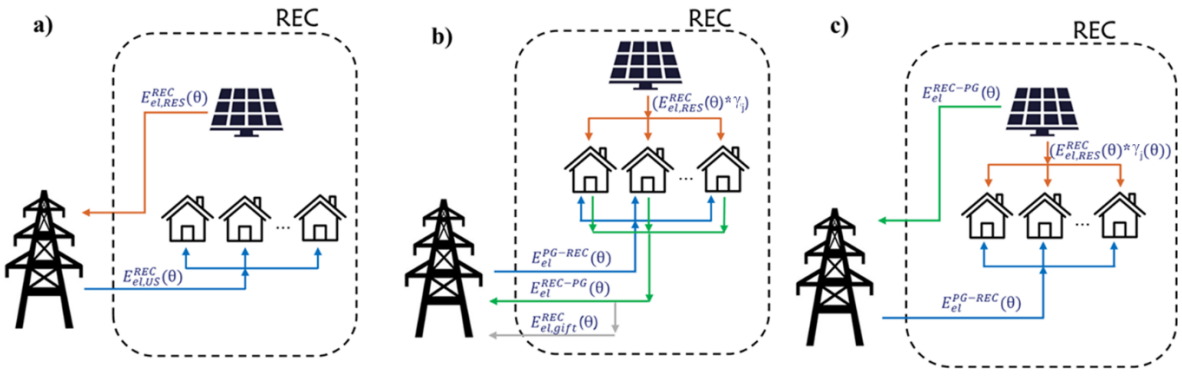

Figure 2.29 Energy sharing layouts: (a) Italian sharing model, (b) static allocation coefficients model, (c) dynamic allocation coefficients model.

The Italian virtual energy sharing model evaluates the hourly (θ) energy shared by the REC ($E^{REC}_{el,SH}(\theta)$) equal to the minimum between energy demand ($\sum_{j=1}^{J} E_{el,j}(\theta)$) of all members of the REC (J) and the energy generated and fed into the PG by community RES plants ($E^{REC}_{el,RES}(\theta)$), as reported in the Equation 2.23. According to the Italian economic remuneration

for RECs context, the shared energy is associated with the economic incentive, as explained in detail in next Section titled "*Economic remuneration scheme for RECs*".

$$E_{el,SH}^{REC}(\theta) = \min\left(\sum_{j=1}^{J} E_{el,j}^{REC}(\theta);\ E_{el,RES}^{REC}(\theta)\right) \qquad \forall\, \theta \in T \qquad (2.23)$$

In accordance with the Spanish legislative context the energy generated by the REC plant is allocated to each member ($E_{el,RES_j}^{REC}(\theta)$) through allocation coefficients (γ_j) which can be defined following different rules, Equation 2.24. The energy shared by the individual member ($E_{el,SH_j}^{REC}(\theta)$) is therefore rated as the minimum between the energy consumed ($E_{el,j}^{REC}(\theta)$) and allocated in the same time interval, Equation 2.25. Consequently the energy shared by the REC is the sum of the energy shared by all members, as reported in the Equation 2.26.

$$E_{el,RES_j}^{REC}(\theta) = E_{el,RES}^{REC}(\theta) * \gamma_j \qquad \forall\, \theta \in T,\ j \in J \qquad (2.24)$$

$$E_{el,SH_j}^{REC}(\theta) = min(E_{el,j}^{REC}(\theta); E_{el,RES_j}^{REC}(\theta)) \qquad \forall\, \theta \in T,\ j \in J \qquad (2.25)$$

$$E_{el,SH}^{REC}(\theta) = \sum_{j=1}^{J} E_{el,SH_j}^{REC}(\theta) \qquad \forall\, \theta \in T \qquad (2.26)$$

From an economic point of view, the Spanish regulatory framework establishes that the energy shared by a member of a REC does not count for the purposes of the electricity bill (*COST*), as further detailed below. In addition, the electricity bill cannot have a negative value, therefore, a part of the surplus energy transferred to the grid, because it is not shared, is considered given away ($E_{el,gift}^{REC}(\theta)$) as it cannot be associated with economic valorisation, as presented in Equation 2.27.

$$E_{el}^{REC-PG}(\theta) = E_{el,RES}^{REC}(\theta) - E_{el,SH}^{REC}(\theta) - E_{el,gift}^{REC}(\theta) \qquad \forall\, \theta \in T \qquad (2.27)$$

The allocation coefficients considered in this study are static, constant for an entire year for each member of the REC, or dynamic, hourly variable and ex-post defined, meaning they get defined after the moment of consumption. In the latter case, the energy allocated to each member for each hour coincides with energy consumption, Equation 2.28. The surplus of energy ($E_{el}^{REC-PG}(\theta)$) with respect to the overall consumption of the REC is assessed hour by hour through the surplus coefficients ($\gamma_{supr}(\theta)$), as shown in Equation 2.29. In this case, $E_{el,gift}^{REC}$ doesn't occur.

$$E_{el,RES_j}^{REC}(\theta) = E_{el,SH_j}^{REC}(\theta) = E_{el,RES}^{REC}(\theta) * \gamma_j(\theta) \qquad \forall\ \theta \in T,\ j \in J \qquad (2.28)$$

$$E_{el}^{REC-PG}(\theta) = E_{el,RES}^{REC}(\theta) * \gamma_{surp}(\theta) \qquad \forall\ \theta \in T \qquad (2.29)$$

The sum of the static allocation coefficients must always be equal to one, as shown in Equation 2.30. For dynamic allocation coefficients, their sum in addition to the surplus coefficient must be equal to one for each considered time interval, Equation 2.31.

$$\sum_{j=1}^{J} \gamma_j = 1 \qquad (2.30)$$

$$\sum_{j=1}^{J} \gamma_j(\theta) + \gamma_{surp}(\theta) = 1 \qquad \forall\ \theta \in T \qquad (2.31)$$

Economic remuneration scheme for RECs

In each considered layout, the economic value of the electricity bill was assessed in accordance with the Italian tariff system [421]. In particular, the evaluation of the *j*-th user's annual electricity bill ($COST_{j,Y}$) considered the following quota: a variable quota (c_{VAR1}) including all energy quotas for energy consumption, meter transport and management, PG management; a variable quota (c_{VAR2}) for consumption fees, not applied to the first 150 kWh/month of energy consumption, assuming not negative overall values; a fixed quota (c_{FIX1}) including all fixed fees for the bill items listed above and a fixed fee (c_{FIX2}) linked to the contracted power (P_{cont}) of each user. In addition, Value Added Tax (VAT) is applied to the total amount of the bill.

Equation 2.32 reports the mathematical formulation of the electricity bill, in accordance with the Italian framework, so considering the whole share of energy withdrawn from the PG by each member of the REC ($E_{el,j,Y}^{REC}$).

$$COST_{j,Y} = (c_{VAR1} * E_{el,j,Y}^{REC} + (\sum_{m=1}^{12} c_{VAR2} * (E_{el,j,m}^{REC} - 150)) + c_{FIX1} + c_{FIX2} * P_{cont,j}) * (1 + VAT) \qquad (2.32)$$

From an economic perspective, the economic remuneration scheme for a REC (according to the Italian framework) include the incentive tariff fed-in-premium (*TIP*) for the shared energy, consisting of a fixed share (f_{FIX}) depending on the plant size, a variable share (f_{VAR}) depending on the electricity market zone price (P_z) and a share allocated only in the case of PV systems depending on the geographical location (f_{GEO}) [383], Equation 2.33. For the shared energy, the incentive by the Italian Energy Regulatory Authority, ARERA, referred to as *AR*, equal to a

fixed yearly value, is also considered. The energy injected into the PG is reworded by GSE with a feed-in premium tariff, known as the "Dedicated Withdrawal" rate (*DWR*) [399]. The sum of these shares constitutes the income of the REC (I_{REC} (θ)), Equation 2.34.

$$TIP = f_{FIX} + f_{VAR}(P_z) + f_{GEO} \quad (2.33)$$

$$I_{REC}(\theta) = DWR\,(E^{REC}_{el,RES}(\theta)) + TIP\,(E^{REC}_{el,SH}(\theta)) + AR\,(E^{REC}_{el,SH}(\theta)) \quad \forall\, \theta \in T \quad (2.34)$$

As specified above, for scenarios with allocation coefficients sharing energy model, according to the Spanish regulatory framework only the difference between the energy demand and the shared energy of the member *j* ($E^{PG-REC}_{el,j}$), Equation 2.35, is accounted for *COST*, Equation 2.36. In this case $I_{REC,t}$ corresponds to the sum of the savings (I_j) of all members, Equation 2.37.

$$E^{PG-REC}_{el,j}(\theta) = E^{REC}_{el,j}(\theta) - E^{REC}_{el,SH_j}(\theta) \qquad \forall\, \theta \in T,\ j \in J \quad (2.35)$$

$$COST_{j,Y} = (c_{VAR1} * E^{PG-REC}_{el,j,Y} + (\sum_{m=1}^{12} c_{VAR2} * (E^{PG-REC}_{el,j,m} - 150)) + c_{FIX1} + P_{cont,j}) * (1+VAT) \quad (2.36)$$

$$I_{REC}(\theta) = \sum_{j=1}^{J} I_j(\theta) \qquad \forall\, \theta \in T \quad (2.37)$$

REC scenarios

Based on the energy sharing mechanisms and economic remuneration schemes presented, different scenarios were defined:

- S#1.1: REC virtual energy sharing model based on the Italian framework, Equation 2.23, and economic remuneration model whereby the incomes of the REC due to *TIP*, *AR* and *DWR*, Equation 2.34, are equally divided among the members, based on the economic allocation coefficients (σ_j) as defined in Equations 2.38 and 2.39. The annual operating cost of each member ($OC_{j,Y}$) accounts for the cost of the electricity bill calculated based on the user's overall energy demand reduced by the corresponding incentives, Equation 2.40;

$$\sigma_j = 1/J \qquad \forall\, j \in J \quad (2.38)$$

$$I_j(\theta) = I_{REC}(\theta) * \sigma_j \qquad \forall\, \theta \in T,\ j \in J \quad (2.39)$$

$$OC_{j,Y} = COST(E^{REC}_{el,j,Y}) - I_{j,Y} \qquad \forall\, j \in J \qquad (2.40)$$

- S#1.2: virtual energy sharing model, Equation 2.23; REC and users' economic remuneration schemes reflect S#1.1, Equations 2.34, 2.39 and 2.40. In this scenario, the REC's incomes from *TIP*, *AR* and *DWR* are divided among users in proportion to their respective yearly energy demand based on the coefficients defined in Equation 2.41;

$$\sigma_j = (E^{REC}_{el,j,Y} / \sum_{j=1}^{J} E^{REC}_{el,j,Y}) \qquad \forall\, j \in J \qquad (2.41)$$

- S#2.1: energy sharing model based on static allocation coefficients equal for each member, Equation 2.42. The economic remuneration model assumes that the incomes from *TIP* and *AR* are proportional to the energy shared by each user, while the revenues from *DWR* are proportional to the energy allocated to each user, Equation 2.43. Annual operating cost of each member considers the cost of the electricity bill calculated based on the user's overall energy demand, reduced by the corresponding incentives, according to Equation 2.40;

$$\gamma_j = 1/J \qquad \forall\, j \in J \qquad (2.42)$$

$$I_j(\theta) = DWR\,(E^{REC}_{el,RES_j}(\theta)) + TIP\,(E^{REC}_{el,SH_j})(\theta)) + AR\,(E^{REC}_{el,SH_j})(\theta)) \qquad \forall\, \theta \in T,\ j \in J \qquad (2.43)$$

- S#2.2: energy sharing model based on static allocation coefficients proportional to the yearly energy demand of each user, Equation 2.44. REC and users' economic remuneration schemes reflect S#2.1., Equations 2.40 and 2.43;

$$\gamma_j = (E^{REC}_{el,j,Y} / \sum_{j=1}^{J} E^{REC}_{el,j,Y}) \qquad \forall\, j \in J \qquad (2.44)$$

- S#3.1: energy sharing model based on static allocation coefficients equal for each member, Equation 2.42, economic remuneration scheme considers electricity bill reduction proportional to the shared energy by each user and the revenues due to *DWR*, evaluated on the surplus energy of each REC member, Equations 2.45 and 2.46;

$$I_j(\theta) = DWR(E_{el,j}^{REC-PG}(\theta)) \qquad \forall\ \theta \in T,\ j \in J \quad (2.45)$$

$$OC_{j,Y} = COST(E_{el,j,Y}^{REC}) - DWR(E_{el,gift_{j,Y}}^{REC}) - I_{j,Y} \qquad \forall\ j \in J \quad (2.46)$$

- S#3.2: energy sharing model based on static allocation coefficients proportional to the yearly energy demand of each user, Equation 2.44. REC and users' economic remuneration schemes reflect S#3.1., Equations 2.45 and 2.46;

- S#3.3: energy sharing model based on optimized static allocation coefficients evaluated through the optimization model presented in the study [420]. REC and users' economic remuneration schemes reflect S#3.1., Equations 2.45 and 2.46;

- S#3.4: energy sharing model based on optimized dynamic allocation coefficients ($\beta_j(\theta)$, $\beta_{surp}(\theta)$) evaluated through the optimization model presented in the study [420]. The energy analysis is based on the assumption of Equations 2.28 and 2.29. The users' economic remuneration scheme considers a reduction in the electricity bill proportional to the energy shared by each user. The revenues from *DWR*, evaluated on the surplus REC energy injected into the PG, is equally divided among REC members, Equation 2.47. The annual operating cost of each member ($OC_{j,Y}$) accounts for the cost of the electricity bill based on the $E_{el,j,Y}^{PG-REC}$ reduced by the corresponding incentives, Equation 2.48.

$$I_j(\theta) = DWR(E_{el}^{REC-PG}(\theta)) / J \qquad \forall\ \theta \in T,\ j \in J \quad (2.47)$$

$$OC_{j,Y} = COST(E_{el,j,Y}^{PG-REC}) - I_{j,Y} \qquad \forall\ j \in J \quad (2.48)$$

In each scenario, REC and users' economic remuneration are reduced by the management cost (*OPEX*) of the REC and RES-based plant. *Table 2.12* contains the main assumptions related to the sharing model adopted and the economic remuneration mechanism taken into consideration for each scenario.

Table 2.12 Main assumptions of REC scenarios.

Scenario	Energy sharing model and individual share of energy	Economic remuneration scheme
S#1.1	Virtual REC sharing model	*DWR, TIP, AR* equally divided among REC members
S#1.2	Virtual REC sharing model	*DWR, TIP, AR* divided among REC members proportionally to yearly energy demand
S#2.1	Static allocation coefficients equal for each REC member	*DWR* divided among REC members proportionally to allocation coefficients, *TIP* and *AR* proportional to the shared energy by each user
S#2.2	Static allocation coefficients proportional to the yearly energy demand of each REC member	*DWR* divided among REC members proportionally to allocation coefficients, *TIP* and *AR* proportional to the shared energy by each user
S#3.1	Static allocation coefficients equal for each REC member	*DWR* divided among REC members proportionally to allocation coefficients, electricity bill reduction proportional to the shared energy by each user
S#3.2	Static allocation coefficients proportional to the yearly energy demand of each REC member	*DWR* divided among REC members proportionally to allocation coefficients, electricity bill reduction proportional to the shared energy by each user
S#3.3	Optimized static allocation coefficients	*DWR* divided among REC members proportionally to allocation coefficients, electricity bill reduction proportional to the shared energy by each user
S#3.4	Dynamic allocation coefficients	*DWR* equally divided among REC members, electricity bill reduction

	proportional to the shared energy by each user

Economic performance indicators

The evaluation of the various scenarios presented was conducted in energy and economic terms, in order to evaluate the impact of the different energy sharing methods and the economic implications for the REC and individual members.

The economic feasibility of each scenario was assessed by considering economic indicators as Simple Pay Back (SPB), Discounted Pay Back (DPB), Net Present Value (NPV) and Internal Rate of Return (IRR) reported in Equations 2.50, 2.51, 2.52 and 2.53 respectively. SPB measures time to recover the investment's cost, while DPB also considers the time value of money. NPV evaluates profitability by cash flows, and IRR is the discount rate that makes NPV zero, indicating the investment's rate of return. REC cash flows (CF_{REC}) indicate the difference between the costs incurred in the case of no-REC and in the case of REC layout, Equation 2.49. In the first case, the sum of the electricity bills of all users is considered to meet their annual energy demand, while in the second, this is subtracted by the revenue due to the incentives of *TIP, AR, DWR* evaluated based on how expected for each scenario and the management costs of the REC ($OPEX_{REC}$) and the plant ($OPEX_{PV}$) are added. IC_{REC} represents the investment costs of the REC for the purchase of the plant. n is the year index, N is the useful lifetime and a is the interest rate. For n=0, the cash flow associated with IC_{REC} is considered.

$$CF_{REC} = \left(\sum_{j=1}^{J} COST_{j,Y}\right) - \left(\sum_{j=1}^{J} COST_{j,Y} - I_{REC,Y} + OPEX_{REC} + OPEX_{PV}\right) \quad (2.49)$$

$$SPB = \frac{IC_{REC}}{CF_{REC}} \quad (2.50)$$

$$DPB = N \Leftrightarrow \sum_{n=0}^{N} \frac{CF_{REC,n}}{(1+a)^n} = 0 \quad (2.51)$$

$$NPV = \sum_{n=0}^{N} \frac{CF_{REC,n}}{(1+a)^n} \quad (2.52)$$

$$IRR = a \Leftrightarrow NPV = 0 \quad (2.53)$$

2.4.3 Case study

The application of the presented methodology was carried out considering a REC whose members are ten residential users, located in the province of Benevento, Southern Italy. The real hourly electricity consumption for each of them was determined considering the data made available by the electricity distributor operator through the corresponding POD [395]. The main characteristics of the considered users are reported in *Table 2.13*. In addition to the annual energy consumption and contracted power data, information is also reported on the number of residents and the corresponding categories (worker (WR), no-worker (NW), retired (RT), student (SD), child (CD)). Additionally, the data includes details about electric heat pumps (EHP) systems for space heating and cooling, if applicable. *Figure 2.30* shows the hourly energy demand of the considered REC members for an entire year.

Table 2.13 Main characteristics of REC users.

User	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**
$E_{j,Y}^{dem}$ [kWh/year]	1976.92	3978.49	9991.23	2082.56	4397.63	3746.36	5197.01	1999.33	2061.67	4372.08
$P_{cont,j}$ [kW]	3	3	6	3	6	6	3	3	3	3
Residents	4 (2 RT, 2 WR)	3 (2 WR, 1 SD)	5 (2 WR 1 NW 2 SD)	3 (3 WR)	5 (4 WR, 1 CD)	2 (1 WR 1 NW)	4 (1WR 1 NW 2 SD)	3 (3 WR)	4 (2 RT 2 WR)	5 (4 WR 1 NW)
Energy conversion systems	-	1 EHP_{Cool}	1 $EHP_{Cool/Heat}$ 2 EHP_{Cool}	-	3 EHP_{Cool}	1 $EHP_{Cool/Heat}$ 1 EHP_{Cool}	3 EHP_{Cool}	-	-	-

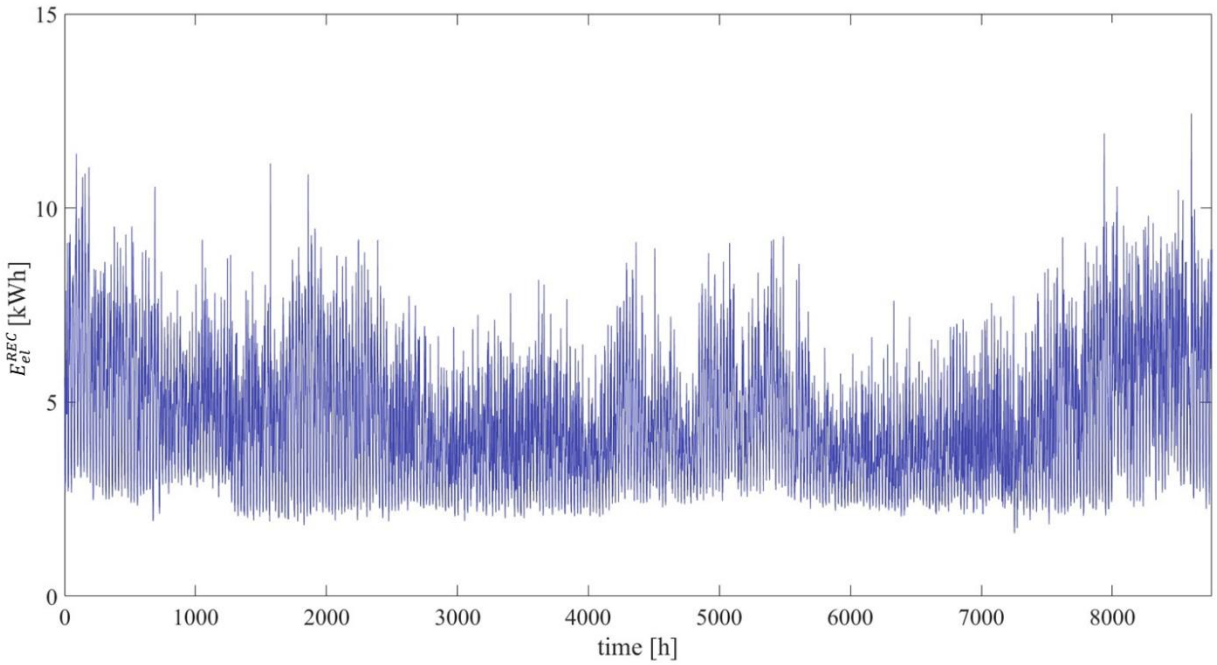

Figure 2.30 REC energy demand on an hourly basis.

For each REC scenario evaluated, a single community PV plant is included, with its producibility simulated for Benevento using PVGIS software [422]. The considered peak powers of the plant are 10 kW, 20 kW, 30 kW, 40 kW, and 50 kW. An inclination angle of 30° and an orientation angle of 0° were considered. For the solar radiation database, 2023 was considered, as the most recent year available. *Figure 2.31* presents the correlation analysis between the production from the PV plant and the energy consumption of the ten residential users. The correlation coefficient shown on the y-axis measures the linear dependence between these two variables. A positive value indicates the user's energy demand is concentrated more in the central hours of the day. Conversely, a negative value indicates the opposite trend. In particular, the annual hourly energy consumption of the users U9 and U10 has the highest positive correlation with the hourly production of the PV system. For the user U2, instead, the highest negative correlation is noted, indicating that as the producibility of the REC system increases, a decrease in the corresponding energy demand is observed.

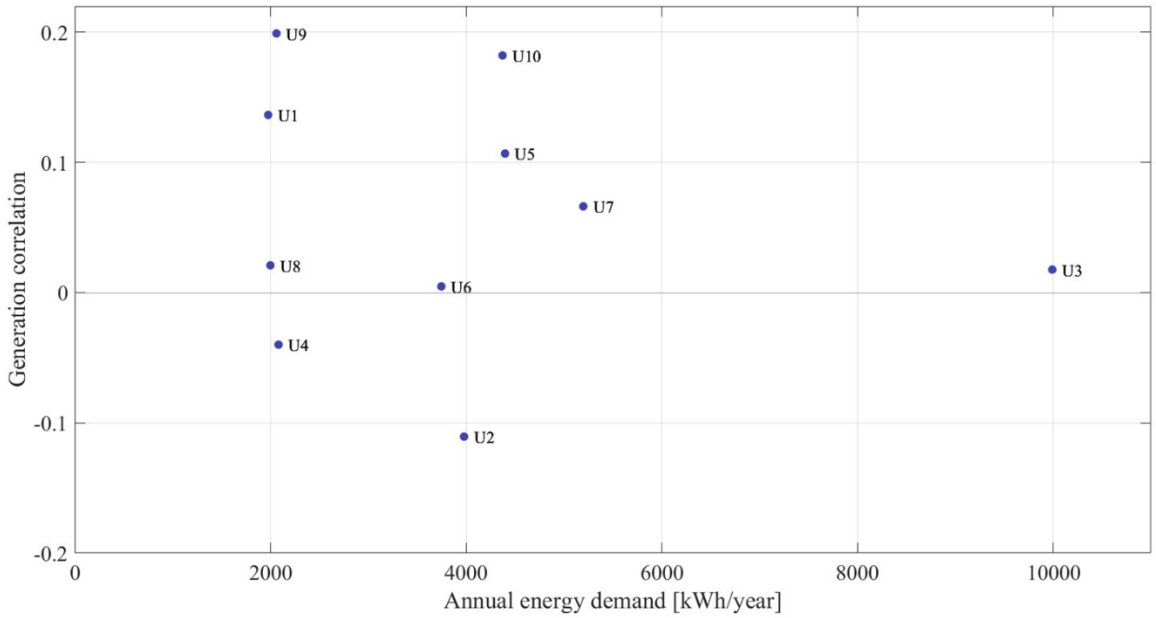

Figure 2.31 Correlation between PV generation and the energy demand of each user.

In accordance with current legislation, for scenarios in which the *TIP* incentive for shared energy is considered the variables reported in Equation 2.33 take on values dependent on the considered conditions for the case study. For calculating the electricity bill, as outlined in Equation 2.32, values that reflect the prevailing electricity market conditions were utilized. *Table 2.14* provides the numerical values assigned to each variable, along with the rationale behind their selection. Additionally, the necessary variable values for economic assessments are included.

Table 2.14 Specification of variables employed for the assessment of REC scenarios.

Variable	Value	Rationale
f_{FIX}	80 €/MWh	PV size less than 200 kW [383]
f_{VAR}	max (0; 180 – P_z)	PV size less than 200 kW [383]
P_z	hourly electricity market price for the considered area in 2024	The most recent available year has been considered [423]
f_{GEO}	0 €/MWh	Location in a Southern Italy region [383]
AR	10.57 €/MWh	Constant value established by ARERA for the considered year [424]
c_{VAR1}	0.205 €/kWh	Market conditions [425]
c_{VAR2}	0.0227 €/kWh	Market conditions [425]
c_{FIX1}	202.08 €/year	Market conditions [425]
c_{FIX2}	25.28 €/year	Market conditions [425]

VAT	10%	Value defined for domestic users, as foreseen by the regulatory context [426]
IC_{REC}	1500 €/kW for plant sizes up to 20 kW; 1200 €/kW for plant sizes from 20 to 50 kW	-
$OPEX_{REC}$	3% of IC_{REC}	-
$OPEX_{PV}$	12% TIP_{REC} for S#1.1	[427]
a	5%	-
N	20 years	-

The maximum hourly value for TIP is 120 €/MWh [383]. For the economic analysis, the replacement of the inverter considered at the tenth year is economically estimated to be equal to 8.5 % of IC_{REC}, depending on the size of the PV plant [428].

The energy and economic evaluation of the considered REC scenarios was carried out with dedicated codes developed in the Matlab environment [281]. The evaluation of allocation coefficients for scenarios S#3.3 and S#3.4 was conducted with Julia [429] code and Gurobi software, based on the study presented in [153,417,420], where the assessment of the electricity bill has been brought into line with what is reported in this study.

2.4.4 Results and discussion

This section presents the energy and economic results from the evaluations conducted. First, energy sharing outcomes are assessed, considering variations in the energy sharing mechanism and PV plant size. Then, economic results are presented for both individual members and the entire REC, addressing the research questions of the study.

Assessment of collective energy performance

Figure 2.32 illustrates the shared energy results across the analyzed scenarios on a monthly basis, in relation to the energy generated by the community plant with 10 kW peak power. Scenarios S#1.1 and S#1.2, which assess the energy shared by the REC according to the Italian context sharing model, present the highest values. These are exactly aligned with shared energy values calculated using the dynamic allocation coefficients proposed in scenario S#3.4. Indeed, among the different types of allocation coefficients, the latter allow for maximising energy sharing. In this case, the allocation of the energy generated to the members of the REC occurs optimally with respect to the energy consumption of the entire community.

For each month, the S#3.3 scenario, which is based on optimized static coefficients, shows generally lower values. These results closely align with the monthly shared energy values recorded for the S#2.2 and S#3.2, which take into account coefficients proportional to the annual energy consumption of each user. The smallest values are observed in scenarios where energy is allocated equally among all users, without accounting for individual consumption relative to the community. In this case, low-energy users are allocated an energy share that exceeds their consumption, while high-energy users are allocated a smaller share compared to their consumption. The benefits of the community are indeed not maximized following this sharing model.

For all scenarios, the highest shared energy values occur during the summer months, due to the greater production capabilities. Nevertheless, the highest self-consumption of renewable energy occurs during the winter months, particularly in January and December, when the community's energy consumption is mainly met by the energy provided.

As the size of the plant increases, the monthly self-consumption value of the REC shows a declining trend. Specifically, in the best-case scenario (S#1.1-S#1.2-S#3.4), the decrease is from 73 % to 19 % in July and from 98 % to 37 % in December, respectively for PV 10 kW and 50 kW, even though the total energy generated quadruples. In fact, the energy consumption of REC users limits the ability to achieve higher values of shared energy.

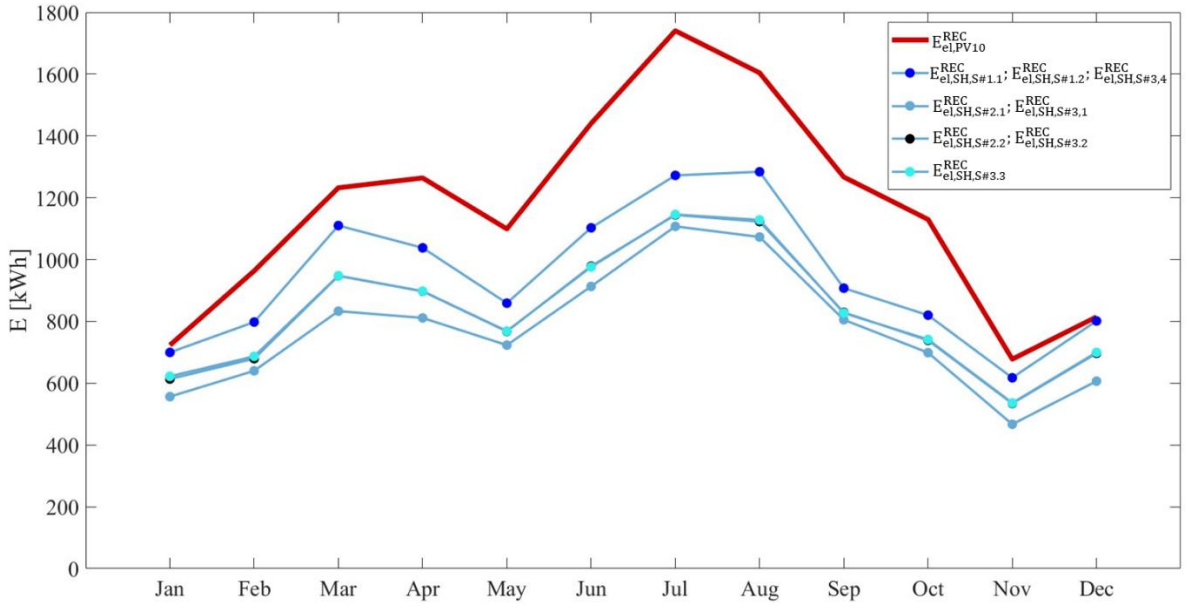

Figure 2.32 Shared energy in each scenario with respect to PV 10 kW generation.

The comparison of the annual shared energy values achieved across different scenarios as the size of the PV system varies, is presented in *Figure 2.33*. As shown, the difference in annual shared energy between the most and the least advantageous scenarios decreases as the system size increases. Specifically, this difference ranges from 18 % to 7 % from PV 10 kW to 50 kW.

Consistently, for the best scenarios, S#1.1, S#1.2 and S#3.4, as the plant size increases, the annual shared energy shows a progressively smaller increase: 28 %, 9 %, 5 % and 3 % respectively for PV 20 kW, 30 kW, 40 kW and 50 kW, compared to the corresponding previous size. This demonstrates the importance of appropriately sizing a system in relation to the energy consumption of the REC, in order to avoid oversizing, which offers limited benefits.

The choice of a specific technology, that generates energy only during the central hours of the day, is closely correlated with the shared energy results achieved. As shown in *Figure 2.31*, end-users present a different attitude to consume energy with respect the PV producibility. However, selecting a plant that can produce energy at various times throughout the day would enable higher shared energy values as the system's size increases. This consideration is particularly relevant for RECs that include residential users, as they typically experience peak energy demand during the evening hours.

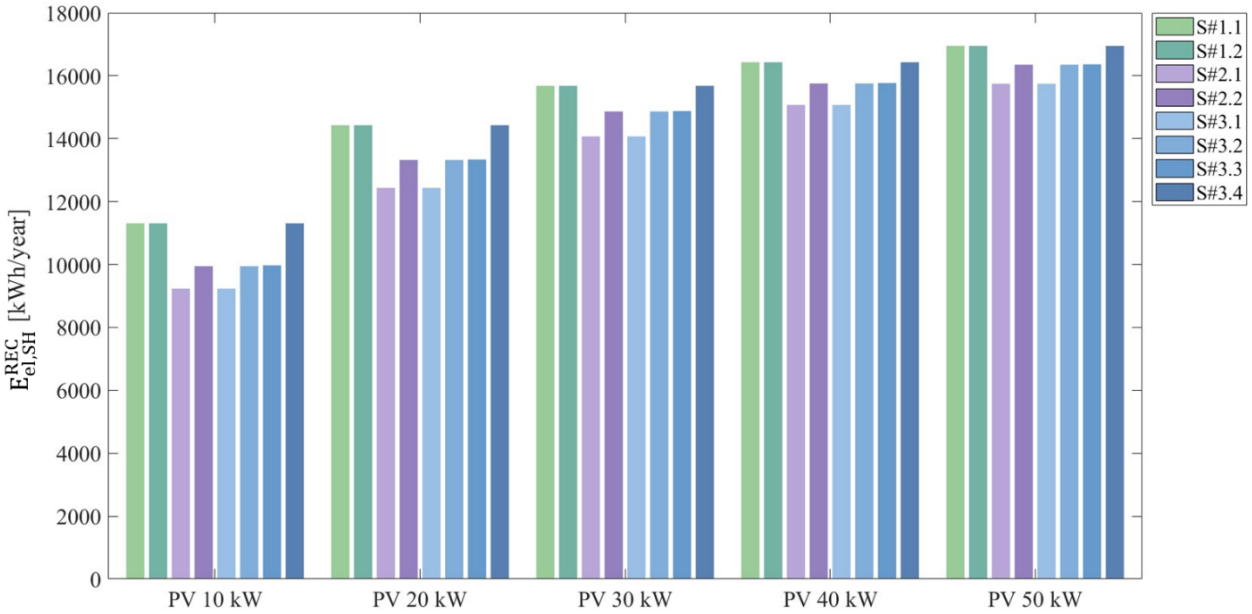

Figure 2.33 Annual shared energy in each scenario for each PV size.

Economic implications for individual REC members

The economic analysis of the scenarios under consideration provides valuable insights by linking the potential energy benefits to the technical and economic feasibility of the configuration.

Figure 2.34 illustrates the economic results for each user of the REC. Specifically, the circular marker represents the cost associated with meeting the user's energy demand without REC membership, relying solely on electricity withdrawn from the PG. The box plot instead depicts the variation in annual costs incurred by each user participating in the REC across different scenarios. As shown, membership in the REC results in economic benefits for all users, in the form of annual savings, regardless of the energy-sharing model or the economic remuneration scheme implemented.

The greatest variation in annual user cost is observed for the most energy-intensive users, particularly U3, who receive more substantial advantages than others, especially in scenarios that consider energy and economic allocations based on each user's demand. For less energy-intensive users, such as U1 and U8, even if they are particularly favoured in scenarios that distribute the REC revenues equally among members, their variation remains smaller because the energy demand (and the respective *COST*) is lower.

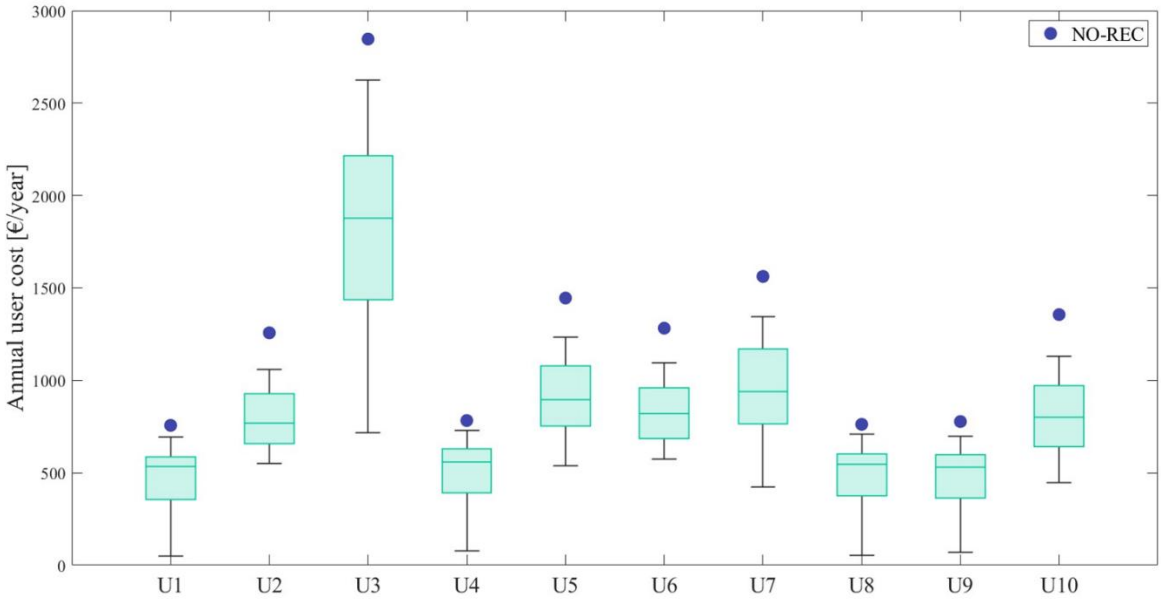

Figure 2.34 Annual cost variation of each user with respect to different scenarios.

Table 2.15 presents, for each user, the best scenario, associated with the lowest annual costs, and the worst scenario, associated with the highest annual costs. As highlighted, for less energy-

intensive users, the best scenario is S#1.1. Conversely, this scenario represents the worst for more energy-intensive users, such as U3.

The outcomes also highlight that for users with similar annual energy demand (*Figure 2.31*), the same best/worst scenarios apply: U1-U4-U8-U9, U2-U6, U5-U7.

It is important to note that for scenarios S#3.1, S#3.2 and S#3.3, identified as more favourable for certain users, the economic redistribution scheme provides a direct reduction in the electricity bill for each user, in addition to the redistribution of the *DWR* resulting from energy fed into the PG. However, not all shared energy leads to an economic benefit, as the electricity bill cannot be negative, meaning that part of the energy is effectively "gifted" to the PG. Nevertheless, the minimum value of the electricity bill never reaches zero, as the operational costs of the REC and the PV system are additionally taken into account.

As shown by the results, in scenarios where all users incur lower costs, the plant size considered is equal to 50 kW. Although this size results in lower self-consumption coefficients compared to other configurations, the high energy produced and fed into the PG, and consequently remunerated through the *DWR*, provides a significant benefit to all users. In contrast, for the worst-case scenario, the system size is consistently 10 kW.

Table 2.15 Worst and best scenarios with respect to annual cost for each REC user.

User	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**
Best scenario / PV power	S#1.1 50 kW	S#3.1 50 kW	S#3.2 50 kW	S#1.1 50 kW	S#3.3 50 kW	S#3.1 50 kW	S#3.3 50 kW	S#1.1 50 kW	S#1.1 50 kW	S#3.3 50 kW
Worst scenario / PV power	S#3.4 10 kW	S#3.3 10 kW	S#1.1 10 kW	S#3.4 10 kW	S#2.1 10 kW	S#3.3 10 kW	S#2.1 10 kW	S#3.4 10 kW	S#3.4 10 kW	S#1.1 10 kW

The variation in annual savings for each REC user as the size of the PV system varies, shown in *Figure 2.35*, indicates that larger system size results in higher savings for all users, a trend consistent across all considered scenarios, even if it implies increased investment costs.

Remuneration mechanisms that incorporate direct reductions in the electricity bill deliver superior average annual savings to users compared to those relying on TIP and AR incentives. As seen in the comparative results between scenarios S#2.1-S#3.1 and S#2.2-S#3.2, which

maintain consistent shared energy and sharing mechanisms, while varying the economic remuneration models.

Optimized static allocation coefficients (S#3.3) yield similar average benefits for users compared to S#3.2 even if the shared energy is the same, but they introduce a wider variation in outcomes. Crucially, these optimized coefficients lead to greater savings for users who exhibit a positive correlation between energy consumption and PV energy generation (U1, U5, U7, U9, U10).

Finally, for the same system size, the average savings in S#3.4 are higher than in any other scenario. S#3.4 also exhibits a more homogeneous distribution of benefits, even as the PV size varies, compared to the other scenarios.

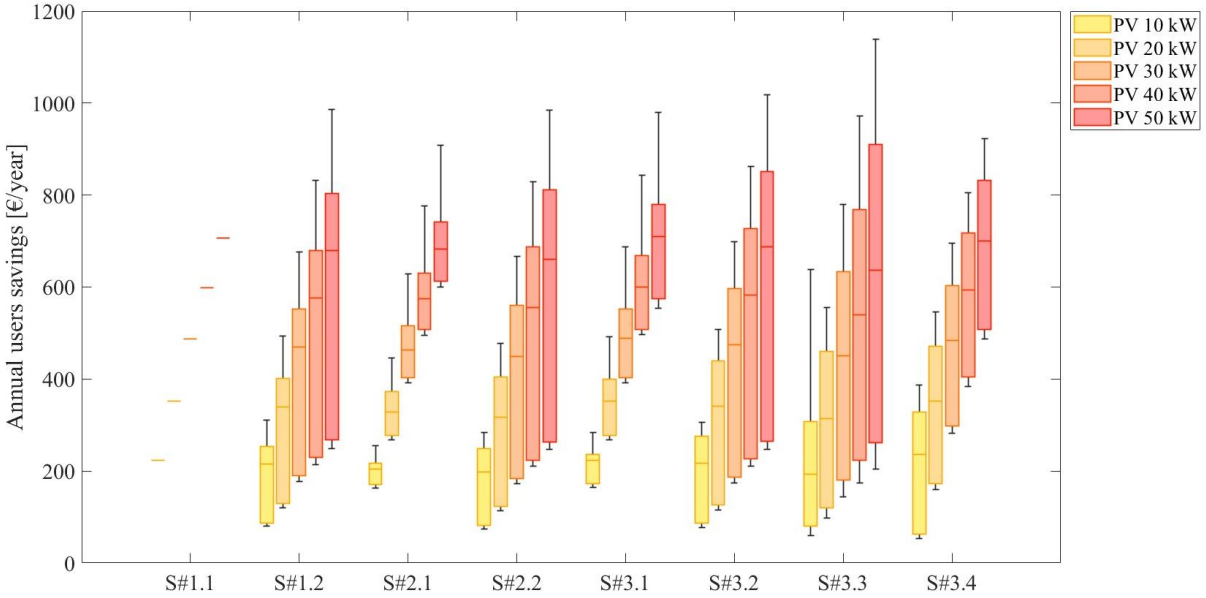

Figure 2.35 Annual users savings variation for each scenario.

Overall economic outcomes of the REC

The economic analysis of the several scenarios provides an overview of how the different energy sharing and economic distribution models among members contribute to the overall economic sustainability of the REC project. In this regard, as shown in *Figure 2.36*, for the same plant size, scenario S#3.4 presents the best economic indicators. Furthermore, scenarios S#1.1 and S#1.2, show increasingly similar NPV and IRR values to S#3.2 and S#3.3, as the community plant size decreases. For these latter scenarios, more favourable cash flows resulting from the direct reduction in the electricity bill for users, affect the difference in NPV as the PV size increases.

The impact of the different IC_{REC} is particularly noticeable when moving from PV 20 kW to 30 kW, as the same unitary cost is applied for the first two sizes and for the remaining three. As a consequence, the highest values of SPB and DPB are achieved for PV 20 kW, which represents the case with the highest investment costs compared to annual cash flows.

Scenario S#2.1 presents the worst results of the economic indices for all plant sizes considered. These findings highlight the allocation of energy and the sharing of economic benefits equally among users, which minimizes the benefits achievable throughout the configuration. Although the less energy-intensive members in this case can reduce the relative energy costs to a minimum, an unfair distribution of economic benefits disadvantages other users and undermines the overall cohesion of the community.

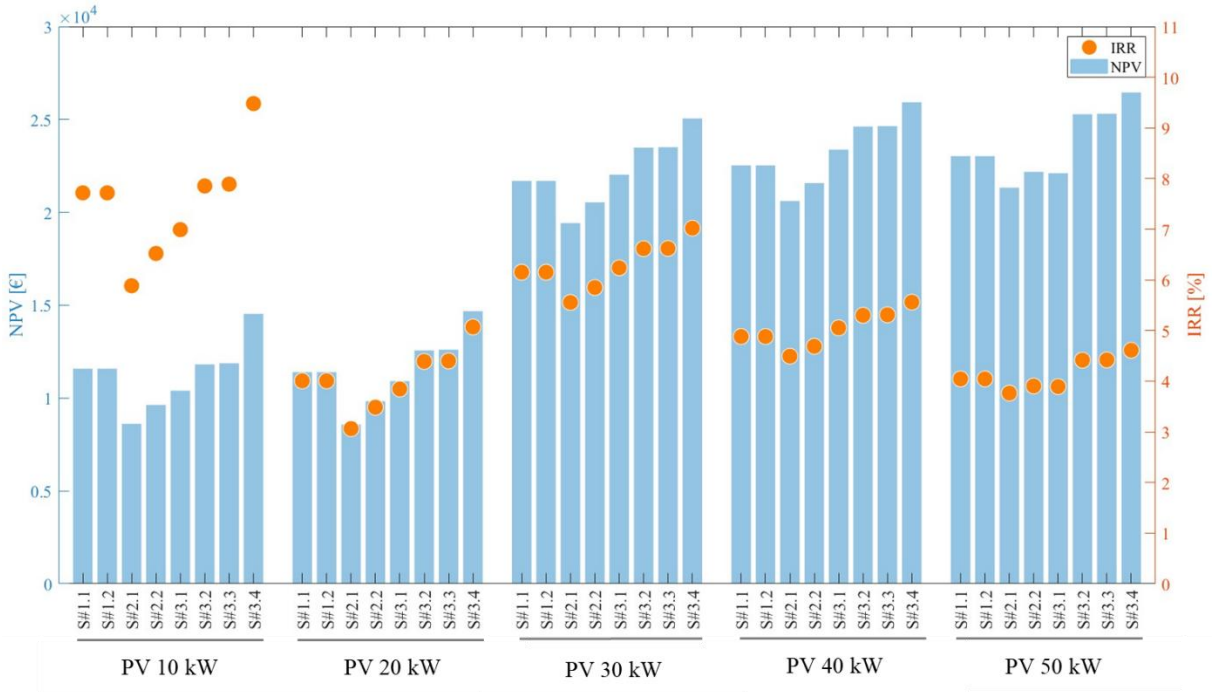

Figure 2.36 Economic assessments for each scenario and PV size.

The results also indicate that, although economic savings for all REC users increase as the system size grows, primarily due to the surplus energy generated and fed into the PG, oversizing the system negatively impacts economic returns.

Increasing the system size is economically advantageous only if the energy sharing increases with a trend comparable to the increase in generated energy. For the REC considered in this study, in fact, a smaller system proves to be more beneficial, offering a quicker return on investment and higher profitability. Specifically, the highest IRR values occurs with PV 10 kW, while NPV has no significant increase going from 30 to 50 kW.

It is crucial to highlight that the results are significantly influenced by the market prices used in the analysis. When the same evaluations are performed using the market prices of Spain for the same year, positive IRR and NPV values are only achieved for the PV size equal to 10 kW, and in any case, significantly lower than those reported in this analysis. In this context, it is essential to note that grid tariffs play a pivotal role, and their increasing significance in the future makes it crucial to correctly collocate generation and consumption, also through the adoption of new energy models.

To highlight the key aspects of the different economic schemes applied to RECs, whether based on economic incentives or direct electricity bill reduction, *Table 2.16* outlines the major strengths and weaknesses of these schemes, emphasizing the outcomes of this study and offering insights for policy implications.

Table 2.16 Strengths and weaknesses of different economic remuneration schemes for RECs.

Economic remuneration scheme for RECs	**Strengths**	**Weakness**
Economic incentive	- greater benefits for less energy-intensive users; - greater benefits for large-sized RES plants.	- minor benefits for most energy-intensive users; - users only recognize the economic savings after some time.
Direct electricity bill reduction	- higher average annual savings for end-users; - greater benefits for most energy-intensive users; - greater benefits for small-sized RES plants; - users perceive direct savings.	- minor benefits for less energy-intensive users.

Although the analyzed case study provides relevant insights into economic mechanisms and energy-sharing models within RECs, it presents several limitations related to the underlying assumptions. In particular, the conducted analysis considers only residential users within the REC. While the assumptions adopted for evaluating electricity bills are based on realistic conditions, variations may arise in contexts where users face different initial conditions, especially in energy systems outside the Italian framework, potentially leading to different results. For instance, some users may benefit from subsidized tariffs linked to specific socioeconomic conditions, or the REC may include prosumers owning RES installations. In

such cases, the impacts on both energy sharing and economic benefits could differ significantly, particularly when the user-owned RES technology coincides with that of the community plant.

To enhance the generalizability of the results, future developments of the model could incorporate additional RES technologies and a broader range of user types within the REC. Similarly, extending the analysis to include tariff structures from other countries would further strengthen the scope and robustness of the investigation.

Nevertheless, the current state of the study enables the derivation of relevant considerations with implications for REC-related policy. The findings suggest that the effective deployment of RECs depends on the design of appropriate energy-sharing models and economic remuneration schemes capable of supporting the energy transition while delivering additional co-benefits. In this regard, the study highlights the importance of maximizing these benefits through mechanisms that account for the total community demand, a principle already embedded in the Italian framework and potentially extendable to other contexts, such as Spain, through ex-post dynamic allocation coefficients. From an economic viewpoint, despite the limitations associated with the case study and the Italian electricity market conditions, the results indicate that direct bill-reduction mechanisms tend to provide greater average benefits at the individual level. In light of forthcoming European regulatory developments, the Italian incentive-based scheme could therefore be revised to incorporate direct reductions in electricity bills for shared energy, aligning more closely with approaches anticipated in Spanish regulatory contexts.

Chapter III: Towards the development of Positive Energy Districts

Urban areas are large contributors to energy consumption and GHG emissions, thereby having a major impact on climate change [430]. Along with the transport sector, the building sector is recognized to be one of the key responsible for cities' CO_2 emissions, which account for 75 % of total CO_2 emissions at a global level [431]. Hence, the sustainability of cities is called to be enhanced to tackle climate change and achieve carbon neutrality by 2050 [15,230].

The European Commission launched the EU Strategy on adaptation to climate change in 2013 [432], which was then updated in 2021 [433]. The main goal is to support the development of mitigation and adaption measures at the regional or local level for gradually increasing the resilience to climate change of all Europe. Cities are especially encouraged to sign up the Covenant of Mayors for Climate and Energy. The vision of signatory authorities is to promote the decarbonization of cities and to increase their resilience, providing sustainable, affordable, and secure energy to citizens. Among others, their main commitments concern the use of the Baseline Emission Inventory (BEI) as a common methodological approach for measuring GHG emissions in the baseline year and the development of the Sustainable Energy and Climate Action Plan (SECAP) to define the comprehensive set of measures to be under taken to achieve the goals set by 2030 [434]. In this context, groups of buildings offer interesting opportunities for speeding the decarbonization of urban areas [435].

The European regulatory framework has emphasized district and community-based approaches to achieve the "zero-energy" goal, and even the more ambitious "positive energy" target. Within this context, Positive Energy Districts (PEDs) can represent a natural evolution of RECs, characterized by an expanded operational and governance paradigm. This evolution entails a shift from relatively constrained, geographically bounded configurations to more flexible, scalable spatial frameworks. PEDs adopt a

multi-sectoral perspective, integrating electricity, thermal and mobility demands into a unified energy system. Such sector coupling enhances overall system efficiency and enables more effective optimization of local resources, demand-side flexibility, and infrastructure utilization. By broadening both the scope and the functional objectives of energy communities, PEDs aim not only to balance local energy consumption with renewable generation, but to consistently achieve a net-positive energy balance. This transition significantly amplifies the potential benefits, including increased self-sufficiency, improved economic performance, reduced greenhouse gas emissions, and enhanced resilience of local energy systems. Furthermore, PEDs facilitate structured interactions with external actors and neighbouring energy systems, thereby extending the concept of energy sharing beyond internal community boundaries. This outward-oriented approach supports multi-actor, multi-level collaboration, fostering integrated energy ecosystems better aligned with large-scale decarbonization goals. In this sense, PEDs represent a critical step toward a more systemic and cooperative model of the energy transition, capable of delivering climate neutrality at the district level and beyond.

PEDs have been defined as: "*mixed-use energy-efficient districts that have net zero CO_2 emissions and actively manage an annual local surplus production of renewable energy. They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations*" [27]. Lindholm et al. [436] categorized PEDs into three types: autonomous, dynamic or virtual, based on system boundaries and import/export conditions. In particular:

- PED autonomous: a district defined by well-identified geographical boundaries that operates in full energy autonomy, whereby its entire energy demand is met through locally produced renewable energy. Consequently, the district does not rely on energy imports from the external electricity grid or from district heating or gas networks. However, the export of surplus renewable energy is permitted;
- PED dynamic: A district characterised by clearly defined geographical boundaries in which annual on-site renewable energy generation exceeds the annual energy demand. The district is allowed to actively interact with other PEDs, as well as with the external electricity grid and district heating or gas networks;

- PED virtual: a district that permits the deployment of virtual renewable energy systems and energy storage assets located outside its geographical boundaries. The aggregated annual energy generation from both virtual and on-site renewable energy systems must exceed the district's annual energy demand.

Since the scope of scientific research is broadening from the building towards a wider scale, new methods and metrics are required [437]. The framework available strives to encompass all key pillars of sustainability through the evaluation of multiple key performance indicators [438]. Available tools mainly focus on strategies for renovating the existing building stock and mapping existing initiatives, especially at the European level [439,440]. At the city level, many methods exist for developing GHG inventories [441]. The methods adopted for building-oriented analysis are frequently transposed at the district level [442,443]. In this context, this chapter first introduces a novel approach to the environmental analysis of communities and districts and second presents the application of the proposed mathematical model, implemented within a developed tool that addresses the detailed plant configuration of the district.

Given that the existing scientific literature on PEDs still lacks a standardized methodology capable of comprehensively accounting for all energy carriers while balancing accuracy and ease of implementation, this chapter proposes a novel approach for the environmental assessment of energy districts. The methodology is designed to bridge the gap between theoretical robustness and real-world application and is supported by a ready-to-use, user-friendly tool, thereby facilitating its adoption and contributing to the broader deployment and evaluation of PEDs in practical contexts.

3.1 A novel methodology for supporting the transition of districts and communities in PEDs

The methodology proposed in this section is based on a detailed mathematical model that proposes to accurately determine energy and environmental balances related to every kind of user aggregation (i.e., RECs, PEDs, etc.). Compared to existing methods, it strives to move beyond a purly mathematical approach and also to verify the achievement of the goals of PEDs. In particular, it seeks to encompass all energy vectors adopted in districts.

Besides, it is intended to include the energy demand of residential, tertiary, commercial buildings, in addition to industrial facilities and other activity sectors relevant to the energy demand of the district or community being analysed. As shown in *Figure 3.1*, the proposed approach focuses on thermal, cooling, and electric energy demand and supply during the operation phase of the district. The implementation of energy efficiency measures addressed to reduce the energy demand of the district under investigation, such as the energy renovation of building envelope, is left out of the proposed framework. Energy and emission balances are determined on an annual basis, according to the definition of PEDs [27]. In the case of existent districts, actual input data collected from bills, surveys, smart meters, etc., can be used. In the case of new districts, estimated data should be adopted. Similar considerations apply to the producibility of plants. Since yearly balances are evaluated, annual data regarding energy demand and supply should be provided as input. Aggregated data can be regarded as the sum of data available on a shorter timestep. In this way, significant factors affecting the energy balance of the district (e.g., the simultaneity of energy demand and supply from renewable-based plants) may be considered for more accurately determining the share of energy self-consumption, surplus, and deficit production. The proposed methodology also allows to encompass the life-cycle perspective if life-cycle based emission factors are adopted. The methodology developed in this study is built on the BEI and therefore refers to comprehensive guidelines developed by EU institutions [444].

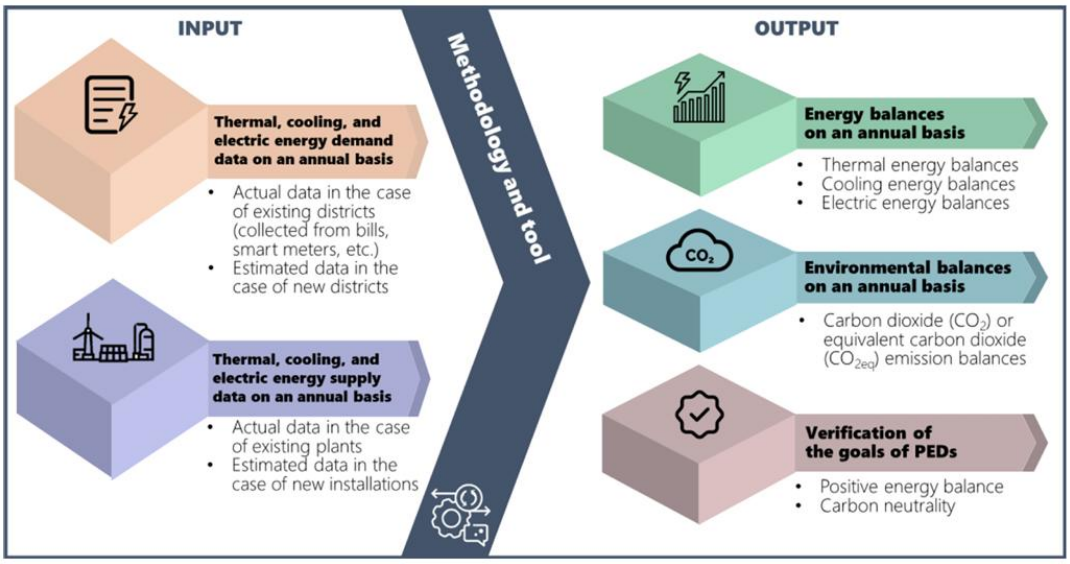

Figure 3.1 Overview of the proposed methodology.

3.1.1 District-level emission inventories

As defined by Bertoldi et al., the BEI "*quantifies the amount of CO_2 emitted in the key sectors and other activity sectors in the territory of the Covenant signatory for the baseline year*" [434]. Its main purpose is to identify the most relevant anthropogenic sources of GHGs for prioritizing the reduction measures defined within the SECAP accordingly [444]. The BEI accounts for the GHG emissions due to energy consumption in four key macro-sectors: building, transport, non-energy related and energy supply [445]. Emission sources covered by the EU Emissions Trading System are not considered [446]. The activity sectors considered in each macro-sector are:

- Building: municipal buildings, equipment/facilities; tertiary buildings, equipment/facilities; residential buildings; public lighting;
- Transport: municipal fleet; public transport; private and commercial transport;
- Energy supply: local production of electricity; local production of thermal and cooling energy;
- Non-energy related: waste management; wastewater management.

Beyond those listed, the agriculture, forestry, and fisheries sectors may be encompassed whenever proper mitigation measures in the SECAP have been defined. The same applies to non-energy related activities concerning waste disposal and wastewater management when not intended for energy supply. In the latter case, their emissions should be accounted with those pertaining to energy supply. Within the energy supply macro-sector, all GHG emissions due to local thermal, cooling, and electric energy supply are quantified. Both fossil and renewable-based generation units, inside or outside the boundaries of the local authority, are considered. In the case of renewable-based electric energy production plants, the total electric energy supply must be reduced by the amount of energy which meets the criteria for guarantee of origin [447] and is sold outside the boundaries of the local authority as certified green energy.

In the frame of the BEI, both direct and indirect GHG emissions can be determined using the emission factor associated with the energy carrier adopted [445]. The BEI suggests the monitoring of three main GHGs, namely CO_2 , methane (CH_4), and nitrous oxide (N_2O). The approach chosen can be activity or life cycle-based. On the one hand,

activity-based emission factors (EFs) quantify direct emissions due to the combustion of fuels. On the other, they account for indirect emissions due to electric, thermal, and cooling energy supply through the PG, DHNs, and district cooling networks (DCNs), respectively. The activity-based approach is in line with the Intergovernmental Panel on Climate Change (IPCC), and it is therefore adopted in national GHG inventories included in the framework of the United Nations Framework Convention on Climate Change and Kyoto Protocol [448]. Moreover, it fits the European regulatory framework on climate and energy [449]. Conversely, EFs based on LCA quantify the emissions released during the whole life of energy carriers. Emissions are usually reported using the universal unit of measurement accounting for the global warming potential (GWP) of various gases, known as CO_{2eq} , which is not the same as in the case of CO_2.

The calculation methodology proposed for assessing the achievement of the targets of PEDs, that is, a positive energy balance and carbon neutrality on an annual basis, is introduced in next section.

Overview about energy flows in districts

The conditions defined in the BEI still apply in the proposed methodology. Indeed, the emissions of other activity sectors than buildings, such as industries, agriculture, forestry, and fisheries, may be encompassed whenever relevant to the energy consumption of the district being analysed. As regards the evaluation of the emissions of the transport sector, the use of average data regarding fuel consumption at national level has already been proven to be affected by spatial bias. The latter could be reduced by using local data, as suggested by the guidelines referring to the development of the BEI [450]. For the purposes of BEI, the bottom-up territorial approach was suggested to be adopted. Yet, local data sources, municipal transport departments or even national authorities for road management might seldom provide information about the traffic flows in district street networks. The use of the top-down fuel sale method, instead, was discouraged even in the frame of the BEI. Indeed, the information related to the sale of fuels is deemed to be very basic at local level. Similar considerations apply to the resident activity method, that is, the second bottom-up approach proposed for the BEI. The latter considers all trips of people living within the borders of the territory being analysed, which could turn out to deliver misleading results if used for focusing on little neighbourhoods. Hence, since the

allocation of GHG emissions related to the transport sector is very difficult to realize within the limited boundaries of districts, it has been neglected in this first methodology proposal.

For the estimation of district annual energy and CO_2 (or CO_{2eq}) emissions balances related to thermal, cooling, and electric energy supply and demand, the same procedure as the BEI is adopted. Indeed, EFs are multiplied by activity data, which can be estimated distinguishing between the different energy carriers provided to users. *Figure 3.2* shows a simplified diagram describing the energy flows involved in common districts characterized by electric (E_{el}), thermal (E_{th}) and cooling (E_{co}) energy requests.

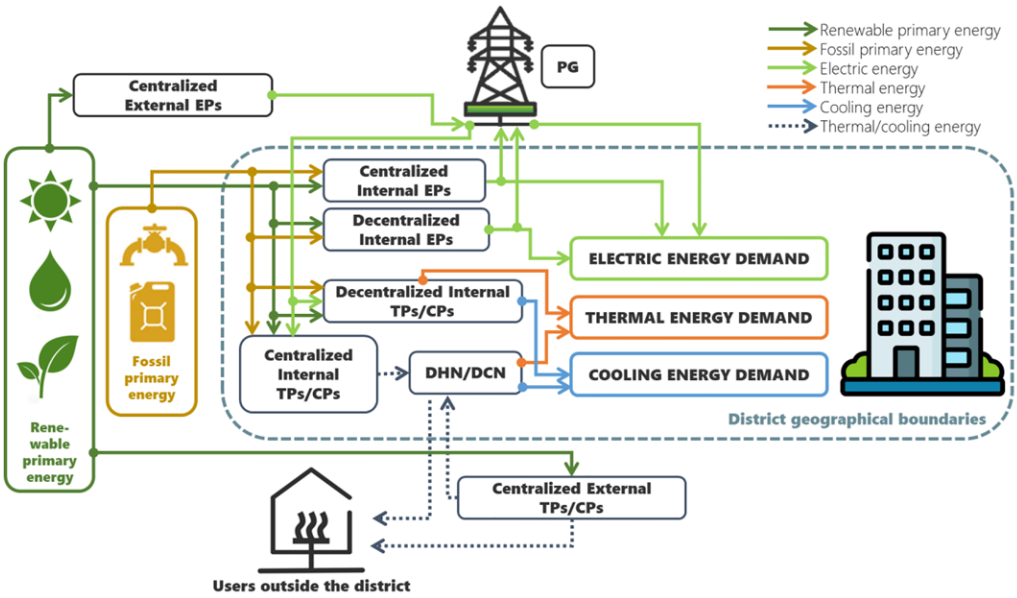

Figure 3.2 Example layout of energy flows involved in a generic district.

Centralized or decentralized plants can be installed to cover users' energy needs. The production plants can convert the primary energy (E_p) supplied by renewables or fossil fuels (FFs), as well as electric energy in the case of plants supplying thermal/cooling energy. According to the definition of virtual PEDs given by Lindholm et al. [436], electric (EP), thermal (TP) and cooling (CP) energy production plants exploiting renewables can be located even outside of the geographical boundaries of the district. Conversely, the energy supplied by centralized and decentralized renewable-based plants located within the boundaries of the district and exceeding the demand of users can be exported outside of the geographical boundaries of the district. In *Figure 3.2*, energy exports are shown by the arrows starting from the blocks representing internal energy

production plants as well as DHN/DCNs and crossing the dotted box representing the geographical boundaries of the district. Electricity surplus, for instance, can be injected into the PG. In turn, electricity can be taken from the PG in the case of deficit production from renewable-based plants. Hereinafter, the superscripts Int_{Cen} and Ext_{Cen} are used to identify all centralized energy production plants serving the district and located inside and outside of its boundaries, respectively. The superscript Int_{Dec} is instead reserved to decentralized energy conversion systems installed in the district and owned by single users. This generalised categorization allows the proposed methodology to involve all kind of TPs, CPs and EPs. Boilers, every type of heat pumps (such as absorption, ground-source, gas engine-driven, electric-driven, etc.) and all other kinds of fossil and renewable-based plants for thermal, cooling and electric energy supply plants can be encompassed, including plants for the combined production of heat and power and polygeneration (combined cooling, heating and power) plants. Short-term or seasonal energy storages may be included too, along with P2X technologies.

Energy and emissions balances related to thermal and cooling energy demand and supply

Figure 3.3 shows an example of the thermal and cooling energy flows that can be involved in a generic district. Thermal energy can be supplied by decentralized TPs owned by single users, or instead by centralized TPs activating DHNs. The total thermal energy delivered to the DHN includes thermal energy imports from external TPs supplied by RES. Conversely, it neglects the share of thermal energy supplied by renewable-based TPs and exported outside the district. To evaluate the final amount of thermal energy supplied to the users on an annual basis, the losses within the DHNs may be considered too. The latter also include the losses due to thermal energy storage tanks. For evaluating the CO_2 (or CO_{2eq}) emissions associated with the activation of TPs, a distinction is needed between electric-driven TPs and TPs converting the primary energy supplied by FFs or RESs. In the latter case, emissions can be evaluated by multiplying the primary energy demand of the plant by the EF of the FF used or the RES exploited. On the contrary, in the case of an electric-driven TP, the activity data to consider for evaluating corresponding indirect emissions is the electric energy input to the energy conversion system. Similar considerations apply to cooling energy flows and related energy and emissions balances.

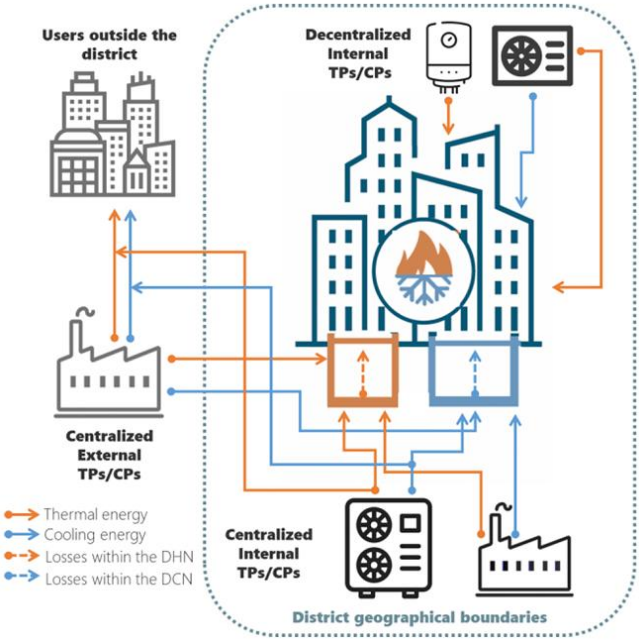

Figure 3.3 Example layout of thermal and cooling energy flows involved in a generic district.

The annual thermal energy demand of the users in the district (E_{th}^{Dis}) can be evaluated according to Equation 3.1.

$$E_{th}^{Dis} = E_{th}^{DHN^{US}} + \sum_{i=1}^{NTP^{Int_{Dec}}} E_{th_i}^{TP^{Int_{Dec}}} \quad (3.1)$$

$E_{th}^{DHN^{US}}$ is the yearly thermal energy delivered to the users (US) by the DHN, whereas $E_{th_i}^{TP^{Int_{Dec}}}$ is the yearly thermal energy supplied to the users by decentralized thermal energy production plants (TPs). The sum is calculated from 1 to $NTP^{Int_{Dec}}$, which is the total number of decentralized TPs within the district. $E_{th}^{DHN^{US}}$ results from Equation 3.2, where $E_{th,net}^{DHN}$ represents the total net thermal energy available from the DHN on a yearly basis and $E_{th,exp}^{DHN}$ the annual thermal energy exported outside of the district. In turn, $E_{th,net}^{DHN}$ equals the difference between the gross thermal energy delivered to the DHN ($E_{th,gross}^{DHN}$) and the losses occurring within the DHN ($E_{th,loss}^{DHN}$), as stated in Equation 3.3. The latter account for all types of losses, including those related to thermal energy storage tanks. $E_{th,gross}^{DHN}$ accounts for the sum of the yearly thermal energy supplied by external RES-based TPs and imported in the district ($E_{th,imp}^{DHN}$) and the annual thermal energy

supplied by the centralized internal TPs ($E_{th}^{TP^{Int_{Dec}}}$), whose total number is referred to as $NTP^{Int_{Cen}}$ in Equation 3.4.

$$E_{th}^{DHN^{US}} = E_{th,net}^{DHN} - E_{th,exp}^{DHN} \quad (3.2)$$

$$E_{th,net}^{DHN} = E_{th,gross}^{DHN} - E_{th,loss}^{DHN} \quad (3.3)$$

$$E_{th,gross}^{DHN} = E_{th,imp}^{DHN} + \sum_{i=1}^{NTP^{Int_{Cen}}} E_{th_i}^{TP^{Int_{Cen}}} \quad (3.4)$$

The annual primary energy demand related to the supply of thermal energy (E_p^{TP}) is given by Equation 3.5. In particular, E_{th}^{Dis} can be supplied by TPs supplied by fossil energy sources (primary energy) or electric energy. For evaluating the annual primary energy demand of thermal energy production plants supplied by primary energy (E_p^{TP}), their primary energy ratio (*PER*) must be considered. In addition, the distinction between FFs and RESs-based plants must be made. The yearly primary energy demand of the i-th TP fuelled with a FF ($E_{p_i}^{TP_{FF}}$) is given by Equation 3.6. Accordingly, the yearly primary energy demand of the i-th TP exploiting a RES ($E_{p_i}^{TP_{RES}}$) is given by Equation 3.7. Conversely, the annual electric energy request of the i-th electric-driven TP ($E_{el_i}^{TP_{el}}$) can be determined using Equation 3.8, where COP_i represents the coefficient of performance of the i-th TP.

Substituting $E_{th_i}^{TP_{FF}}$ and $E_{th_i}^{TP_{RES}}$ with $E_{th_i}^{TP^{Int_{Dec}}}$ in Equations 3.6 or 3.7, the primary energy demand due to the activation of decentralized FFs ($E_p^{TP_{FF}^{Int_{Dec}}}$) or RESs-based ($E_p^{TP_{RES}^{Int_{Dec}}}$) TPs, respectively, can be estimated. Equation 3.7 can be used for determining the primary energy demand of RESs-based TPs installed outside the boundaries of the PED ($E_p^{TP_{RES}^{Ext}}$) too. In this regard, two alternatives exist: if the district is provided with all the thermal energy supply of the plant, then its gross annual thermal energy production ($E_{th_i}^{TP_{RES}^{Ext}}$) should be used in the numerator; but if only a part of the thermal energy supplied by the TP is provided to the district, then the numerator should be equal to the yearly thermal energy import of the district increased by the losses occurring within the DHN

connecting the TP with the district itself ($E_{th,imp}^{DHN}$). The primary energy demand due to the yearly thermal energy exports ($E_{p,exp}^{TP_{RES}^{Int_{Cen}}}$) accounts for the primary energy demand due to the yearly thermal energy exports, and results from the ratio of E_{th,exp_i}^{DHN} to the *PER* of the i-th renewable-based TP supplying the thermal energy exported according to Equation 3.9.

$$E_p^{TP} = \sum_{i=1}^{NTP_{FF}^{Int_{Cen}}} E_{p_i}^{TP_{FF}^{Int_{Cen}}} + \sum_{i=1}^{NTP_{RES}^{Int_{Cen}}} \left(E_{p_i}^{TP_{RES}^{Int_{Cen}}} - E_{p,exp_i}^{TP_{RES}^{Int_{Cen}}} \right) + \sum_{i=1}^{NTP_{FF}^{Int_{Dec}}} E_{p_i}^{TP_{FF}^{Int_{Dec}}} + \sum_{i=1}^{NTP_{RES}^{Int_{Dec}}} E_{p_i}^{TP_{RES}^{Int_{Dec}}} + \sum_{i=1}^{NTP_{RES}^{Ext}} E_{p_i}^{TP_{RES}^{Ext}} \quad (3.5)$$

$$E_{p_i}^{TP_{FF}} = \frac{E_{th_i}^{TP_{FF}}}{PER_i} \quad (3.6)$$

$$E_{p_i}^{TP_{RES}} = \frac{E_{th_i}^{TP_{RES}}}{PER_i} \quad (3.7)$$

$$E_{el_i}^{TP_{el}} = \frac{E_{th_i}^{TP_{el}}}{COP_i} \quad (3.8)$$

$$E_{p,exp}^{TP_{RES}^{Int_{Cen}}} = \frac{E_{th,exp_i}^{DHN}}{PER_i} \quad (3.9)$$

Lastly, the annual CO_2 (or CO_{2eq}) emissions due to thermal energy demand and supply within the district ($CO_2^{E_{th}^{Dis}}$) can be determined according to Equation 3.10. The latter has been obtained by multiplying all terms of Equation 3.5 by the EF of the source exploited in each TP, which is referred to as β and is expressed in kg_{CO_2}/kWh_p (or $kg_{CO_{2eq}}/kWh_p$). It should be noticed that Equation 3.5 neglects the emissions of electric-driven TPs, whose contribution is accounted for below.

$$CO_2^{E_{th}^{Dis}} = \sum_{i=1}^{NTP_{FF}^{Int_{Cen}}} E_{p_i}^{TP_{FF}^{Int_{Cen}}} * \beta_i + \sum_{i=1}^{NTP_{RES}^{Int_{Cen}}} \left(E_{p_i}^{TP_{RES}^{Int_{Cen}}} - E_{p,exp_i}^{TP_{RES}^{Int_{Cen}}} \right) * \beta_i + \sum_{i=1}^{NTP_{FF}^{Int_{Dec}}} E_{p_i}^{TP_{FF}^{Int_{Dec}}} * \beta_i + \sum_{i=1}^{NTP_{RES}^{Int_{Dec}}} E_{p_i}^{TP_{RES}^{Int_{Dec}}} * \beta_i + \sum_{i=1}^{NTP_{RES}^{Ext}} E_{p_i}^{TP_{RES}^{Ext}} * \beta_i \quad (3.10)$$

The methods discussed in this section may also be used for quantifying CO_2 (or CO_{2eq}) emissions due to the demand and supply of cooling energy ($CO_2^{E_{co}^{Dis}}$).

Energy and emissions balances related to electric energy demand and supply

Figure 3.4 shows an example of electricity flows characterizing a generic district. The electric energy production plants (EPs) serving it may be installed inside or outside its geographical boundaries. In the former case, decentralised and centralised EPs can be distinguished. Users can take electricity from the PG in the case of a deficit production from renewable-based EPs. Conversely, electricity can be injected into the PG whenever the supply from renewable-based EPs exceeds users' demand. Indirect emissions are related to the electricity taken from the PG and can be determined using the EF of the PG. A distinction is needed regarding EPs fuelled with FFs or exploiting RESs. In the former case, emissions are usually evaluated by multiplying the primary energy demand of the plant by the EF associated with the combustion of the FF used. The same applies to renewable-based EPs activated by combustion, for example of renewable fuels, biomass, etc. On the other hand, the EF associated with non-combustion-based EPs (such as PV plants, wind turbines, hydroelectric plants, etc.) is referred to the electric energy supplied.

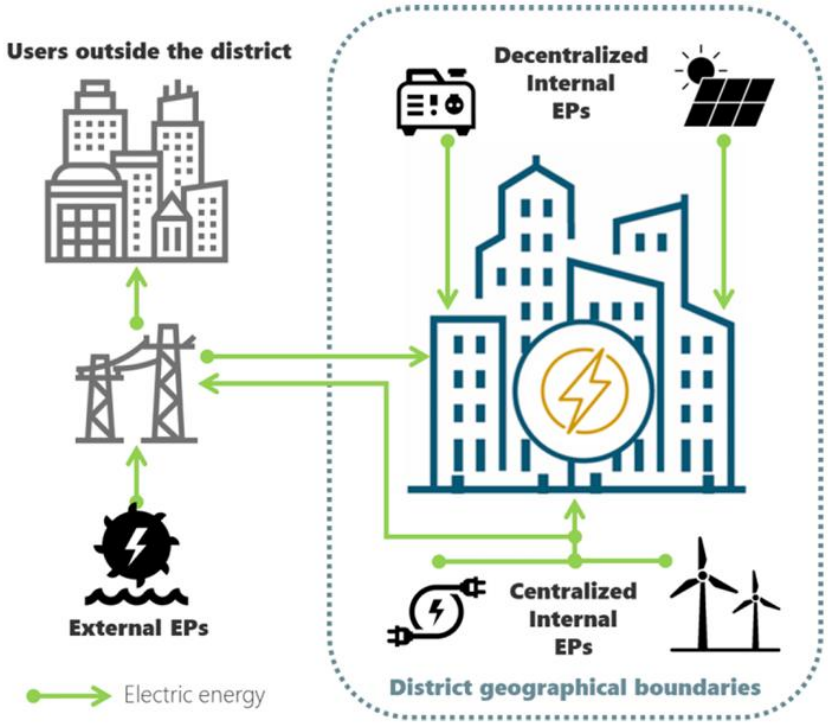

Figure 3.4 Example layout of electric energy flows in a generic district.

As already mentioned, Equation 3.10 neglects the indirect carbon emissions related to electric-driven TPs. In fact, they can be accounted with those referred to the annual electric energy demand of the district (E_{el}^{Dis}). This can be estimated as stated in Equation 3.11, where E_{el}^{US} is the yearly electricity demand of users and $E_{el}^{TP_{el}^{Int_{Cen}}}$ and $E_{el}^{CP_{el}^{Int_{Cen}}}$ are the requests due to the activation of centralized electric-driven TPs and CPs, respectively, calculated on an annual basis. $E_{el}^{TP_{el}^{Int_{Cen}}}$ can be determined as stated in Equation 3.12, where the term $E_{el_i}^{TP_{el}^{Int_{Cen}}}$ results from Equation 3.8. Similar considerations apply to $E_{el_i}^{CP_{el}^{Int_{Cen}}}$, which can be evaluated using the same formulation by substituting $E_{th_i}^{TP_{el}}$ with $E_{co_i}^{TP_{el}}$ and COP_i with the energy efficiency ratio of the i-th CP (EER_i).

$$E_{el}^{Dis} = E_{el}^{US} + E_{el}^{TP_{el}^{Int_{Cen}}} + E_{el}^{CP_{el}^{Int_{Cen}}} \tag{3.11}$$

$$E_{el}^{TP_{el}^{Int_{Cen}}} = \sum_{i=1}^{NTP_{el}^{Int_{Cen}}} E_{el_i}^{TP_{el}^{Int_{Cen}}} \tag{3.12}$$

The annual net electric energy provided by the centralized internal EPs fuelled with FFs ($E_{el,net}^{TP_{el}^{Int_{Cen}}}$) is given by Equation 3.13. It equals the sum of each plant's electric energy gross production ($E_{el,gross}^{TP_{el}^{Int_{Cen}}}$) decreased by electricity self-consumption ($E_{el,SC}^{TP_{el}^{Int_{Cen}}}$) on an annual basis. Equation 3.14 can be instead used to determine the yearly electric energy supplied by centralized EPs exploiting RESs ($E_{el,net}^{TP_{el}^{Int_{Cen}}}$). This value must be reduced by the electricity exports ($E_{el,exp}^{TP_{el}^{Int_{Cen}}}$) too. The sums in Equations 3.13 and 3.14 are evaluated over the total number of electric generation plants inside the district fuelled with FFs ($NEP_{FF}^{Int_{Cen}}$) and exploiting RESs ($NEP_{RES}^{Int_{Cen}}$), respectively. Equation 3.14 can apply also to decentralized EPs. Yearly net electric energy supplied by external RESs-based EPs ($E_{el,net}^{EP_{RES}^{Ext}}$), whose total number is given by NEP_{RES}^{Ext}, can be estimated using Equation 3.15. In addition to the each plant's self-consumption ($E_{el,sc_i}^{EP_{RES}^{Ext}}$), also the transmission and distribution (T&D) losses ($E_{el,T\&D}^{EP_{RES}^{Ext}}$) due to the transit of electricity on the PG must be counted as a subtractive term. The latter can be determined using a specific factor, which is typically provided by the national Transmission System Operator (TSO) [451]. Furthermore, the annual gross electricity supply of each external EP ($E_{el,gross_i}^{EP_{RES}^{Ext}}$) must be reduced by the share of electricity exported ($E_{el,exp_i}^{EP_{RES}^{Ext}}$). Lastly, Equation 3.16 can be adopted to estimate the net electric energy supplied to the users by decentralized EPs ($E_{el,net}^{EP^{Int_{Dec}}}$) on an annual basis and activated either by FFs or RESs. In the latter case, also electricity exports ($E_{el,exp_i}^{EP_{RES}^{Ext}}$) must be considered.

$$E_{el,net}^{EP_{FF}^{Int_{Cen}}} = \sum_{i=1}^{NEP_{FF}^{Int_{Cen}}} E_{el,gross_i}^{EP_{FF}^{Int_{Cen}}} \tag{3.13}$$

$$E_{el,net}^{EP_{RES}^{Int_{Cen}}} = \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Cen}}} - E_{el,sc_i}^{EP_{RES}^{Int_{Cen}}} - E_{el,exp_i}^{EP_{RES}^{Int_{Cen}}} \right) \tag{3.14}$$

$$E_{el,net}^{EP_{RES}^{Ext}} = \sum_{i=1}^{NEP_{RES}^{Ext}} (E_{el,gross_i}^{EP_{RES}^{Ext}} - E_{el,sc_i}^{EP_{RES}^{Ext}} - E_{el,exp_i}^{EP_{RES}^{Ext}}) - E_{el,T\&D}^{EP_{RES}^{Ext}} \quad (3.15)$$

$$E_{el,net}^{EP_{FF/RES}^{Int_{Dec}}} = \sum_{i=1}^{NEP^{Int_{Dec}}} \left(E_{el,gross_i}^{EP_{FF/RES}^{Int_{Dec}}} - E_{el,sc_i}^{EP_{FF/RES}^{Int_{Dec}}} - E_{el,exp_i}^{EP_{FF/RES}^{Int_{Dec}}} \right) \quad (3.16)$$

Once known E_{el}^{Dis}, the electric energy supplied by centralized fossil-based EPs ($E_{el,net}^{EP_{FF}^{Int_{Cen}}}$), centralized renewable-based EPs ($E_{el,net}^{EP_{RES}^{Int_{Cen}}}$), external renewable-based EPs ($E_{el,net}^{EP_{RES}^{Ext}}$) as well as decentralized EPs ($E_{el,net}^{EP^{Int_{Dec}}}$), the electricity yearly purchased from the PG (E_{el}^{PG}) can be evaluated as stated in Equation 3.17.

$$E_{el}^{PG} = E_{el}^{Dis} - E_{el,net}^{EP_{FF}^{Int_{Dec}}} - E_{el,net}^{EP_{RES}^{Int_{Dec}}} - E_{el,net}^{EP_{FF}^{Int_{Cen}}} - E_{el,net}^{EP_{RES}^{Int_{Cen}}} - E_{el,net}^{EP_{RES}^{Ext}} \quad (3.17)$$

The annual primary energy demand of the district related to electric energy demand and supply (E_p^{EP}) is given by Equation 3.18. It includes only the contributions due to the activation of combustion-based EPs, whose calculation methods are introduced in Equations 3.19 and 3.20. These terms can be used to estimate corresponding emissions through the emission factor β of the source exploited. Equation 3.19 allows to determine the annual primary energy demand of the i-th EPs fuelled with FFs ($E_{p_i}^{EP_{FF}^{Int_{Cen/Dec}}}$), being it centralized or not. η_i is the electric efficiency of the i-th EP. Likewise, the primary energy demand of decentralized or centralized renewable EPs ($E_{p_i}^{EP_{RES}^{Int_{Cen/Dec}}}$) can be determined as stated in Equation 3.20. Indeed, the primary energy demand due to electricity exports must not be taken into account in the total emission balance of the district. As regards the primary energy demand of external EPs ($E_{p_i}^{EP_{RES}^{Ext}}$), two alternatives exist. On the one hand, if the external EP supplies electric energy to the district only, then its gross electric energy supply ($E_{el,gross_i}^{EP_{RES}^{Ext}}$) should be considered. Conversely, the electric energy imports increased by the T&D losses which occur within the PG should be taken into account. For obtaining the total primary energy demand, the primary energy demand related to the electricity taken from the PG should be considered too, as well as the

primary energy demand of non-combustion based renewable EPs. In particular, the primary energy demand of the PG can be evaluated using the efficiency of the PG [451].

$$E_p^{EP} = \sum_{i=1}^{NEP_{FF}^{Int_{Cen}}} E_{p_i}^{EP_{FF}^{Int_{Cen}}} + \sum_{i=1}^{NEP_{FF}^{Int_{Dec}}} E_{p_i}^{TP_{FF}^{Int_{Dec}}} + \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{p_i}^{TP_{RES}^{Int_{Cen}}} + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{p_i}^{Int_{Dec}} + \sum_{i=1}^{NEP_{RES}^{Ext}} E_{p_i}^{TP_{RES}^{Ext}} \quad (3.18)$$

$$E_{p_i}^{EP_{FF}^{Int_{Cen/Dec}}} = \frac{E_{el,gross_i}^{EP_{FF}^{Int_{Cen/Dec}}}}{\eta_i} \quad (3.19)$$

$$E_{p_i}^{EP_{RES}^{Int_{Cen/Dec}}} = \frac{E_{el,gross_i}^{EP_{RES}^{Int_{Cen/Dec}}} - E_{el,exp_i}^{EP_{RES}^{Int_{Cen/Dec}}}}{\eta_i} \quad (3.20)$$

Annual carbon emissions due to electric energy demand and supply ($CO_2^{E_{el}^{Dis}}$) can be estimated according to Equation 3.21. Indirect emissions due to non-combustion-based EPs can be determined by multiplying the emission factor α of the EP by the electric energy supplied. α is usually expressed in terms of kg_{CO_2}/kWh_{el} (or $kg_{CO_{2eq}}/kWh_{el}$). Indirect CO_2 (or CO_{2eq}) related to the electricity taken from the PG can be determined using the EF of the PG, which is referred to as α_{PG}. The latter is multiplied by the difference between E_{el}^{PG} and the sum of the electricity injected into the PG by renewable EPs centralized or decentralized. Indeed, this accounts for an emission credit which lowers total emissions. The adoption of α_{PG} greatly eases the calculation, since it avoids collecting data regarding the national electricity production mix. It should be noted that the emission factor α of non-combustion-based renewable EPs is usually zero, except under the life-cycle approach.

$$
\begin{aligned}
CO_2^{E_{el}^{Dis}} = & \sum_{i=1}^{NEP_{FF}^{Int_{Cen}}} E_{p_i}^{EP_{FF}^{Int_{Cen}}} * \beta_i + \sum_{i=1}^{NEP_{FF}^{Int_{Dec}}} E_{p_i}^{EP_{FF}^{Int_{Dec}}} * \beta_i \\
& + \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{p_i}^{EP_{RES}^{Int_{Cen}}} * \beta_i + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{p_i}^{EP_{RES}^{Int_{Dec}}} * \beta_i \\
& + \sum_{i=1}^{NEP_{RES}^{Ext}} E_{p_i}^{EP_{RES}^{Ext}} * \beta_i + \left(E_{el}^{PG} - \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{el,exp_i}^{EP_{RES}^{Int_{Cen}}} \right. \\
& \left. - \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{el,exp_i}^{EP_{RES}^{Int_{Dec}}} \right) * \alpha_i \\
& + \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Cen}}} - E_{el,exp_i}^{EP_{RES}^{Int_{Cen}}} \right) * \alpha_i \\
& + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Dec}}} - E_{el,exp_i}^{EP_{RES}^{Int_{Dec}}} \right) * \alpha_i \\
& + \sum_{i=1}^{NEP_{RES}^{Ext}} \left(E_{el,gross_i}^{EP_{RES}^{Ext}} - E_{el,exp_i}^{EP_{RES}^{Ext}} \right) * \alpha_i
\end{aligned}
\tag{3.21}
$$

Positive energy balance and carbon neutrality check

The district being analysed reaches the positive energy balance target whenever the conditions expressed by Equations 3.22, 3.23 and 3.24 are met simultaneously. That is, the thermal, cooling, and electric energy supply of renewable-based plants exceeds the thermal, cooling, and electric energy demand of the district at the same time, respectively.

$$
\sum_{i=1}^{NTP_{RES}^{Int_{Cen}}} E_{th_i}^{TP_{RES}^{Int_{Cen}}} + \sum_{i=1}^{NTP_{RES}^{Int_{Dec}}} E_{th_i}^{TP_{RES}^{Int_{Dec}}} + \sum_{i=1}^{NTP_{RES}^{Ext}} E_{th,imp_i}^{TP_{RES}^{Ext}} > E_{th}^{Dis} \tag{3.22}
$$

$$
\sum_{i=1}^{NCP_{RES}^{Int_{Cen}}} E_{co_i}^{CP_{RES}^{Int_{Cen}}} + \sum_{i=1}^{NCP_{RES}^{Int_{Dec}}} E_{co_i}^{CP_{RES}^{Int_{Dec}}} + \sum_{i=1}^{NCP_{RES}^{Ext}} E_{co,imp_i}^{CP_{RES}^{Ext}} > E_{co}^{Dis} \tag{3.23}
$$

$$\sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Cen}}} - E_{el,sc_i}^{EP_{RES}^{Int_{Cen}}} \right) + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Dec}}} - E_{el,sc_i}^{EP_{RES}^{Int_{Dec}}} \right) + \sum_{i=1}^{NEP_{RES}^{Ext}} E_{el,imp_i}^{EP_{RES}^{Ext}} > E_{el}^{Dis} \quad (3.24)$$

The net annual CO_2 (or CO_{2eq}) emissions of the district being analysed (CO_2^{Dis}) can be determined as stated in Equation 3.25, that is as the sum of emissions due to electric ($CO_2^{E_{el}^{Dis}}$), thermal ($CO_2^{E_{th}^{Dis}}$) and cooling energy ($CO_2^{E_{co}^{Dis}}$) demand and supply.

$$CO_2^{Dis} = CO_2^{E_{el}^{Dis}} + CO_2^{E_{th}^{Dis}} + CO_2^{E_{co}^{Dis}} \quad (3.25)$$

The condition of carbon neutral district is reached whenever the resulting value is null or negative. Indeed, such a result proves that the emissions due to the thermal, cooling, and electric energy supply are counterbalanced by the emissions credit due to the electricity exports to the PG. Surplus thermal and cooling energy exported outside of the district boundaries could be considered for the evaluation of emission credits too. However, choosing the reference EF for evaluating carbon emissions avoided owing to the export of thermal and/or cooling energy surplus could turn out to be not straightforward as in the case of electricity. In the latter case, the EF of the PG can always be adopted. Since an equivalent of the PG for thermal and cooling energy supply is lacking, the EF of the source used outside of the district and substituted by surplus thermal and cooling energy exports, respectively, should be used.

3.2 A user-friendly tool for the technological design of PEDs

Effective design of the energy system configuration within a district is fundamental for achieving sustainability objectives. By strategically leveraging locally available energy resources, it is possible to enhance energy efficiency, progress towards energy autonomy and ultimately attain carbon neutrality. A comprehensive and well-coordinated

approach to system design ensures optimal utilization of resources, fostering long-term environmental and economic sustainability for the district.

In light of the methodology introduced previously, this section presents the development of a user-friendly tool to support the creation of PEDs with particular reference to the Mediterranean area. In particular, the tool aims to define, based on the real availability of sources and the technical operation of the system configuration chosen by the user, the optimal size of each RES-based conversion system to achieve the PED condition.

The tool was developed in Excel environment [350] to make it easy to use for a wide range of users. The main steps regard:

- entry of all input data, including:
  - district end-use electric ($E_{el}^{Dis^{US}}(\theta)$), thermal ($E_{th}^{Dis}(\theta)$), cooling ($E_{co}^{Dis}(\theta)$) and DHW ($E_{DHW}^{Dis}(\theta)$) energy demand on an hourly basis;
  - district location;
  - selection of energy conversion systems;
  - total available area for PV and solar thermal collectors installation (if these systems are selected);
- evaluation of the size of each selected energy conversion system, based on technical constraints and energy demand of the district;
- visualisation of the obtained results, verification of the energy balances and carbon neutrality condition of the district.

Regarding the initial district energy demand, hourly input data resolution is required. Data covering a full year must be provided in order to enable the evaluation of the PED on an annual basis. For thermal and cooling energy demand, it is possible to input the energy shares corresponding separately to space heating and cooling, and to process-related thermal and cooling uses, such as those associated with data centre cooling.

With regards to the district location, the geographical focus is on the Mediterranean area, particularly on the regions of Southern Italy, including Campania, Apulia, Basilicata, Calabria and Sicily. The user can select a province within these regions as the location for the district to be simulated, as shown in *Figure 3.5*. The choice of location significantly

affects the availability of renewable sources. Specifically, the external air temperature ($T_{air,ext}$), solar irradiation, and wind speed at different heights are considered according. This information is essential for assessing the operating conditions of various RES-based plants, which the user can select for the district's plant layout.

Figure 3.5 Selectable district location.

Technological configurations

The technological configuration of the district involves a choice by the user among the planned energy conversion systems, including:

- solar thermal collectors (STh), to meet the district's DHW energy demand;
- photovoltaic plant (PV), to meet the district's electric energy demand;
- wind turbine (Wt), to meet the district's electric energy demand;
- combined heat and power system (CHP), to meet the district's electric, thermal and DHW energy demand, powered by biomethane. This unit is considered in combination with an electric chiller that can also meet the cooling energy demand of the district;
- electric heat pump (EHP), to meet the district's requests for thermal and cooling energy, electrically driven.

Backup systems are also provided to meet energy demands not covered by the selected plant configuration, including:

- boiler (B), to meet the district's thermal and DHW energy demand, powered by biomethane;
- chiller (CH), to meet the district's cooling energy demand, electrically driven;
- power grid (PG), to meet the district's electric energy demand, powered by a technological mix related to the corresponding country.

The system configuration can be defined by the user selecting from the proposed options. However, it is essential to ensure that the chosen configuration satisfies the requirement that each energy demand (heating, cooling, electricity, and DHW) is served by at least one energy conversion system. However, it should be noted that the cooling energy demand must be fulfilled exclusively by electrically driven systems. Consequently, electricity produced by other systems may be used to supply cooling technologies, making such configurations eligible for selection. In total, nineteen possible energy conversion system combinations are available. *Figure 3.6* illustrates the plant configuration corresponding to the case in which all systems are selected. The energy flows within the district are highlighted, while the backup systems are shown within the blue box.

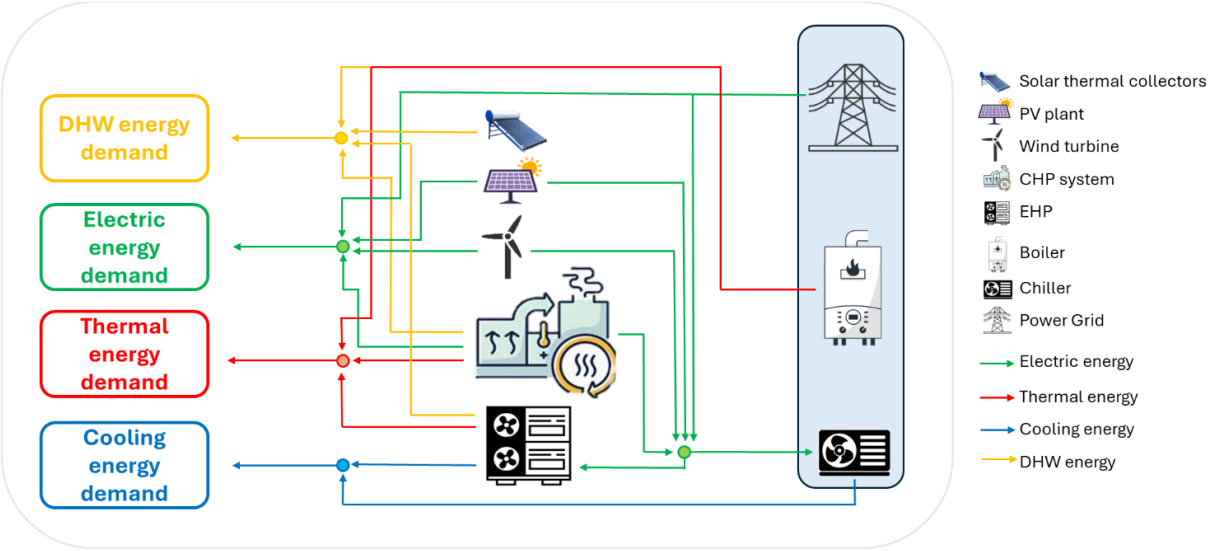

Figure 3.6 District plant configuration resulting from the selection of all available plants.

The complexity of the achievable configurations is governed by technical constraints, particularly those related to the operating priorities of energy conversion systems that can meet the same district energy demand. Specifically, when the plant configuration includes a CHP unit, it is given priority in satisfying all corresponding energy demands (E_{el}^{Dis}, E_{th}^{Dis}, E_{DHW}^{Dis}). When an EHP is included, it takes precedence over other systems in meeting thermal energy and DHW demand. With respect to the district's electric energy demand, if both wind turbine and PV plant are included, priority of operation is assigned to the wind turbine. Solar thermal collectors are exclusively used to meet the district's DHW demand. The following subsections provide detailed descriptions of the operating principles and sizing criteria for each considered energy conversion system.

Combined heat and power system, CHP

The operation of the CHP unit follows a thermal-driven strategy, whereby simultaneous generation of thermal and electrical energy occurs only in response to a demand for thermal energy. Since the economic viability of operating a complex system such as a CHP unit depends on achieving a sufficient number of operating hours per year, a minimum operating threshold is imposed. In this context, the tool sets a lower limit of 2,000 h/year, below which the CHP unit cannot be activated, even if the user has selected it as the system serving the district. This constraint is evaluated based on the aggregated thermal and DHW energy demand. The relatively low threshold is justified by the fact that thermal energy demand is predominantly concentrated in winter months, and the considered location in Southern Italy generally experiences mild winters. If the total thermal demand exceeds the minimum threshold of 2,000 operating hours per year, the CHP unit is activated and supplies thermal and electrical energy simultaneously during the corresponding hours. System sizing is performed by selecting the most suitable unit from a predefined database [452]. The available systems are based on ICE, with thermal power outputs (P_{th}^{CHP}) ranging from 3.25 kW to 3.17 MW and corresponding electrical power outputs (P_{el}^{CHP}) between 1.00 kW and 3.04 MW. Once the minimum operating-hour constraint is satisfied, the thermal load duration curve is constructed, and the nominal P_{th}^{CHP} is selected based on the value corresponding to 2000 h/year of operation. *Figure 3.7* shows the P_{th}^{CHP} of CHP units in the database with respect to the corresponding thermal efficiency (η_{th}^{CHP}).

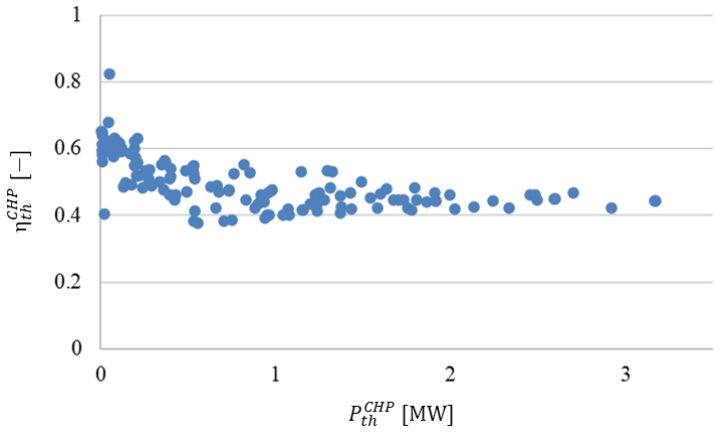

Figure 3.7 CHP thermal power and corresponding thermal efficiency.

Electric heat pump, EHP

An air-to-water (A/W) EHP is considered to meet the space heating and cooling energy demand of the district. The thermal (P_{th}^{EHP}), cooling (P_{co}^{EHP}) and electric power (P_{el}^{EHP}) of the reference EHP used for the component model development, along with the Coefficient of Performance (*COP*) and Energy Efficiency Ratio (*EER*) under rated conditions, are reported in *Table 3.1* [453].

Table 3.1 EHP nominal data.

Parameters	**Heating**	**Cooling**
$\boldsymbol{P_{th}^{EHP}/P_{co}^{EHP}}$[kW]	293.5	230.7
$\boldsymbol{P_{el}^{EHP}}$[kW]	94.6	107.9
Nominal COP / EER [-]	3.10	2.14

The operating modes of the EHP were analyzed using manufacturer-provided performance data for the selected system [453,454]. Fixed outlet water temperature of 55 °C in winter and 9 °C in summer was assumed. Fitting procedures were implemented in the Matlab [281] environment, based on the manufacturer's performance data, to derive analytical expressions for estimating EHP performance as a function of $T_{air,ext}$. The latter data were acquired on a hourly basis for the year 2022 from PVGIS [422] for each of the Southern Italy provinces and were used to evaluate the EHP performance. Polynomial functions were identified for each operating parameter. As an example, Equation 3.26 presents the polynomial expression adopted for the COP. The coefficients adopted for the

evaluation of COP, EER, normalized P_{th}^{EHP} ($\overline{P_{th}^{EHP}}$), P_{co}^{EHP} ($\overline{P_{co}^{EHP}}$), P_{el}^{EHP} ($\overline{P_{el}^{EHP}}$) are reported in *Table 3.2*.

$$COP(\theta) = x_1 * T_{air,ext}^4(\theta) + x_2 * T_{air,ext}^3(\theta) + x_3 * T_{air,ext}^2(\theta) + x_4 * T_{air,ext}(\theta) + x_5 \quad (3.26)$$

Table 3.2 Function coefficients of EHP parameters.

	x_1 [°C^{-4}]	x_2 [°C^{-3}]	x_3 [°C^{-3}]	x_4 [°C^{-1}]	x_5
***COP**(θ)*	5.2987E- 06	-1.8559E-04	-7.3974E-04	0.1096	1.6500
***EER**(θ)*	6.6667E- 07	-1.1926E-04	7.6611E-03	-0.2517	5.7975
$\overline{P_{th}^{EHP}}(\theta)$	2.5681E-06	-9.0258E-05	-8.4873E-05	4.44253E-02	0.6200
$\overline{P_{el}^{EHP}}(\theta)$ (Heating)	-2.3553E-06	1.1109E-04	-1.8156E-03	1.4211E-02	1.1601
$\overline{P_{co}^{EHP}}(\theta)$	6.6667E-07	-9.2593E-05	4.6611E-03	-0.1114	2.2275
$\overline{P_{el}^{EHP}}(\theta)$(Cooling)	6.6667E-07	-7.9259E-05	3.4611E-03	-5.7725E-02	1.1875

In addition, the Partial Load Factor (*PLF*) has been evaluated on an hourly basis, by comparing the required thermal/cooling power with the maximum available capacity. A fixed operating range was defined for the *PLR*, with a minimum value of 0.27 and a maximum value of 1. The sizing of the EHP is performed based on the space heating and cooling energy demand. Depending on the user-selected plant configuration of the district, different portions of the energy demand are considered: if the CHP unit is included, the remaining thermal and DHW energy demand not supplied by the higher-priority system is considered; if both a CHP and a STh are included, only the residual thermal energy demand is taken into account; if only an STh system is present, the EHP is sized based solely on the thermal energy demand. The procedure for determining the appropriate EHP size is based on calculating monthly thermal and cooling energy demands, from which the required power is derived by accounting for the number of operating hours per day and the number of days per month. The resulting power is then correlated with the average monthly $T_{air,ext.}$ Finally, the EHP size (P_{th}^{EHP}/P_{co}^{EHP}) is selected based on the winter and summer design temperatures according to [455]. The higher value obtained between the two seasons is adopted as the overall EHP capacity. Based on the resulting P_{th}^{EHP} and P_{co}^{EHP}, the operating mode of the EHP is evaluated on an hourly basis

as a function of $T_{air,ext}$. The electric energy requests due to the activation of EHP are accounted in addition to E_{el}^{Dis}.

Wind turbine, Wt

The availability of wind resources is heterogeneous across the territory of Southern Italy. To support the system selection phase for the district, a map illustrating wind resource availability in the Italian provinces under consideration is provided to the user, as shown in *Figure 3.8*. For each province, the area where the windy production is higher than 2500 MWh/MW is considered, based on data from the Italian wind Atlas database [456]. The wind producibility maps were developed through analyses of the Italian anemological database, which comprises 30 years of hourly wind data with a spatial resolution of 1.4 km [456]. Based on the retrieved data and the user-selected location, the tool provides an indication of wind resource availability in the corresponding province, classified as high, medium, or low.

Figure 3.8 Wind source availability map for the considered Italian provinces.

The sizing of the wind turbine (P_{el}^{Wt}) serving the district is carried out by considering the annual electrical energy demand (or the residual share, if part of it is already covered by higher-priority systems included in the configuration), in relation to the annual

operating hours of a wind turbine in the selected province. Based on the resulting value, one of the following rated plant sizes is selected: 225 kW, 500 kW, 850 kW, 1500 kW, 2000 kW. For each capacity, the performance map of the most widely deployed wind turbine model in Italy was considered [457]. The available electrical power on an hourly basis is obtained as a function of the site-specific wind speed. As an example, the performance map of the Vestas V29 wind turbine (225 kW) [458], which shows the electrical power and electrical efficiency as a function of wind speed, is presented in *Figure 3.9.* Depending on the size of the considered wind turbines, and in accordance with the corresponding data sheet, wind speed values at different heights above ground are taken into account. Specifically, wind speed at 50 m is used for the 225 kW and 500 kW turbines, at 75 m for the 850 kW and 1500 kW turbines, and at 100 m for the 2000 kW turbine. Hourly wind speed data at the relevant hub heights are derived from the Italian wind Atlas [456].

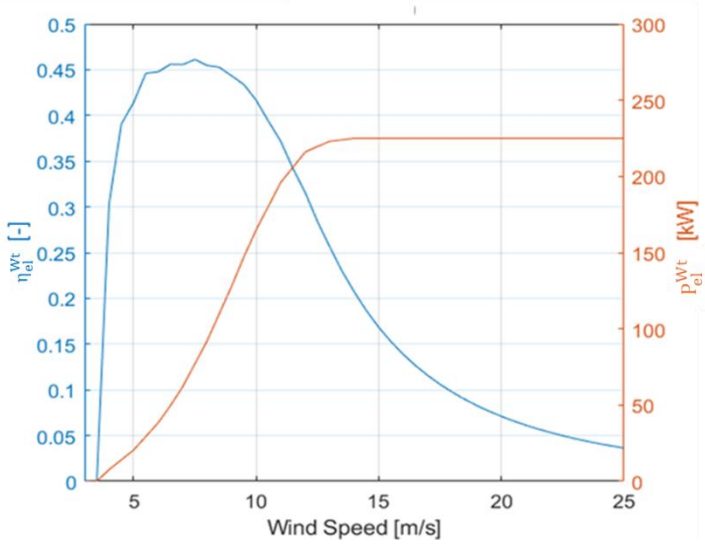

Figure 3.9 Performance of 225 kW wind turbine (Vestas V29).

PV plant

The sizing of systems based on the exploitation of solar energy depends on the available installation area (A), which is provided by the user as an input parameter. Users are also required to specify whether the available area is flat or tilted to accurately assess the installation of PV and STh modules. For tilted surfaces, the effective installation area is assumed to be reduced by 15 %. For system configurations that include only one of the two technologies, the entire available area is allocated to that system. When both systems

are included, 20 % of the available area is assigned to the sizing the STh system, while the remaining 80 % is allocated to the PV plant. Depending on the location selected by the user for the district, the corresponding $T_{air,ext.}$ and global irradiance (G), expressed in W/m^2, for a 30° tilted plan are considered [422]. The hourly energy output of the PV plant (E_{el}^{PV}) is calculated in accordance with Equation 3.27. An overall loss coefficient (*losses*) of 25 % is applied to account for effects such as overheating, soiling/erosion, mismatching, shading, as well as inverter and electrical connection losses. The PV system efficiency (η^{PV}) is evaluated as a function of the $T_{air,ext.}$, which varies with location, in accordance with Equation 3.28 and based on the nameplate data of the selected module [397]. Specifically, the nominal efficiency (η_{nom}^{PV}) is equal to 0.201, the temperature coefficient (δ) is 0.35 %/°C, and the Nominal Operating Cell Temperature (*NOCT*) is equal to 45 °C.

$$E_{el}^{PV}(\theta) = G(\theta) * \eta^{PV}(\theta) * A^{PV} * (1\text{-}losses) \quad (3.27)$$

$$\eta^{PV}(\theta) = \eta_{nom}^{PV}\left(1 - \frac{\delta}{100} * \left(T_{air,ext}(\theta) + NOCT - 20\right)\right) \quad (3.28)$$

Solar thermal collectors

The sizing of the STh system takes into account the E_{DHW}^{Dis} as well as the available installation area, according to the constraints described above. The operation of the STh plant depends on the district location defined by the user, which determines the $T_{air,ext}$ and G, and the selected system model, from which the operating parameters are derived. Specifically, the available energy from the system (E_{DHW}^{STh}) can be obtained according to the Equation 3.29, as a function of the STh efficiency (η^{STh}) and the installation area (A^{STh}).

$$E_{DHW}^{STh}(\theta) = G(\theta) * \eta^{STh}(\theta) * A^{STh} \quad (3.29)$$

The η^{STh} is evaluated in accordance with Equation 3.30. In particular, the absorber optical efficiency (a_0) and the thermal loss coefficients of the absorber (a_1, a_2) depend on the selected solar collector model [459], and are equal to 0.787, 4.1 W/m^{2}K and 0.0084 W/m^{2}K^2, respectively. The temperature variation (ΔT) is calculated as the difference between the average collector temperature (T_c), defined as the mean of the collector outlet

temperature (T_{out}) set at 50°C, and the annual average outdoor air temperature and the $T_{air,ext}$ for the corresponding hour.

$$\eta^{STh}(\theta) = a_0 - a_1 * \left(\frac{\Delta T\,(\theta)}{G\,(\theta)}\right) - a_2 * \left(\frac{\Delta T\,(\theta)}{G\,(\theta)}\right)^2 \quad (3.30)$$

Backup systems: boiler, chiller and PG

The backup systems for the district's plant configurations are sized to ensure that energy demands not met by the primary systems in the defined configuration are fully satisfied, as well as any thermal and cooling energy demands for process use that may not be covered by the surplus production of the systems sized and operated according to the defined operational constraints. The backup systems include a biomethane-fired boiler to meet thermal and DHW demands, an electrically driven chiller for cooling energy demand, and the PG to cover all remaining electric energy demand.

The boiler is assumed to operate with an efficiency (η^B) equal to 0.979, based on the selected commercial model [460], and is sized to meet the residual thermal and DHW demand of the district on an hourly basis. The sizing procedure ensures that the boiler capacity (P^B) is at least equal to the maximum thermal load required by the system. The chiller is electrically driven, and its operation is modelled according to the performance map of the EHP in cooling mode, as described in the corresponding subsection [454]. For all system configurations, two chillers are considered: one sized to meet the process cooling demand and therefore operating throughout the year, and a second one sized to cover the residual space cooling demand, operating only during the summer period. The sizing of the chiller dedicated to space cooling is based on the maximum hourly cooling energy demand, accounting for the corresponding normalized power available under those operating conditions. Accordingly, the chiller capacity (P^{CH}) is selected to ensure full coverage of the cooling load.

3.2.1 Energy flow management and PED-related conditions

District operation is based on optimized energy flow management to maximize the hourly use of energy from RES-based plants. In this framework, surplus energy from RES-based systems is first prioritized to meet any remaining district energy demands,

even if these demands were not directly considered in the sizing of the systems themselves. For example, if the CHP unit produces electrical energy in excess of the district users' demand, this surplus can be partially used to supply working electrically driven systems demand. Similarly, when the thermal energy exceeds the space heating demand of the district, it is used to also cover thermal requirements for process uses, if required.

As specified above and reported in the Equation 3.31 the overall hourly electric energy demand of the district ($E_{el}^{Dis}\ (\theta)$) considers, in addition to $E_{el}^{Dis^{US}}(\theta)$, the electric energy request for EHP and CH operation ($E_{el}^{EHP_{el}}(\theta)$, $E_{el}^{CH_{el}}(\theta)$).

$$E_{el}^{Dis}(\theta) = E_{el}^{Dis^{US}}(\theta) + E_{el}^{EHP_{el}}(\theta) + E_{el}^{CH_{el}}(\theta) \tag{3.31}$$

The electricity required for electrically-driven plants operation can be supplied by surplus electric energy from the primary systems or by the PG, depending on the specific plant configuration, hour by hour. The PG, as a backup system, indeed guarantees full coverage of the district's electricity demand, including both end-use electrical loads and the power requirements of electrically driven systems.

The energy produced by RES-based systems of the considered configuration, which exceeds the entire electric energy demand of the district, is injected into the PG, as reported in Equation 3.32. As a consequence, the electric energy withdrawn by the PG ($E_{el}^{PG}(\theta)$) is evaluated in accordance to Equation 3.33. The net electric energy related to the CHP unit, wind turbine and PV plant is, according to the methodology presented in Section 3.1.1, evaluated as the difference between the electric energy produced and exported.

$$E_{el,exp}^{PG}(\theta) = E_{el,exp}^{CHP}(\theta) + E_{el,exp}^{Wt}(\theta) + E_{el,exp}^{PV}(\theta) \tag{3.32}$$

$$E_{el}^{PG}(\theta) = E_{el}^{Dis}(\theta) - E_{el,net}^{CHP}(\theta) - E_{el,net}^{Wt}(\theta) - E_{el,net}^{PV}(\theta) \tag{3.33}$$

The aim of the tool is to provide the user with indications on the sizing of all plants included in the selected technological configuration of the district, in compliance with the

operational constraints of the technologies and with the requirement to satisfy the district's energy demands.

To assess the PED condition, the analyzed district is considered to achieve a positive energy balance and carbon neutrality when the conditions defined by Equations 3.34, 3.35 and 3.36 are simultaneously satisfied. Specifically, the district meets the PED criteria when, on the one hand, the annual thermal and electrical energy supplied by RES-based plants exceeds the corresponding annual thermal and electrical energy demand; on the other hand, the CO_2 emissions associated with the district's energy supply are fully offset by emission credits. These emission credits derive from electricity exported to the PG and from thermal/cooling energy exported to users outside the district, which displaces an equivalent amount of energy production otherwise produced by conventional systems. To account for this effect, the surplus electric energy generated by RES-based plants, as wind turbine, PV plant and CHP unit, is entirely considered as exported to the PG, and multiplied on an hourly basis by the PG CO_2 emission factor, calculated in accordance with the methodology presented in [353], and subsequently aggregated on an annual basis (n index ranges from 1 to N, equal to 8760). To evaluate the emissions credits due to thermal energy export, the natural gas CO_2 emission factor (β^{NG}) is multiplied by the primary energy corresponding to the surplus thermal and DHW energy produced by CHP unit, EHP, boiler and STh system. A reference efficiency for a conventional natural gas boiler ($\eta^{B,NG}$) equal to 0.85 is assumed. An analogous approach is adopted for cooling energy export, accounting for the electric energy required to produce the exported cooling energy. In this case, the EER and α^{PG} are considered on an hourly basis, and the annual sum is used for the final assessment. Since both the boiler and the CHP unit are fuelled by biomethane, the corresponding CO_2 emission factor (β^{BM}) is adopted for the energy produced by these technologies [461]. Emission factors for non-carbon-neutral conditions are considered.

$$\sum_{n=1}^{N} E_{th}^{CHP}(\theta_n) + \sum_{n=1}^{N} E_{DHW}^{STh}(\theta_n) + \sum_{n=1}^{N} E_{th}^{B}(\theta_n) > \sum_{n=1}^{N} E_{th}^{Dis}(\theta_n) + \sum_{n=1}^{N} E_{DHW}^{Dis}(\theta_n) \quad (3.34)$$

$$\sum_{n=1}^{N} E_{el}^{CHP}(\theta_n) + \sum_{n=1}^{N} E_{el}^{Wt}(\theta_n) + \sum_{n=1}^{N} E_{el}^{PV}(\theta_n) > \sum_{n=1}^{N} E_{el}^{Dis}(\theta_n) \quad (3.35)$$

$$\left[\sum_{n=1}^{N}\left[\left(E_{el,imp}^{PG}(\theta_n)-E_{el,exp}^{CHP}(\theta_n)-E_{el,exp}^{Wt}(\theta_n)-E_{el,exp}^{PV}(\theta_n)\right)*\alpha^{PG}(\theta_n)\right]\right] + \left[\left(\frac{\sum_{n=1}^{N}E_{th}^{CHP}(\theta_n)}{\eta^{th,CHP}}+\frac{\sum_{n=1}^{N}E_{th}^{B}(\theta_n)}{\eta^{th,B}}\right)*\beta^{BM}\right] - \left[\left(\frac{\sum_{n=1}^{N}(E_{th,exp}^{CHP}(\theta_n)+E_{th,exp}^{EHP}(\theta_n)+E_{th,exp}^{STh}(\theta_n)+E_{th,exp}^{B}(\theta_n))}{\eta^{B,NG}}\right)*\beta^{NG}\right] - \left[\sum_{n=1}^{N}\left[\left(\frac{E_{co,exp}^{EHP}(\theta_n)+E_{co,exp}^{Ch}(\theta_n)}{EER}\right)*\alpha^{PG}(\theta_n)\right]\right] \leq 0 \quad (3.36)$$

3.2.2 Case study

In order to validate the tool, a case study is considered with the aim of defining the sizing of the selected district's plant configuration, which includes different RES-based energy conversion systems for the supply of renewable energy, targeting the PED conditions.

District users' characterization

The district being analysed is located in Benevento, a city in the South of Italy (climatic zone C [462], and involves both non-residential and residential users, namely:

- six residential users (Us#1, Us#2, Us#3, Us#4, Us#5 and Us#6);
- an office building (Us#7).

Residential users' electric, thermal, and cooling energy load profiles have been dynamically simulated. Conversely, real electric load profiles of office building (that is, Us#7) have been obtained from the Italian electricity distributor [395] with a fifteen minutes timestep. Us#7 is equipped with an EHP. Based on electric energy demand, occupancy building data, temporal information, and energy conversion system parameters, a dedicated procedure has been implemented to evaluate energy demand for space heating and cooling [352].

All residential users live in single family houses located nearby the office building. In particular:

- Us#1 includes two employed persons and three young people. The floor area of the house, which is on one floor, is equal to 210 m^2;
- Us#2 includes two employed persons. The house is on one floor and has a floor area equal to 240 m^2;
- Us#3 includes four employed and two unemployed persons. The house is on two floors and has a floor area of 268 m^2;
- Us#4 includes five employed persons and two children. The floor area of the house is equal to 210 m^2 floors and there are two inhabited floors;
- Us#5 includes six inhabitants, all employed. The house is on two floors and has a floor area equal to 210 m^2;
- Us#6 includes two inhabitants, both retired. The house has one inhabited floor and a floor area equal to 280 m^2.

All single-family houses have the same building envelope. To determine residential users' electric, thermal, and cooling energy demand through dynamic simulations, the ground-floor transmittance has been estimated. The conductivity of the ground, made of sand or gravel, has been assumed as equal to 2.0 W/(mK). Windows glass is low-e type and filled with argon. The transmittance of windows has been calculated, assuming the aluminium frame occupies about 15 % of the transparent surface. In addition, windows are supposed to be automatically overshadowed during the summer months to cut solar gain. In each season, daily occupancy schedules for residential flats and offices have been determined using a high-resolution model built on survey data gathered in the United Kingdom and implementing first-order Markov-chain techniques [463]. Once generated stochastic sequences, electric load profiles of appliances and lighting have been calculated on the basis of resulting occupancy profiles. Residential users' DHW demand has been determined using a dynamic simulation software, which takes into account the number of occupants of each house and the maximum daily DHW request, equal to 50 l/person [464]. The simulations have been carried out adopting a 1.5 min timestep. Likewise, building simulations have been performed using a 1.5 min timestep in TRNSYS 18 [377] for determining residential users' thermal and cooling energy demand, as well as the electric load due to the activation of electric appliances, including plugs and lights. The evaluation of space heating and cooling energy needs has been performed in compliance with the Italian legislation [462]. The city of Benevento is characterised by

1316 heating degree days. As such, the heating period begins on 15th November, ends on 31st March, and allows at most 10 operating hours per day. Conversely, the cooling period starts on 1st June and ends on 30th September. During intermediate months, only the demand for DHW needs to be met. Indoor comfort conditions considered for calculating users' thermal and cooling energy demand have been derived from the Italian regulatory framework too. In particular, the set-point indoor temperature has been set equal to 20 ± 2 °C in heating mode and 26 ± 2 °C in cooling mode [465].

The yearly results obtained from dynamic simulations are listed in *Table 3.3*. Overall, residential users' total thermal energy demand is equal to 47 MWh/y, total cooling energy demand is equal to 10 MWh/y, total electric energy demand for appliances is equal to 56 MWh/y and DHW demand is equal to 14 MWh/y. Us#6 is characterised by the highest thermal and cooling energy need because of the larger volume to heat in winter and cool in summer. Conversely, DHW requests of Us#6 are slightly higher than Us#2, which has the lowest demand among all users. In fact, both Us#2 and Us#6 include two inhabitants. Highest DHW and electric energy requests pertain to Us#3, which includes six occupants.

Table 3.3 Energy demand of district users.

User	$E_{el,j}$ [MWh/y]	$E_{th,j}$ [MWh/y]	$E_{DHW,j}$ [MWh/y]	$E_{co,j}$ [MWh/y]
Us#1	6.4	5.8	2.9	1.6
Us#2	3.3	9.3	0.9	1.6
Us#3	17.0	8.0	3.2	1.8
Us#4	13.3	6.9	3.2	1.3
Us#5	12.8	5.8	2.9	1.8
Us#6	3.1	11.2	1.0	2.1
Us#7	66.8	79.9	0.0	22.0
Dis	122.8	127.0	14.2	32.1

The total available surface for the installation of PV and STh systems, considering the rooftops of all buildings within the district, amounts to 881.60 m² (inclined surface).

Tool outcomes and discussion

Input data related to the district's energy demand on an hourly basis, as well as the available surface area for solar-based systems, have been implemented in the tool. The selected plant configuration includes all the technologies selectable by the tool (CHP unit,

EHP, wind turbine, PV plant and solar thermal collectors). *Figure 3.6* illustrates the layout of the plant configuration adopted for the tool simulation. In *Figure 3.10* the results obtained by the tool implementation are reported. On the left side, the size of each plant is shown. The CHP unit is characterized by a P_{th}^{CHP} of 25.00 kW and a P_{el}^{CHP} equal to 20.00 kW, in accordance with the sizing procedure described in the previous section. This results in an annual thermal energy production of 152.83 MWh/year, of which 83.92 MWh/year are exported, and respective annual electric energy generation of 122.23 MWh/year, with 17.56 MWh/year exported. The EHP is sized to meet the residual thermal energy demand and is characterized by a P_{th}^{EHP} equal to 293.50 kW and P_{co}^{EHP} equal to 230.70 kW. The corresponding annual thermal and cooling energy production are 149.94 MWh/year and 132.25 MWh/year, respectively, assuming a *PLF* varying between 0.27 to 1. The exported thermal and cooling energy amounts to 78.53 MWh/year and 101.21 MWh/year, respectively. With regard to the wind turbine, its size is selected based on the remaining electric energy demand of the district and the availability of wind source in the selected location. The P_{el}^{Wt} equal to 225.00 kW is considered, resulting in an annual electric energy production of 731.83 MWh/year, with 75 % exported to the PG. The PV plant is sized according to the residual electric energy demand and the allocated share of the available area provided by the user as input data. The resulting installing capacity P_{el}^{PV} is 113.50 kW, yielding an annual electric energy production of 159.26 MWh/year, of which 68 % is exported to the PG. The DHW energy demand, not covered by energy surplus of thermal energy production systems, is considered for sizing solar thermal collectors, which have a total surface A^{STh} of 0.52 m^2. An electrically driven chiller, biomethane based boiler and the PG are considered to supply the remaining energy demand of the district. Additional chiller for process cooling are not included, as the process use energy demand is zero.

The lower part of *Figure 3.10* shows whether the PED conditions are satisfied, considering the thermal and electric RES balance and the carbon neutrality check, as defined by Equations 3.34, 3.35 and 3.36. In the Benevento district case study, all three are fulfilled, indicating the proposed technological design enables for the implementation of a PED.

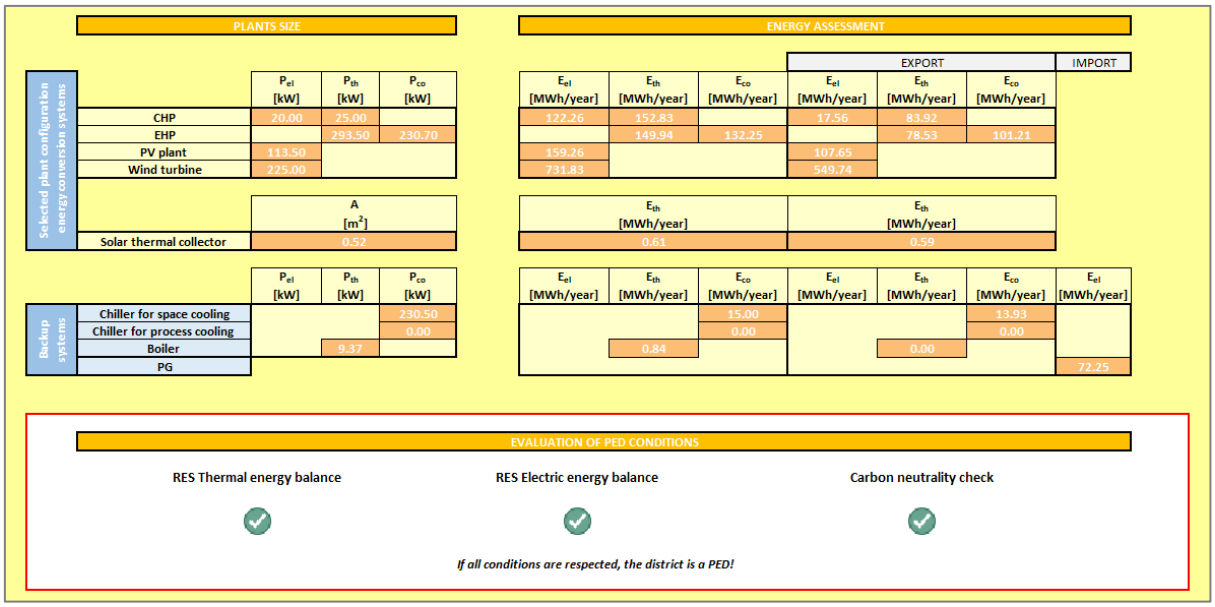

Figure 3.10 Results obtained from the implementation of the case study district.

The presented tool is a preliminary PED condition verification instrument, designed to assess project feasibility by providing indicative guidance on potential outcomes. The sizing of the systems within the selected plant configuration complies with the defined technical constraints and the availability of RES, supporting a design approach based on performance maps and the capacities available for each plant model, along with location-based data. The proposed modelling approach requires a preliminary analysis of the district, particularly focusing on its energy consumption, which represents one of the key input data required. In this context, the role of the planner is central to the use of the tool, as the selected plant configuration significantly influences the achievable outcomes.

Beyond facilitating the initial exploration of PED concepts, the tool is designed to serve as a comparative planning instrument for evaluating different urban planning strategies. Specifically, the selection of energy systems included in the configuration can be modified to simulate different energy conversion technologies under the same district energy demand. Alternatively, by maintaining the same technological configuration, it is possible to assess different system sizes based on variations in district energy demand, which may depend on the number of buildings included or on scenarios before and after the implementation of energy efficiency measures.

Future developments will focus on enhancing certain functionalities, as expanding the range of available sizes for systems such as the CHP unit or wind turbine, and

incorporating additional performance maps from several plant models to optimize the system sizing based on the load to be met, as in the case of the EHP. These improvements will help prevent both oversizing and undersizing of the systems. Furthermore, the integration of electrical and thermal energy storage will enable a reduction in energy exports to the PG and outside the district, thereby maximizing the utilization of energy produced within the district. This approach also allows for reduced system capacities, which, in accordance with the established load-satisfaction priority strategies, can operate under optimized conditions.

Chapter IV: Environmental impact reduction of energy consumption

The energy framework is currently undergoing a significant transformation, primarily driven by the rapid expansion of RES for electricity generation within the broader energy transition. In this evolving context, configurations such as RECs and PEDs have demonstrated the potential of collective, system-level solutions to enhance renewable integration, improve efficiency, and foster local cooperation. However, alongside these structured systems, the role of end-users emerges as a critical enabling factor for achieving tangible and scalable impacts. As a consequence of energy sector transformation, the CO_2 emission factor of the PG is progressively decreasing, while also exhibiting significant hourly variability. This shift remarks the strategic importance of end-users, whose active participation, both within organized energy systems but also through individual actions, can directly influence load profiles and contribute to emissions reduction. In this perspective, the chapter examines the hourly variation in both residential load profiles and the PG CO_2 emission factor, considering different seasons and types of days. Building on this analysis, an innovative approach for optimizing load profiles with the objective of minimizing associated emissions is introduced. To further support user engagement, a set of economic compensation mechanisms is proposed, including dynamic electricity tariffs, remunerative certificates for avoided emissions, and fiscal incentives. Finally, the applicability of the methodology is demonstrated through its implementation for a group of residential and commercial end-users, highlighting its potential to support both individual and collective contributions to the energy transition.

The study addresses a key research gap, as load shifting strategies are typically driven by energy or economic signals, while the environmental dimension remains underexplored. By prioritising emissions reduction, the proposed approach aligns with broader sustainability objectives and provides relevant insights for energy policy design. In particular, it supports the development of more effective regulatory frameworks and incentive schemes aimed at integrating environmental signals into DSM. In this sense, the results offer valuable guidance

for policymakers and public authorities, contributing to more informed decision-making processes and to the definition of strategies capable of accelerating the transition toward low-carbon and climate-neutral energy systems.

4.1 Innovative methodology based on the power grid CO_2 emission factor for environmental impact reduction of residential end-users

The increase in global average temperature has resulted in a surge in energy demand in recent years [466]. The connection among climate change, environmental degradation and the energy sector led the EU to adopt a common strategy. In 2021, the *European Green Deal* introduced the ambitious goal of carbon neutrality by 2050 for the whole continent, by improving energy efficiency and increasing the share of renewable energy [13]. The necessity to reduce the environmental impact of energy demand is the core of the *Fit for 55 %* package: to reduce net GHG emissions by at least 55 % by 2030 with respect to 1990 levels [14]. The economic growth of the renewables sector has over time brought a decrease in the technologies' installation cost, promoting their diffusion [467]. In 2022, the highest installation of RES plants was recorded, but in order to reduce the impact of the Covid-19 pandemic and the Russia-Ukraine conflict on economies, fossil fuel investments have not decreased [468]. The Glasgow Climate Pact (COP26) emphasizes accelerating and scaling up energy efficiency measures [469], which, by reducing the consumption of primary energy to meet the same energy demand, contribute to environmental sustainability [470].

Future overall energy consumption is predicted to increase, particularly in the building sector, due to global population growth, warmer global and local climate conditions, and rising household incomes that bring larger residences and consumption capacity, despite the focus on environmental sustainability and technological improvements in appliances [471]. The building sector nowadays represents one of the most energy-intensive sectors, accounting for about 30 % of global energy consumption and 27 % of global CO_2 emissions [472]. In the EU, households accounted for 25.8 % of final energy consumption in 2022 [473]. Increasing trends during the last few years are due to the rising use of air conditioning and limited improvement in energy efficiency. The increase in energy demand during specific periods, as high-temperature hours due to effects of global warming [474], leads to significant electricity

consumption peaks, causing intense PG stress and reliability problems. To mitigate these critical issues, strategies to shift end-users' load to times of lower demand can be applied [475]. DSM also allows the balancing of load curves based on the variability and non-programmability of RES-based plant production [476]. In this regard, the transformation of PG in recent years has been based on the development of decentralized RES plants and the implementation of smart microgrids. Indeed, positive trends can be observed regarding the environmental impact of electricity generation. The CO_2 emissions factor of the PG decreases over the years in countries that are significantly investing in the deployment of RES [353]. Evaluating the emissions factor of the PG on an hourly basis also provides crucial information about the times associated with a less environmental impact of electricity generation [477]. DSM can also contribute to environmental challenges by lowering peak demand, thereby decreasing the need to construct new traditional power plants [478], and shifting energy consumption to periods with low CO_2 emissions. Substantial changes to the energy production system should come with end-user awareness of their energy consumption, which can contribute to achieving energy and environmental goals.

The assessment of end-users energy needs is a widely discussed topic due to its impact on the energy system and its environmental consequences. Energy demand can be described using load profiles which highlight the variation during a specific period, such as a daily basis, and with different timesteps [479]. These are used for various tasks, such as managing supplies, predicting electricity needs and designing systems, as well as analysing demand for creating tariffs or determining which types of members to include in energy-sharing configurations [137]. The evaluation of the real energy load profile of residential end-users is a complex and not immediate process since real data are usually unavailable for privacy reasons or DSO protect them due to the correlated commercial value. In scientific literature two main approaches, "*bottom-up*" and "*top-down*", for estimating power demand in the residential sector are mainly examined [67]. The difference between the two lies in the source of input data. Bottom-up models estimate electricity demand for a small number of households, which reflects a broader spatial scale; then, the individual findings are extended [67]. Usual input data include technical evaluation of the most diffused domestic appliances, along with their corresponding load consumption, users behaviours, habits, occupancy types, dwelling characteristics and weather conditions [68]. Also data on the probability of appliances use are collected [480]. This methodology presents high precision, but is often correlated to a large amount of required input data and high complexity. The top-down method analyses statistical information or aggregated

data from national energy institutions or substation measurements to estimate the total load profiles of residential sector users. Used variables commonly include macroeconomic indicators, such as employment rates and price indices, climatic conditions, rates of housing construction and demolition, estimates of appliance ownership and residential sector unit numbers [70]. The study of these different approaches allows researchers to combine their strengths into new techniques and particularly provides crucial information for analysing the variables that most influence load profile trends. The four main categories of characteristics relate to buildings, appliances, occupant behaviour and climate [481]. A novel bottom-up multi-scale model, using a Monte Carlo semi-Markov approach, simulates residential users' energy consumption based on the probability and duration of specific actions, incorporating statistical information for the outcome of weekday and weekend load profiles [65]. Bignucolo et al., [482] evaluated residential end-users' behaviour from the analysis of the LV distribution network in a selected area. Acquisition of 1-minute time steps data for over one year led to the evaluation of a typical load profile with the assumption of significant interdependent variables: average daily temperature, hours of daylight and day type. Modelling household electric loads combining a statistical approach and collection of real data by experimental campaign, has been conducted to the definition of 14 dwelling archetypes, based on different family composition, appliances and building characteristics in order to categorise respective daily profiles in week day, Saturday, and non-working day [483]. The influence of user behaviour has been specifically analysed to justify the mismatch between measured and design values of buildings' energy consumption [484]. Nevertheless, studies focused on socioeconomic conditions and building characteristics as variables for residential energy needs, particularly due to space heating and cooling, highlight the number of rooms as the main factor [485]. The model developed by [486] hypothesizes that household energy consumption is positively affected by household income, which promotes greater policy understanding and energy knowledge. Hamdani et al., [487] demonstrate that the amount of electricity used increases with income. The influence of economic factors led to fairness-based models for the optimization of tariffs according to household incomes [488]. Once load profiles representative of real end-users' energy consumption are obtained, a variety of optimization methodologies can be employed. These primarily focus on the energy performance and economic savings, and are also applied to building design to act on parameters that directly impact energy demand reduction. Tools for facilitating user involvement can encompass applications based on ICT systems for managing energy usage in accordance with their preferences [489]. Sulaiman & Mustaffa [490] propose applications of mathematical algorithms focused on the achievement of a significant level of

user comfort and simultaneous minimization of energy consumption. Multi-objective method that combines bayesian optimization and genetic algorithm concerns energy consumption, thermal comfort, and daylighting, the three main factors of residential users [491]. A combination of energy and economic aspects is explored by [492]: energy consumption in a residential building is optimized for economic outflows reduction, although thermal comfort is guaranteed. Energy use intensity was also correlated to the maximization of useful daylight illuminance, considering different variables depending on the evaluated case study in [493]. A decision model to manage household energy demand is instead based on the signals of the community aggregator in which consumers take part. The main objective is minimizing the energy bill. The model simultaneously manages RES generation units with energy storage, shiftable, thermal and interruptible loads [494]. Also the decision-making system developed by [495] for actively managing household electricity consumption in smart grids with solar panels and energy storage minimizes the homeowner's electricity expenses. Mota et al. [496], present a load shifting strategy for residential users participating in DR events, aiming to minimize electricity expenses. The management of controllable load is proposed to reduce peak demand on the utility, by shifting it in favour of off-peak period, thereby reducing energy cost [497]. An integrated optimization problem combines the simultaneous management of consumption and generation in a microgrid with the evaluation of market impact, achieving reductions in energy import from the PG and so in users' bills [498]. The application of DSM strategies in residential communities is also explored in [499], where the focus is on managing peak demand. A case study of DSM on a university campus reports an average peak load reduction of about 10 %, leading to a proportional decrease in energy-related expenditures [500]. As shown, most optimization and load shifting models primarily aim at achieving economic savings and reducing energy consumption, which only as a consequence lead to a reduction in environmental impact.

DR programs usually present emissions reduction only as an indirect advantage because they decrease emissions by reducing peak demand, when the generating units with high emissions are activated, as the ones with lower emissions are already at maximum capacity [501]. As better clarified below, this study instead aims to propose the reduction of environmental impact directly related to the user's energy consumption profile variation as the main objective, filling this literature gap. The proposed methodology is in line with the achievement of SDGs that represent a decisive call for immediate actions from all countries, with particular reference to

SDG7 "*Affordable and clean energy*" – Target 7.2.1 "*Renewable energy share in the total final energy consumption*" [230].

In particular, this study aims to make a correlative analysis between the load profiles of residential users and the CO_2 emission factor of the PG, to propose a novel methodology aimed at shifting end-users' energy consumption to achieve the minimum corresponding environmental impact. In addition, with specific reference to Italy, the current structure of electricity tariffs is analysed concerning their correlation with environmental aspects, and economic compensation methods which can promote changes in end-user habits aimed at reducing GHG emissions, are proposed.

4.1.1 Methodology

Collective and single-user connection

In order to satisfy the electric energy demand of end-users, a reliable power system is required. The uncertainty in predicting user energy demands and plant production, particularly for RES-based systems, which depend on the availability of the concerned source, makes it necessary to have a complex structure. The power system consists of four main parts: production, transmission, distribution, and the user subsystem, as shown in *Figure 4.1.*

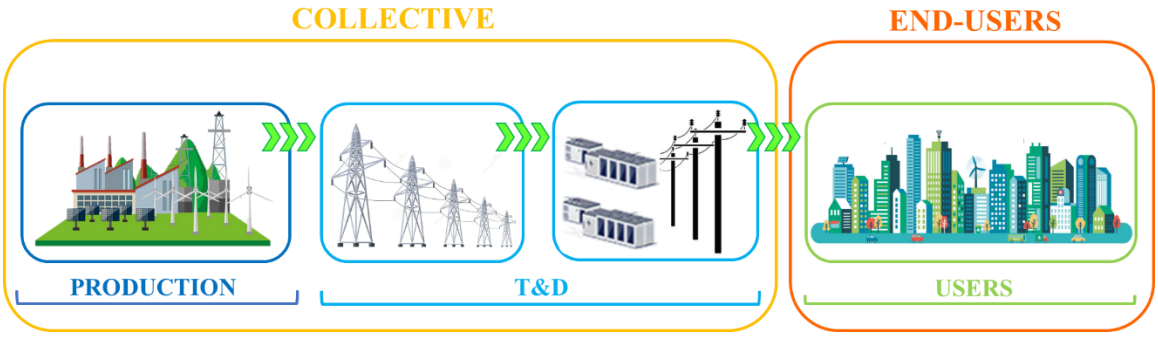

Figure 4.1 Subsections of the energy system.

The production subsystem concerns all the plants that exploit energy sources to obtain electricity. Energy sources are classified into RES and fossil fuels. The first class includes solar and wind as non-programmable RES, geothermal, bio-fuels and hydro as programmable [353]. Respective technologies are consolidated and widespread. Also marine energy, which includes wave energy, tidal energy and salinity gradient, is considered RES, but the respective technologies are less diffused and tested for research applications [502]. To support more significant usage of RES, governments could propose an incentivisation system to reduce production costs and discourage the use of plants with high GHG emissions, introducing carbon

dioxide taxes [503]. However, high RES penetration in energy systems needs an accurate assessment of limitations and critical issues, as protection strategies to isolate a PG portion in the event of plant problems [504]. The second class includes natural gas, hard coal, coal-derived gas, oil, other liquid, solid and gaseous fuels [353]. Their massive consumption depletes natural deposits easily accessible, therefore these are also called non-renewable sources. Nuclear energy represents an alternative to the presented classification, for which technologically advanced plants and relevant financial capacity are required. Although current nuclear power plants have low CO_2 emissions, their main issue concerns nuclear wastes [505]. The installation of nuclear plants is not permitted by law in some countries, so in the following investigation it will not be considered.

The transmission subsystem involves the transfer of the produced energy from the centralized plants for huge distances in order to reach the distribution lines. The share of energy produced entails HV transmission. Electrical substation from HV to MV indicates the beginning of the distribution subsystem. Its branched-out structure allows it to carry electricity to end-users. Electrical substations HV/MV, MV/LV and transformers are included in this subsystem. Despite different voltage levels and transition to the local level, these subsystems have the same function, so they could be grouped as Transmission & Distribution (T&D). PG covering the entire national territory allows the achievement of all users but amplifies the possibility of being damaged, increasing its vulnerability, for example, due to climate change, which will cause more and more windstorms and floods in the future [506]. Finally, the electricity arrives at end-users, who can be residential, tertiary, or industrial users.

Production and T&D constitute a macro subsystem which regards users as a unit because of the system's impact on them, while the last part of the power system individually concerns end-users, as highlighted in *Figure 4.1*. Each end-user is called to reward the complex power system for the service offered by paying the energy bills. The most common tariff worldwide is time-of-use (TOU): the day is divided into fixed parts with different electricity prices. A less used is dynamic TOU, which considers fixed price points applied to variable hours day by day [507].

Energy characterization of end-users

The residential users' load profile can be influenced by several aspects. These are considered by load profile evaluation methods as input to the forecasting models or as variables for the obtained results analysis, but giving priority to those not dependent on the specific case, which are most useful for energy and techno-economic analysis. To this end, climate aspects and social

factors are relevant. The first concerns the variation of the daylight hours or external temperature, to which the increase or decrease in summer space cooling and winter space heating requirements is directly related, and is mainly due to the alternation of the seasons. The second, as different appliance habits and the propensity to spend time at home, can be traced to alternating working days and weekends. In order to take into account each of these, the proposed methodology categorizes energy consumption based on:

- season: Spring (SR), Summer (SM), Autumn (AM), Winter (WN);
- typology of the day: Weekday (WD), Saturday (ST), No working day (ND) (Sunday and public holidays included).

The hourly energy consumption ($E_{s,t}(h_f)$) corresponding to each season (s) and day typology (t) is evaluated as the average of all the energy consumption values corresponding to the fixed hour (h_f) for the days (d) of the season belonging to each typology of day (Equation 4.1). The number of WD, ST and ND ($N_{s,t}$) that fall in the corresponding season is considered. t is equal to 1 for WD, 2 for ST and 3 for ND. The evaluation is conducted for the four seasons: s is equal to 1 for SR, 2 for SM, 3 for AU and 4 for WN. The fixed hour, h_f, instead, depends on the energy time slots f as established by the electricity tariff structure.

$$E_{s.t}(h_f) = \frac{1}{N_{s,t}} \sum_{d=1}^{N_{s,t}} E_d(h_f) \qquad \forall\, s, t, f \qquad (4.1)$$

Environmental impact of residential end-users

Electricity consumption is directly associated with environmental impact related to the corresponding mix of technologies used by the production subsystem. In particular, the typology of energy sources used impacts differently in terms of equivalent CO_2 emissions. To consider this effect, the CO_2 emission factor (α) of the PG, expressed in g_{CO_2}/kWh_{el}, is evaluated. In environmental impact analysis, the value of α is usually considered constant on a yearly basis for a specific country, but it represents an approximation of the real values, which are time and space-dependent. The methodology proposed above is applied in order to obtain trends for each day typology and season, Equation 4.2.

$$\alpha_{s,t}(h_f) = \frac{1}{N_{s,t}} \sum_{d=1}^{N_{s,t}} \alpha_d(h_f) \qquad \forall\, s, t, f \qquad (4.2)$$

Considering the respective number of WD, ST and ND for each season ($N_{s,t}$), their environmental impact is estimated in terms of CO_2 emissions ($CO_{2_{s,t}}$), as reported in Equation 4.3. Total CO_2 emissions ($CO_{2_{s,tot}}$) of each whole season are calculated in accordance to Equation 4.4.

$$CO_{2_{s,t}} = N_{s,t} * \sum_{f=1}^{3} \sum_{h_f} (E_{s,t}\,(h_f) * \alpha_{s,t}(h_f)) \qquad \forall\, s,\, t \qquad (4.3)$$

$$CO_{2_{s,tot}} = \sum_{t=1}^{3} CO_{2_{s,t}} \qquad \forall\, s \qquad (4.4)$$

Load profiles optimization methodology

In recent years, end-users have developed a more conscious interest in reducing the environmental impact of human activities. This aim can also be achieved by optimizing the end-user load profile to minimize GHG emissions associated with electricity production in the same time interval. End-user energy consumption follows technical (external temperature and daylight hours), social (working hours and days), and economic reasons (to consume during the hours when energy is cheaper according to the electricity tariff structure). For the first two reasons, the daily energy consumption cannot be shifted only during those hours where the respective environmental impact is minimal, since not all loads are movable, but some can be shifted in order to obtain a reduced environmental impact, also considering the same daily energy consumption. The proposed methodology does not investigate the type of devices to move, but aims to present an optimized load profile with a minimum value of CO_2 emissions. In particular, the methodology assumes that the time range in which the end-user can directly act excludes night hours, so it is proposed to reallocate the energy consumption from 6 a.m. to midnight ($H^{(0)}$=7,8,…,24). In accordance with [482], the load related to specific electric uninterrupted working mode appliances has been considered as the base load ($E_{s,t}^{MIN}$). As reported in Equation 4.5, this term has been evaluated as the minimum hourly energy consumption value of each day. Equation 4.6 reports that the base load reduces the share of daily energy consumption to reallocate for optimization ($E_{s,t}^{*}(h)$) for each hour. The sum of $E_{s,t}^{*}(h)$ for the whole time period represents the energy load to optimize daily. Thus, the method proposes to reallocate energy consumption in an inverse proportional way to the respective environmental impact, through the hourly α value, that is, by associating the hours with lower emission factor with a higher energy consumption. As reported in Equation 4.9, the weighted

value of α for each concerned hour ($\alpha_{s,t}^{W}(h)$) is evaluated, as the ratio between the hourly CO_2 emission factor reduced by the minimum in the considered time range (Equations 4.7 and 4.8), and the sum of α values in the same time period.

$$E_{s,t}^{MIN} = \min(E_{s,t}(h)) \qquad h \in H^{(0)} \quad \forall\, s,\, t \qquad (4.5)$$

$$E_{s,t}^{*}(h) = E_{s,t}(h) - E_{s,t}^{MIN} \qquad h \in H^{(0)} \quad \forall\, s,\, t,\, h \qquad (4.6)$$

$$\alpha_{s,t}^{MIN} = \min(\alpha_{s,t}(h)) \qquad h \in H^{(0)} \quad \forall\, s,\, t \qquad (4.7)$$

$$\alpha_{s,t}^{*}(h) = \alpha_{s,t}(h) - \alpha_{s,t}^{MIN} \qquad h \in H^{(0)} \quad \forall\, s,\, t,\, h \qquad (4.8)$$

$$\alpha_{s,t}^{W}(h) = \frac{\alpha_{s,t}^{*}(h)}{\sum_{h=7}^{24} \alpha_{s,t}^{*}(h)} \qquad h \in H^{(0)} \quad \forall\, s,\, t,\, h \qquad (4.9)$$

The results of Equation 4.9 constitute the set $A_{s,t}^{(0)}$ for each season and day type. The system of Equations 4.10 illustrates the mathematical formulation of the proposed method. The procedure is iterative, and *k* is the iteration index. Initial condition (for *k*=1) consider the whole set of hours in which the energy shares are expected to be reallocated ($H^{(1)} = H^{(0)}$) and the whole set of weighted values of α ($A^{(1)} = A^{(0)}$). For each iteration, for each season and type of day, the lowest and highest value of the weighted value of α ($\alpha_{s,t}^{W-MIN\,(k)}$, $\alpha_{s,t}^{W-MAX\,(k)}$) are considered. In correspondence of the hour associated to the lower value ($h_{\alpha^{W-MIN}}^{(k)}$), the optimized energy consumption ($E_{s,t}^{op\,(k)}$) is evaluated as proportional to the daily $E_{s,t}^{*}$ with respect to the $\alpha_{s,t}^{W-MAX\,(k)}$, adding the base load to obtain the final outcome. For the next iteration (*k+1*) the procedure is repeated, not considering the hour and maximum α weighted value already taken into account, until all energy values are reallocated ($H^{(k)}$=Ø). The sum of optimized energy consumption on a daily basis must be equal to non-optimized energy consumption for each season and typology of day (Equation 4.11). The methodology was developed in Matlab environment [281].

$$\begin{cases} \alpha_{s,t}^{W-MIN\,(k)} = \min\left(\alpha_{s,t}^{W}(h)\right) & h \in H^{(k)},\ \alpha_{s,t}^{W} \in A^{(k)} \\ \alpha_{s,t}^{W-MAX\,(k)} = \max\left(\alpha_{s,t}^{W}(h)\right) & H^{(k)}=H^{(k-2)}\text{-}h_{\alpha^{W-MIN}}^{(k-1)} \\ E_{s,t}^{op\,(k)}(h_{\alpha^{W-MIN}}^{(k)}) = (\alpha_{s,t}^{W-MAX\,(k)} * \sum_{h=7}^{24} \mathrm{E}_{s,t}^{*}(h)) + E_{s,t}^{MIN} & A^{(k)}=A^{(k-2)}\text{-}\alpha^{W-MAX\,(k-1)} \\ & \forall\ s,\ t \end{cases} \quad (4.10)$$

$$\sum_{h=7}^{24} \mathrm{E}_{s,t}(h) = \sum_{h=7}^{24} \mathrm{E}_{s,t}^{op}(h) \qquad \forall\ s,\ t \qquad (4.11)$$

Economic mechanisms for reward

The impact of user energy consumption depends mainly on the type of device used and the mix of technologies considered by the production subsystem, and therefore, in particular, on the energy source to obtain the required electricity share. On the first aspect, the user can act by choosing devices with greater energy efficiency, which involve a lower energy consumption for the same required effect. On the second aspect, the end-user is unable to operate directly because of the lack of indications from the TSO on the environmental impact of consumption hours. However, these indications can be provided to end-users through an economic scheme based on a tariff structure divided into different consumption ranges. Indeed, financial factors have the biggest impact on people's willingness to save energy, with ecological concerns coming in a close second [508]. The flexibility markets can support adjustment in end-users' energy consumption through market-based DSM techniques. Energy efficiency and DR methods are included. The latter can be price-based and incentive-based DR. The first does not take into account the preferences of end-users, who receive bill credits or payments for load reductions by the pre-contractor [509]. The second partially overcomes this limit, making provisions. These methods can be classical, where system operators contract with customers to control their load, and market-based, when end-users are rewarded if they choose to contribute to a DR event [510]. In regard to the proposed methodology, to encourage people to respect indications on optimization of energy consumption for reduced environmental impact, specific compensation methods can be introduced:

1. *new CO_2-oriented tariff structure*: the most economical consumption time slots should concern time intervals where the lowest α values are recorded. Energy consumption in the remaining hours should be more expensive;
2. *CO_2 emissions certification scheme*: end-users who adapt their load curves to reduce the environmental impact can be rewarded with certificates that attest achievement

of a share of avoided CO_2 emissions. In order to implement it, the national competent authority of each state must provide for measurement mechanisms. The acquired certifications should have an economic value. Such schemes already exist to reward measures that provide substantial environmental impact reduction, as avoided CO_2 emissions [511,512];

3. *tax reduction*: taxes may be reduced to lower rates for users who adapt their electricity profile by reducing the associated CO_2 emissions, in line with the national targets for GHG emissions reduction.

4.1.2 Application to the Italian residential end-users energy consumption

The methodology proposed in this study is applied to the Italian case study. Electricity production in Italy is still largely dependent on fossil fuels, although the development of RES is constantly increasing. In 2023, 81.8 % of national energy needs were covered by national production, with 34.5 % from RES [513]. To face the Italian energy demand, additional energy imports from other countries are necessary [514]. The growing presence of RES in power systems, on the one hand, reduces the environmental impact of the whole system, but on the other hand, it reduces the programmability of energy production.

To effectively utilize the complex system related to electricity availability, as shown above, end-users must pay according to established tariff schemes. The complexity of pricing systems discourages the implementation of complicated tariffs, so residential users especially prefer static ones. Although the structure of energy tariffs differs from country to country, for the purpose of providing concrete data and obtaining numeric results, the reference electricity tariff system will be based on the Italian structure. However, the methodology can be generalized to other tariff systems.

In Italy, four main sections constitute the electricity bill for a residential end-user:

- expense for the energy;
- expense for the meter transport and management;
- management fees;
- taxes.

The expense for the energy part consists of a fixed part, paid to have an active POD and applied monthly, regardless of the contracted power, and a variable part, paid proportionally to

the energy consumption. The price is different for time slots [515], which current structure was introduced with Deliberation AIR 181/06 by ARERA in 2007 [396]. The hourly subdivision was inserted with the aim of encouraging efficient user behaviours in response to different prices and to provide a more efficient way of remunerating them. Three different time slots for energy consumption are defined:

- F1 (peak): from Monday to Friday, from 8.00 am to 7.00 pm;
- F2 (mid-level): from Monday to Friday, 7:00 am to 8:00 am and 7:00 pm to 11:00 pm, Saturday from 7:00 am to 11:00 pm;
- F3 (off-peak): from Monday to Saturday from midnight to 7.00 am and from 11:00 pm to 12:00 pm; all day on Sundays and holidays [516].

The presented structure is reported in *Figure 4.2*. Electricity price decreases from F1 to F3.

HOUR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Price
Weekday	F3	F3	F3	F3	F3	F3	F3	F2	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F2	F2	F2	F2	F3	High
Saturday	F3	F3	F3	F3	F3	F3	F3	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F2	F3	
Sunday	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	F3	Low

Figure 4.2 The Italian electricity tariff structure.

The expense for the meter transport and management can have a quarterly change and is composed of energy, power and fixed part, proportional to the engaged power and monthly applied. Management fees are variable on a quarterly basis; they are composed of energy, power and fixed part. The second is not applied to domestic users, while the third is not to the primary residence. Taxes include consumption fees applied to energy consumption and VAT applied to the total amount of the bill [517]. Consumption fees are not applied to the first 150 kWh/month of energy consumption. Currently, VAT is equal to 10 % for domestic users and 22 % for non-domestic users [518].

The collected data for the energy assessments are from National Authorities, used to build a plausible load profile for residential users in Italy. ARERA carries out the analysis of energy consumption data for residential end-users in Italy. The procedure is carried out on the basis of measurement data made available by the DSOs via the Integrated Information System. In particular, data are related to:

- aggregate energy consumption data;
- total number of domestic end-users in the electricity sector in Italy, broken down by geographical area.

Data are available on a monthly basis as a percentage distribution for each of the three different time slots [519]. Residential energy consumption data have been filtered considering only the representative categories of most of the population:

- resident consumers: occupied dwellings represent 72.8 % of all dwellings [520];
- engaged power range 1.5-3 kW: it accounts for 85.8 % of all household users, and the share of electricity withdrawn from the PG by these customers represents 76.1 % of the total [521];
- electricity market: both free and protected.

Considering the whole Italian territory, data for 2022 have been considered. Energy consumption percentage values ($p_{m,f}$) for each energy time slot (f, ranges from 1 to 3 for F1, F2, F3 respectively) for the twelve months (m, ranges from 1 to 12) have been considered to obtain the respective energy consumption data ($E_{m,f}$), by multiplying the average monthly energy consumption (E_m), which has been extracted by the ARERA dataset, applying the same previous criteria, Equation 4.12. Results are shown in *Figure 4.3*.

$$E_{m,f} = E_m * p_{m,f} \qquad \forall\, m,f \qquad (4.12)$$

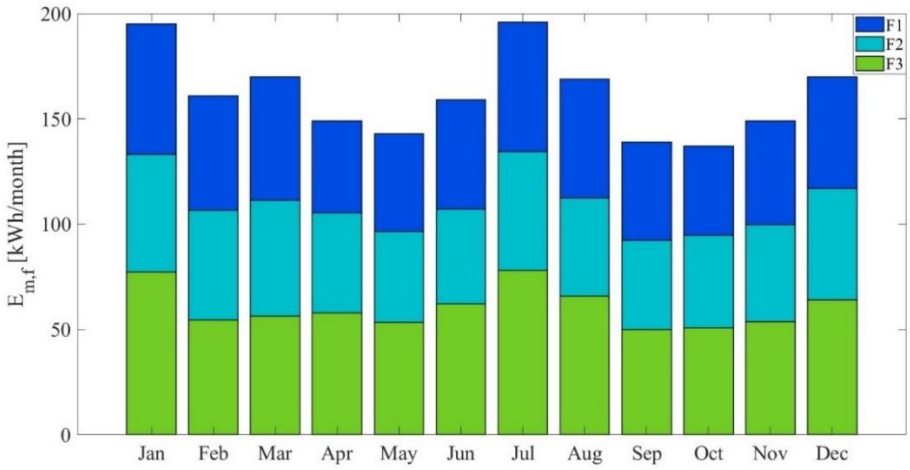

Figure 4.3 Residential user energy consumption for F1, F2, F3 on a monthly basis.

The outcomes facilitate monthly analysis of the different weights of the energy consumption time slots, but it is not possible to have information on the variables that most affect the consumption. However, the consumption peaks are reached in the hottest (July) and coldest months (January), while lower values are observed for the intermediate months, highlighting the seasonal influence on energy consumption.

To assess the dependence on the typology of day, data with deeper detail have been considered. The GSE provides, for each month, the percentage values representative of the weight of each hour belonging to a specific consumption range [522]. Each monthly value (g_m) differs on an hourly basis (h_f) depending on the energy consumption time slot (f).

In order to obtain load profiles for residential users categorized on the basis of season and typology of the day, the quantitative data, energy consumption for each time slot month by month ($E_{m,f}$), and qualitative data, percentage hourly values ($g_m(h_f)$), have been combined. As reported in Equation 4.13, the hourly energy consumption ($E(h)$) has been obtained for the whole year (h from 1 to 8760).

$$E(h) = E_{m,f} * g_m(h_f) \qquad \forall\, h, m, f \qquad (4.13)$$

The dependence on the month has been converted in favour of the season:

- SR: from 21th March to 20th June;
- SM: from 21th June to 22th September;
- AU: from 23th September to 20th December;
- WN: from 21th December to 20th March.

Using the proposed methodology, different seasonal load profiles have been obtained according to the day typology, thus achieving indications about energy consumption for each consumption range: WD (F1, F2, F3), ST (F2, F3) and ND (F3). In *Figure 4.4*, seasonal load profiles are presented.

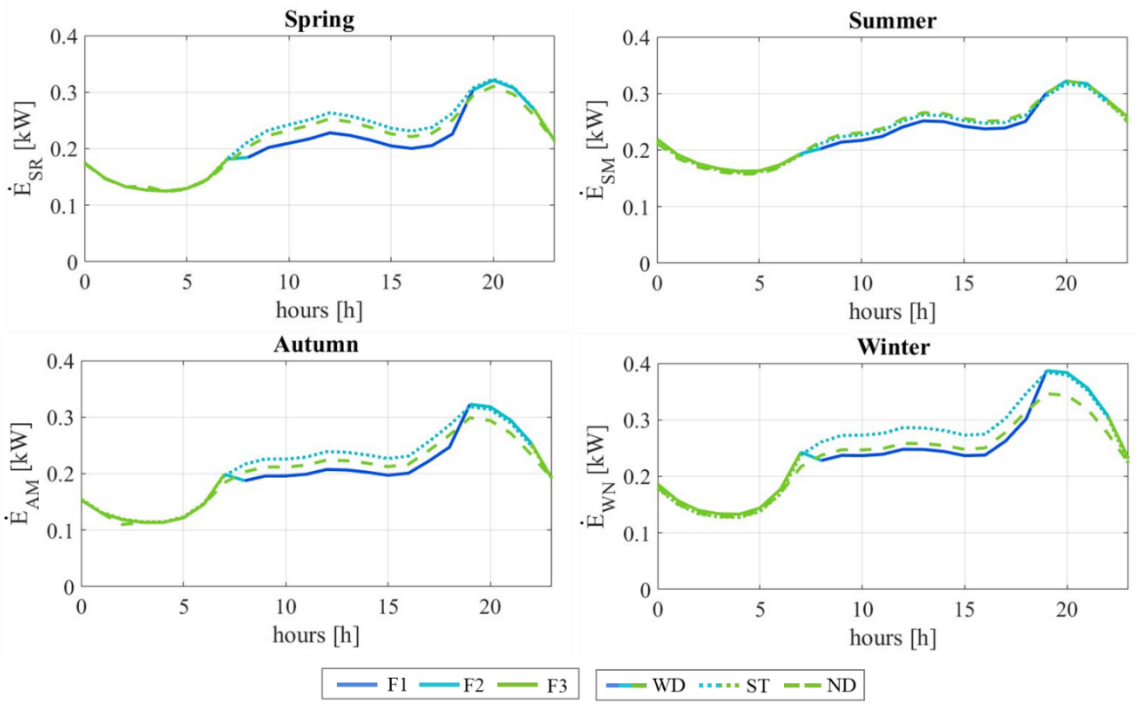

Figure 4.4 Seasonal load profiles for each typology of day.

For each season, the three load profiles are totally superimposed during night hours. SM has higher consumption values than other seasons in this period. In addition, the load profile WD always presents lower consumption values than the respective ST and ND, which is attributable to a lower occupation. WN presents higher hourly consumption values than other seasons during the hours of activity, with particular reference to the peak demand in the evening.

In regard to the environmental impact of electricity generation, [353] demonstrated the significant variation of the CO_2 emission factor for Italian PG, highlighting the variation in each of the Italian market zones, due to the different presence of RES. This methodology estimates it as the ratio between the sum of the product of the specific emission factor of each fossil fuels and corresponding energy production, which represents the overall CO_2 emissions from fossil fuel combustion in thermoelectric plants for electricity generation, and the hourly net electricity production from each source (RES and fossil), reduced by pumped storage hydroelectricity demand and T&D losses through a reduction factor. Following the methodology presented in [353], hourly values of α for Italy have been evaluated for 2022. The obtained seasonal α profiles are shown in *Figure 4.5*.

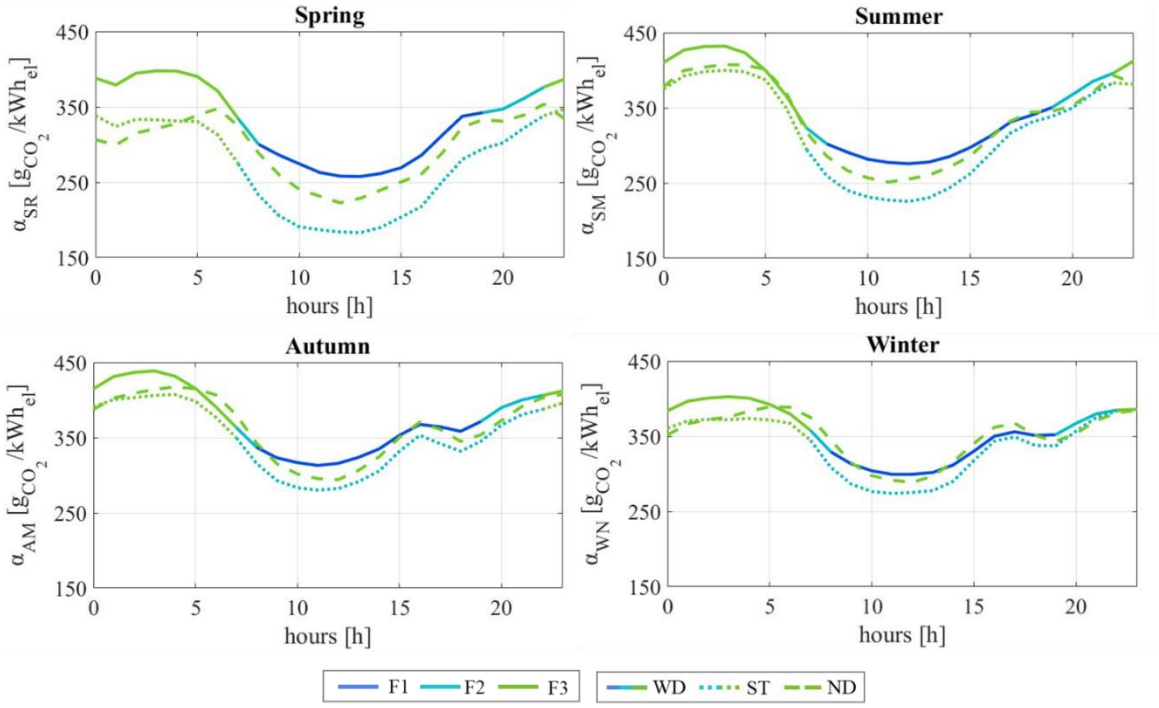

Figure 4.5 Seasonal CO_2 emission factor profiles for each typology of day.

Hourly variation of CO_2 emission factor shows a similar evolution for each of the four seasons and three typologies of day, with the lowest values in the central hours of the day, when the explanation of programmable RES is added to solar PV, which is the RES-based technology with the highest capacity installed in Italy in the last 10 years (20.9 GW in 2019 and 30.3 GW in 2024) [523] and the corresponding productibility is only in daylight hours. The comparison among seasons points out higher α values for WN and AM at equal hour range, significantly affected by the seasonal nature of the solar source. The same trends also reflect the results from [477], which presents the application of a simplified model with an interpolating function for evaluating the CO_2 emission factor of Italian PG.

Outcomes are reported in *Table 4.1* and shown in *Figure 4.6* on a seasonal basis, both overall and for each type of day.

Table 4.1 Number of days, energy consumption, CO_2 emission factor and CO_2 emissions for each typology of day (WD, ST, ND) for each season (SR, SM, AM, WN).

	Type of day	SR	SM	AM	WN
N [day/season]	WD	64	65	62	61
	ST	13	13	13	13
	ND	16	14	15	16
E [kWh/day]	WD	4.90	5.50	4.74	5.70
	ST	5.27	5.57	5.07	6.04
	ND	5.09	5.61	4.81	5.60
	WD	7.97	8.34	9.01	8.53

α [kg_{CO_2}/kWh]	ST	6.51	7.67	8.42	8.11
	ND	7.11	8.05	8.77	8.41
CO_2[kg_{CO_2}/season]	WD	102.72	124.30	108.98	122.41
	ST	18.10	22.90	22.71	26.17
	ND	23.93	26.02	25.91	31.09
	tot	143.15	177.05	155.84	179.67

As reported, WN is the most impactful season from an environmental viewpoint, with 27.4 % percentage weight. This is particularly ascribable to the significant weight of WD emissions, and despite N_{WD} is slightly lower than for other seasons, respective α and energy consumption values for WD are higher. ND emissions for WN, which weigh 29 % of the total NDs, are also significant. WN is followed by SM, mainly due to the high value of N_{WD} and corresponding daily energy consumption.

Figure 4.6 Percentage distribution of CO_2 emissions for each season and typology of day.

4.1.3 Results and discussion

This section presents the results of the proposed methodology, applied to electricity consumption loads, highlighting consequential CO_2 emissions reduction and economic results. The non-optimized and optimized (line with circle markers) energy consumption load profiles and CO_2 emission factor on an hourly basis, are presented for each season for WD (*Figure 4.7*), ST (*Figure 4.8*) and ND (*Figure 4.9*). The optimization methodology was applied considering the same daily energy consumption.

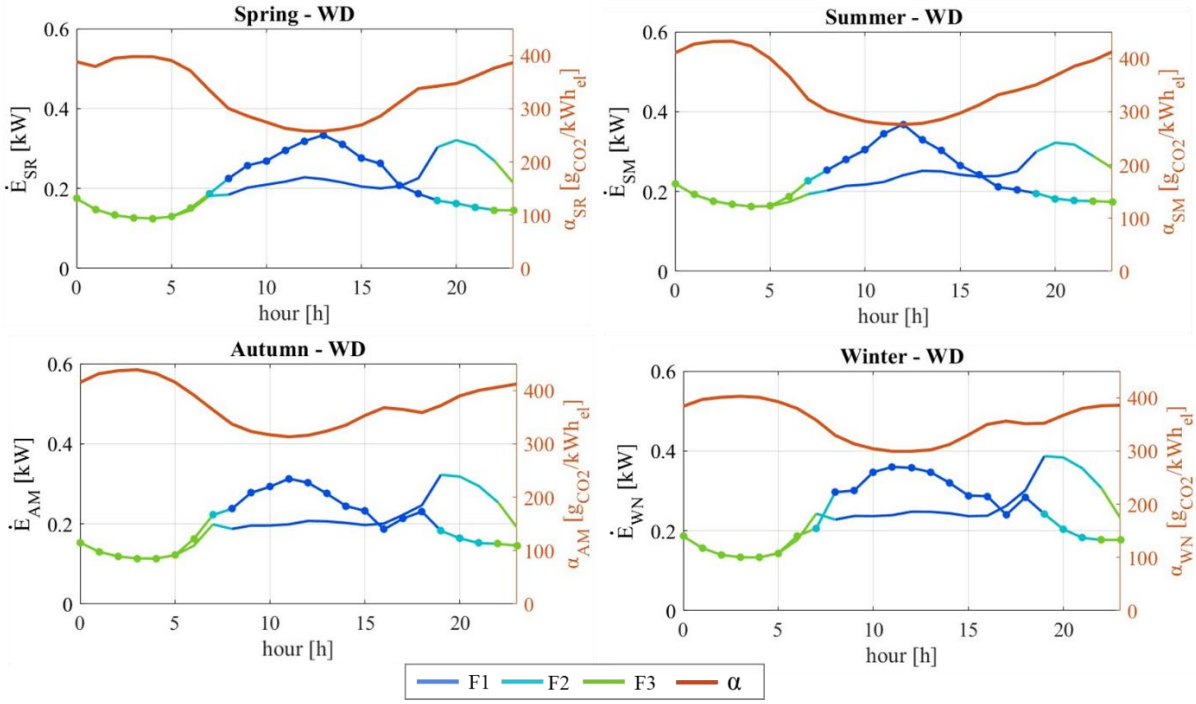

Figure 4.7 Seasonal optimized (circle markers) and non-optimized (no markers) WD load profiles and CO_2 emission factor (orange line).

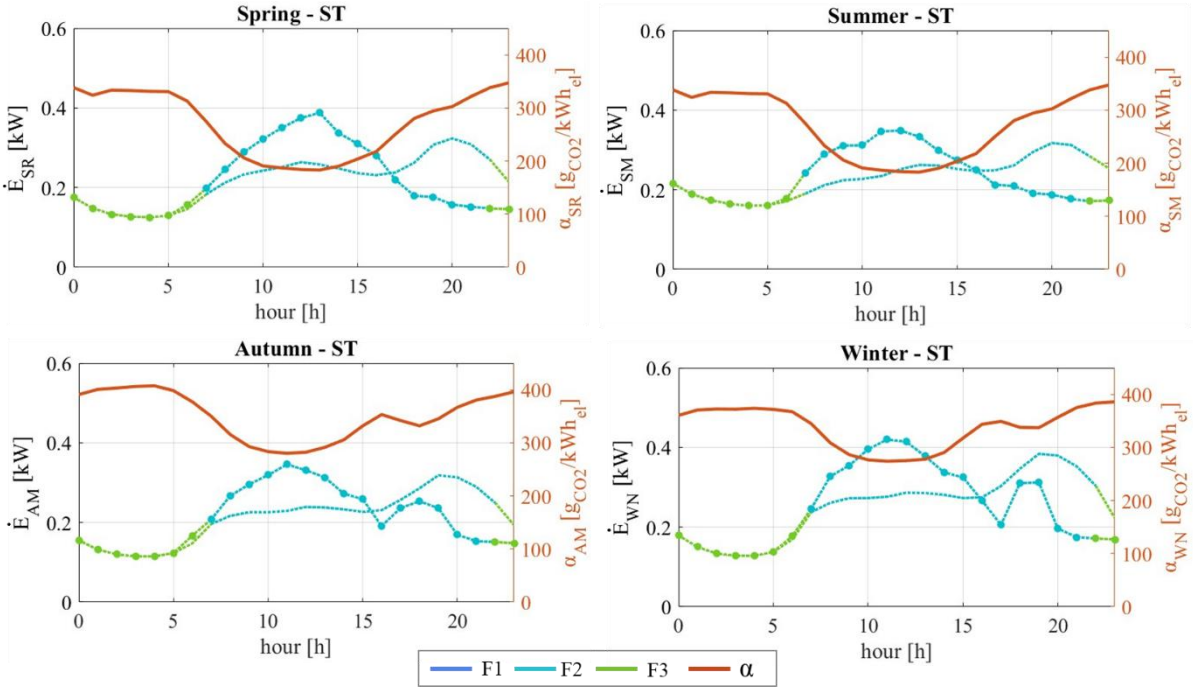

Figure 4.8 Seasonal optimized (circle markers) and non-optimized (no markers) ST load profiles and CO_2 emission factor (orange line).

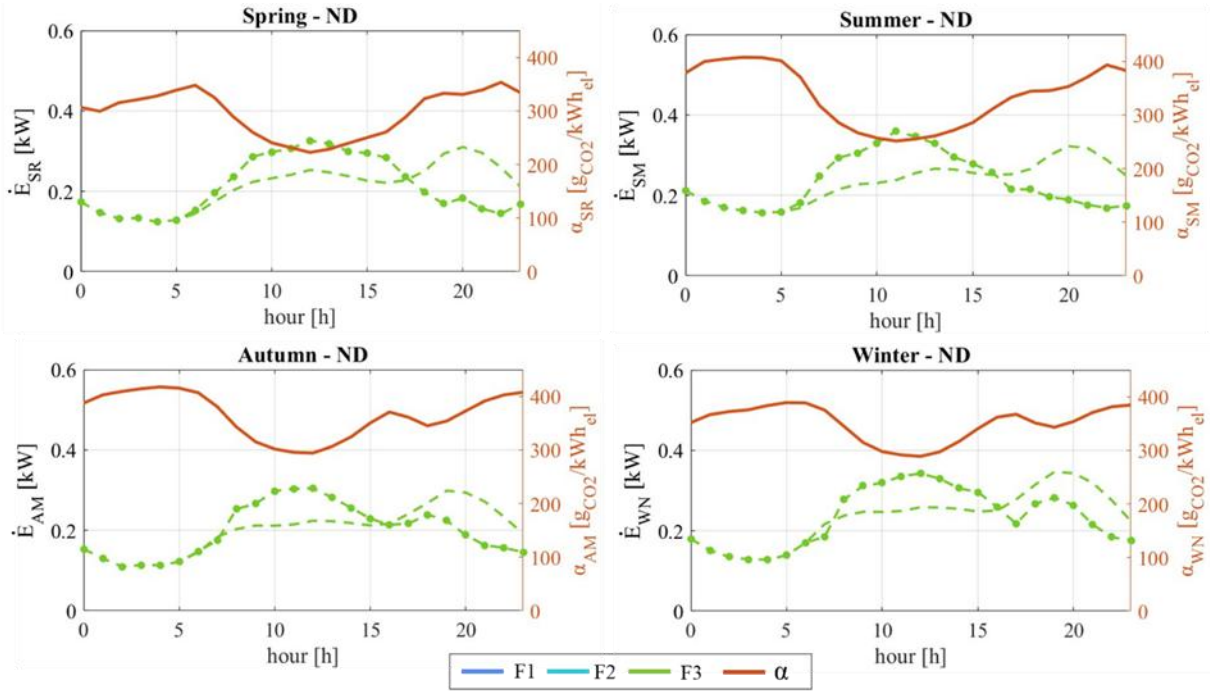

Figure 4.9 Seasonal optimized (circle markers) and non-optimized (no markers) ND load profiles and CO_2 emission factor (orange line).

As expected, the optimized profiles show higher values during the hours when α reaches lower values. The peak electricity consumption observed in the evening hours for non-optimized profiles is largely shifted to the central hours of the day in the optimized profiles. In the case of WD, the load shift is particularly noticeable during the hours corresponding to the F1 band, which, under optimized conditions, experiences higher energy consumption compared to current profiles. PG limitations often restrict the injection and distribution of RES energy generated during periods of low demand. By shifting the load as observed, this issue could be mitigated, enabling greater use of energy by RES during the central hours of the day rather than the evening, even under the same overall demand. A comparison of the optimized load values between WD and ST within the same season reveals that values are generally higher for ST. This difference can be partially explained by the lower α values observed during the same time period. The proposed methodology inherently favours hours with lower emissions, as it assigns greater weight to the share of energy that can be associated with those hours. In ND, the variations in load during the central hours are less pronounced, with an average negative variation equal to -5 % with respect to WD. The load profile is more evenly distributed throughout the central hours of the day, and notably, evening consumption peaks are lower than those recorded on other types of days.

In *Figure 4.10*, CO_2 emissions outcomes are presented by comparing results from non-optimized and optimized energy consumption profiles.

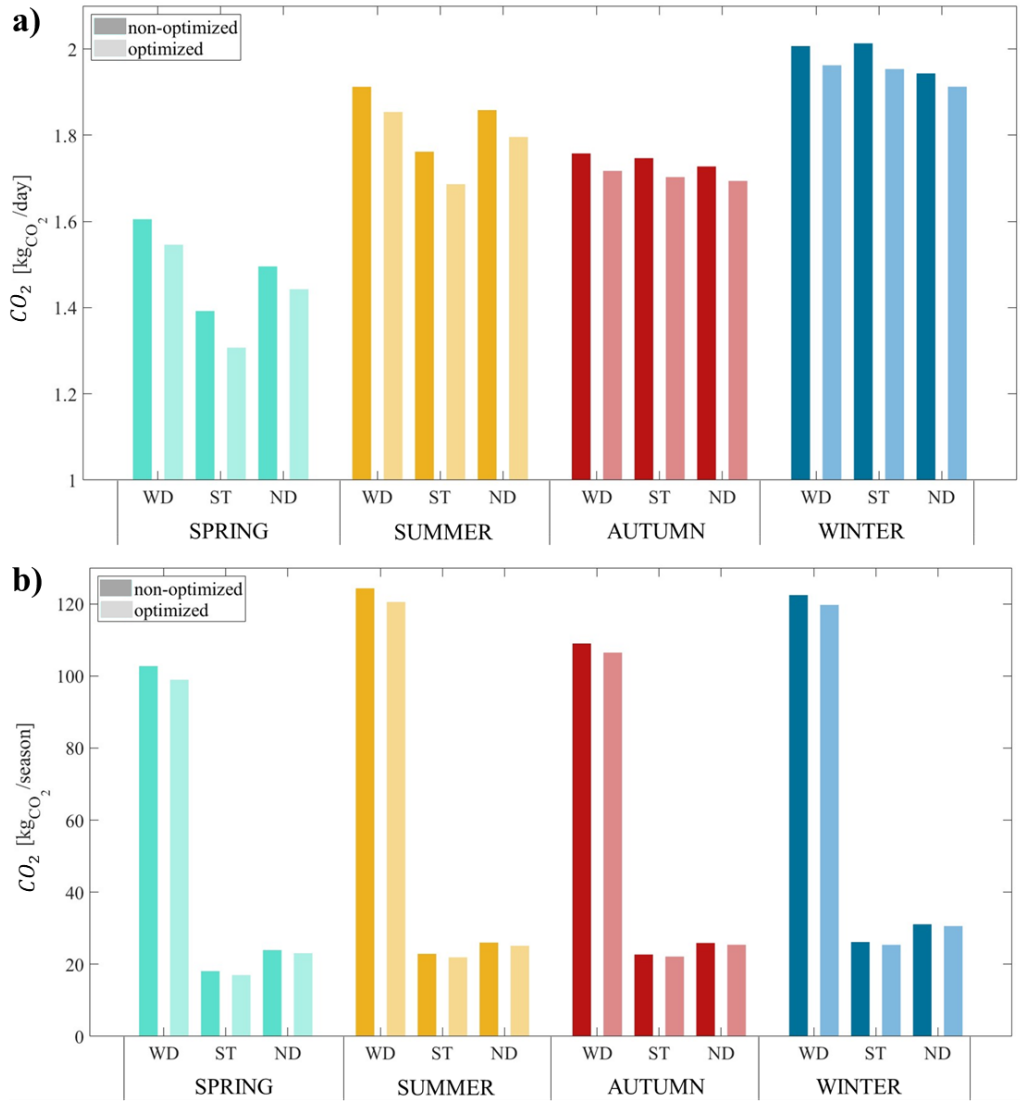

Figure 4.10 CO_2 emissions for each day typology and season, on a daily (a) and season (b) basis.

*Figure 4.10*a shows CO_2 emissions for each day typology and season, thus the impact of the single day in terms of direct environmental impact is evaluated. Summer and Spring present percentage differences higher than Autumn and Winter. In particular, the average percentage difference of all data is equal to 3.13 %, while for ST-Spring and ST-Summer, 6.11 and 4.28 % are reached respectively. During these specific days, the most significant variation of α profiles is observed. The lowest value is for ND-Winter (1.58 %), where the non-optimized energy load presents a flatter profile than others, and optimization methodology leads to a less important energy shift toward the middle hours of the day. *Figure 4.10*b presents CO_2 emissions outcomes on a seasonal basis. Each season presents the highest values for WDs due to the more consistent

number of days with respect to STs and NDs. In particular, WD-Summer presents the highest CO_2 emissions values both for optimized and not energy load profiles, mainly due to the high value of daily energy consumption associated to high N_{WD}. Winter presents the highest values for NDs, due to the high N_{ND} and respective E_{ND}. On the whole, shifting from non-optimized to optimized outcomes, involves 2.89 % reduction (-18.93 kg_{CO_2}/year). WD-Summer presents the highest value of CO_2 emissions avoided with the proposed methodology, equal to 3.80 kg_{CO_2}/season, followed by 3.78 kg_{CO_2}/season of WD-Spring.

In order to analyze in detail the results obtainable with the proposed methodology, a sensitivity analysis was conducted as the fixed base load varied, considering a reduction of $E_{s,t}^{MIN}$ as defined in Equation 4.5, from 5 % to 40 %. The results of the total emissions percentage change obtained with the optimized load profiles compared to the non-optimized case are presented in *Figure 4.11* for each type of day (a) and season (b). As the non-shiftable base load share decreases, the energy to be reallocated on a daily basis increases. It is therefore observed that an increase in the values is reached at the hours corresponding to low α values (central hours) and a decrease at the hours for which the environmental impact is greater (evening hours). As shown in *Figure 4.11*a, ST exhibits a more significant percentage change in associated emissions resulting from more evident variations between maximum and minimum values of the emission factor trend than those observed on other types of days. The percentage change for WD and ND follows the same trend. Comparing the results obtained on a seasonal basis, *Figure 4.11*b, it is shown that the smallest variations occur for WN and AM, followed by SM and SR. This confirms that in cold seasons, the potential for reducing environmental impact is constrained by the α values. In spring and summer, instead, these values are lower due to the higher penetration of RES, making load shifting towards periods of lower environmental impact more beneficial.

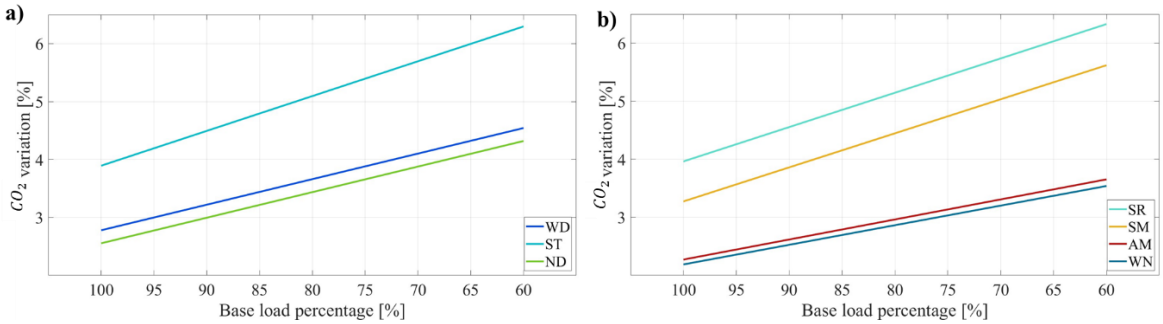

Figure 4.11 Percentage CO_2 emissions variation depending on the share of non-shiftable base load, by day type (a) and season (b).

Numerical results of avoided CO_2 emissions may not seem particularly relevant in percentage and absolute terms, but it is important to remember that assessments have been conducted with equal energy load for residential users. The reduction is therefore only associated with shifting energy consumption to more environmentally advantageous hours. By combining this shift with energy efficiency behaviours, user could meet their needs by reducing electric energy withdrawn from the PG and, consequently, CO_2 emissions. Moreover, the decreasing trend of α values in recent years, mainly due to an increasing presence of RES-based plants, represents a favourable aspect for applying methodologies such as that proposed.

In order to encourage end-user behaviour which may tend to have a load profile that is as complementary as possible to the α profile, detailed economic assessments were carried out. Several scenarios have been evaluated:

- S#0: current electricity tariff applied to non-optimized load profile;
- S#1.1: current electricity tariff applied to optimized load profile;
- S#1.2: new CO_2-oriented proposed tariff applied to optimized load profile;
- S#2.1: current electricity tariff applied to optimized load profile, in addition to carbon certificates;
- S#2.2: new CO_2-oriented proposed tariff applied to optimized load profile, in addition to carbon certificates;
- S#3.1: current electricity tariff applied to optimized load profile, in addition to taxes reduction;
- S#3.2: new CO_2-oriented proposed tariff applied to optimized load profile, in addition to taxes reduction.

In *Table 4.2*, the costs of the electricity bill items considering a tariff currently in force are shown [524]. The fixed share of expense for energy has been evaluated as an average value among the offers available on the Italian electricity market [525].

Table 4.2 Current electric energy tariff costs.

	Energy			**Meter transport and management**	**PG management**	**Taxes**	
	F1	**F2**	**F3**			**Consumption fee**	**VAT**
Energy share [€/kWh]	0.18	0.17	0.15	0.014	0.032	0.023	
Fix share [€/year]		100		22.80	-	-	10%
Power share [€/kW/year]		-		25.28	-	-	

Table 4.3 shows the costs of the electricity bill items considering a new proposed tariff, that implies:

- *new allocation of energy consumption time slots*: F1 from 8.00 am to 7.00 pm, F2 from 7:00 am to 8:00 am and 7:00 pm to 11:00 pm, and F3 from midnight to 7.00 am and from 11:00 pm to 12:00 pm, all day of the week (*Figure 4.12*);
- *CO_2-oriented tariff structure*: F3 energy consumption time slot, to which higher values of α correspond, is more expensive; F1 energy consumption time slot, when α values are lower, is less expensive; the F2 cost remains unchanged.

Table 4.3 CO_2-oriented electric energy tariff and corresponding costs.

	Energy			Meter transport and management	PG management	Taxes	
	F1	F2	F3			Consumption fee	VAT
Energy share [€/kWh]	0.15	0.17	0.18	0.014	0.032	0.023	
Fix share [€/year]		100		22.80	-	-	10%
Power share [€/kW/year]		-		25.28	-	-	

HOUR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Price
Weekday	F3	F3	F3	F3	F3	F3	F3	F2	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F2	F2	F2	F2	F3	High
Saturday	F3	F3	F3	F3	F3	F3	F3	F2	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F2	F2	F2	F2	F3	
Sunday	F3	F3	F3	F3	F3	F3	F3	F2	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F1	F2	F2	F2	F2	F3	Low

Figure 4.12 Structure of CO_2-oriented electricity tariff structure.

In scenarios S#2.1 and S#2.2, the value of certificates was assessed in a proportional way to the European EU ETS market, which pays for economic allowances for each ton of avoided CO_2 emissions [511]. The considered value is an average of market values for January 2025 [526], and it is equal to 0.078 €/kg_{CO_2}avoided. Consumption fees, in accordance with [527], are not applied to the first 150 kWh/month energy consumption. In scenarios S#3.1 and S#3.2 the tax rate is considered zero. This condition, although hardly applicable, represents the case in which the State could decide to favour a less impacting energy consumption of users in line with the environmental targets for the coming years, whose failure would entail economic penalties for the Country. For each scenario, a fixed price charge was considered for non-vulnerable residential users, first house resident with 3 kW engaged power.

Economic results of considered scenarios are shown in *Figure 4.13*. The base case, S#0, presents an electricity bill cost equal to 670.50 €/year. The expense for energy share just accounts for 47.83 %. The annual electricity bill cost of S#1.1 exceeds base case, accounting for 672.17 €/year. The shift from non-optimized to optimized energy load profile has a minimal

impact on final cost because daily energy consumption is the same and its reduction on F2 hours is about totally balanced by increase in F1 hours, and night hours (F3) energy consumption is considered non-shiftable. Considering the CO_2-oriented tariff structure in S#1.2, the total cost is reduced by 1.99 % with respect to S#0, while the expense for energy has a 3.78 % reduction. The economic value of carbon certificates assessed in S#2.1 and S#2.2, in accordance with [526], entails minimal economic savings from S#1.1 and S#1.2, respectively. The economic value indeed is not conveniently commensurate with residential users' energy consumption. Tax reduction considered in S#3.1 and S#3.2 leads to the most convenient economic outcomes from the base case, with corresponding 9.23 % (61.40 €/year) and 11.27 % (75.56 €/year) savings.

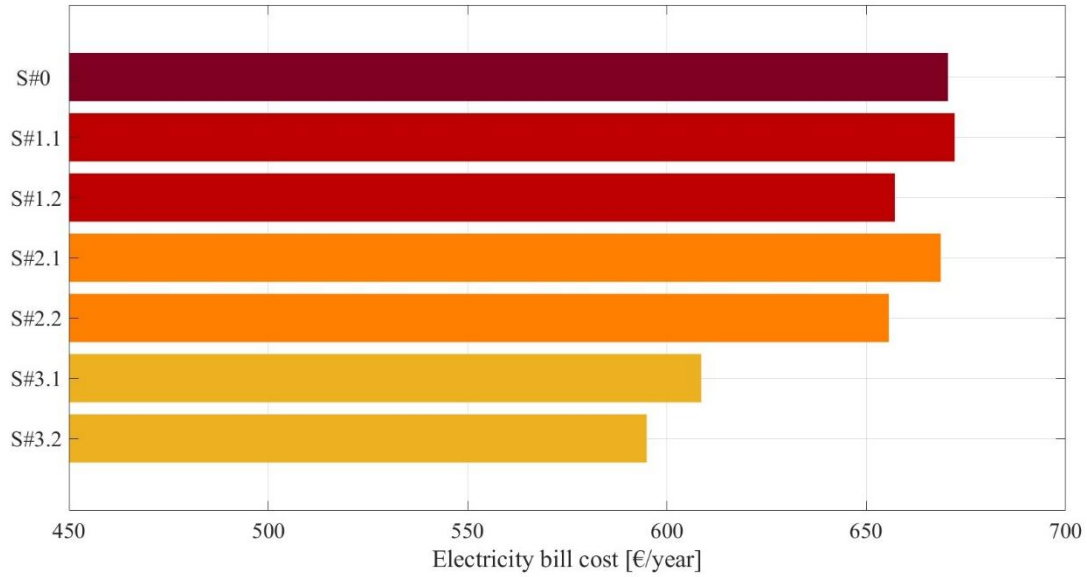

Figure 4.13 Economic results of considered scenarios.

The assignment of carbon certificates could represent an interesting incentive for residential end-users who shift their load profile increasing the energy withdrawn from the PG in time slots with reduced direct environmental impact. However, in S#2.1 and S#2.2 the considered economic value of the carbon certificate [526], is mainly oriented to companies' CO_2 emissions reduction. *Figure 4.14* presents a sensitivity analysis of percentage economic savings for S#2.1 and S#2.2 (compared to S#0) with respect to certificate value. Economic saving of 5 % is addressed with certificate value equal to 1.77 (S#2.1) and 1.74 €/kg_{CO_2} (S#2.2). 10 % saving is achieved for 3.54 and 3.47 €/kg_{CO_2}, 15 % for 5.31 and 5.21 €/kg_{CO_2} , 20 % for 7.08 and 6.94 €/kg_{CO_2}, respectively for scenario with current (S#2.1) and CO_2-oriented electricity tariff (S#2.2) applied to optimized load profile, in addition to carbon certificates. Implementation of a carbon certificate system for the economic evaluation of avoided CO_2 emissions from residential users, with higher values than those granted to companies that have a much greater

potential to reduce their environmental impact, could significantly stimulate behaviour oriented towards shifting loads, as proposed in this study.

The implementation of a carbon certificate system for residential users entails a non-negligible level of complexity. National authorities could introduce specific evaluation mechanisms and dedicated economic schemes, also including direct bill discounts. In this context, cooperation with DSO could be envisaged. Current energy consumption could be compared with standard load profiles to assess the extent of load shifting towards time slots that are environmentally less impactful. The main challenges of such a system, however, lie in data monitoring, standardization efforts aimed at ensuring consistent rules across regions, and the management costs.

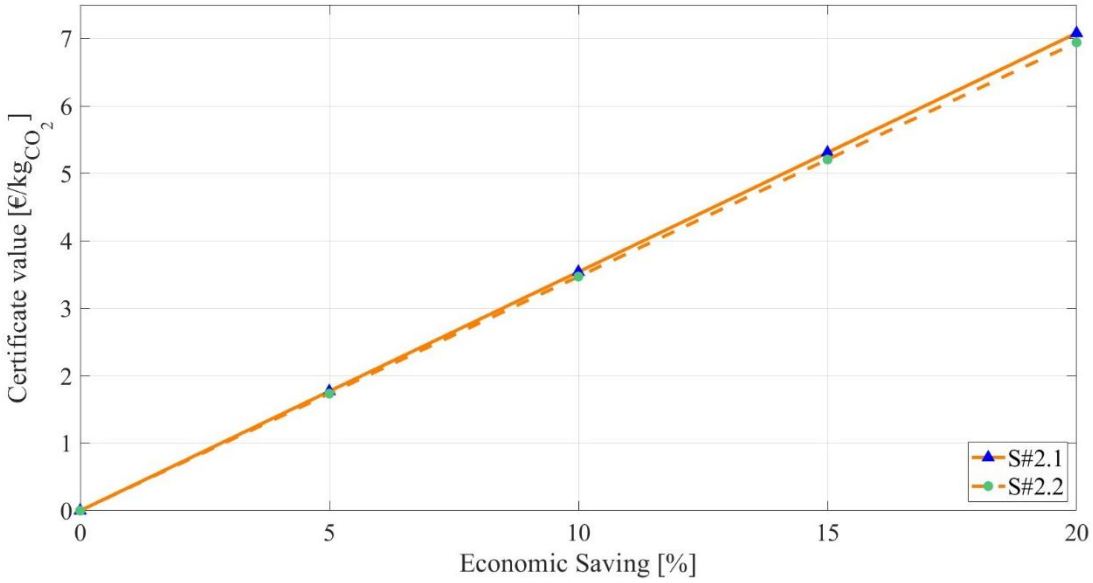

Figure 4.14 Carbon certificate value for different economic saving percentage variation for S#2.1 and S#2.2.

In order to deepen the assessment, a correlating analysis of VAT reduction and carbon certificates value was carried out. In particular, the VAT was reduced to 9.5 %, 9.0 %, 8.5 % and 8.0 %. For each of these cases, the addition of certified carbon was evaluated, whose value is proportional to the achievement of economic savings equal to those reported in the previous analysis. The results are shown in *Figure 4.15*. The lowest values at the same economic savings are obtained for S#2.2 with VAT of 8.0 %, respectively equal to 1.06, 2.78, 4.54 e 6.28 €/kg_{CO_2}. Instead, the highest values are recorded for S#2.1 with VAT of 9.5 %: 1.62, 3.39, 5.16, 6.93 €/kg_{CO_2}. As shown, for the scenario with a CO_2-oriented tariff (S#2.2), lower carbon certificate values are obtained for each of the VAT rates to be applied and the considered economic saving.

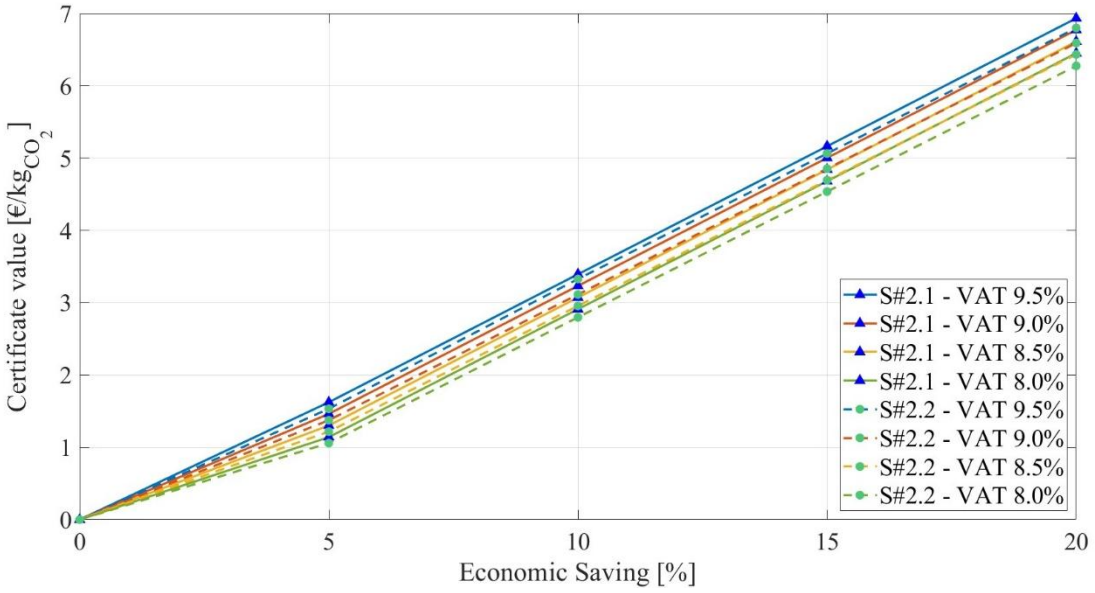

Figure 4.15 Carbon certificate value for different economic saving percentage variations and VAT reduction (9.5%, 9.0%, 8.5%, 8.0%) for S#2.1 and S#2.2.

The methodology presented in this chapter represents a starting point for reducing the environmental impact related to the energy demand of residential users. However, if the shift in energy consumption was adapted to the profile resulting from the planned approach, it would be necessary to take into account a rebound effect that would result in a new equilibrium of the PG production subsystem, and as a consequence, in α values variation. Hopefully, a greater concentration of consumption in the central hours of the day could lead to a greater possibility of the PG receiving energy from RES-based plants at times of large production (as PV in the central hours) that is currently not always allowed. The methodology does not aim to pinpoint which loads should be moved, but it aims to present a load profile to reduce the associated environmental impact. Therefore, to be as general as possible, it has been applied to load profiles representative of residential users. Each user may or may not approach the optimized load profile presented according to his peculiarities, considering social, technical and environmental factors. The introduction of one or more compensation mechanisms, such as a CO_2-oriented tariff, VAT decrease and carbon certificates, would favour users' interest in pursuing the objective of consuming during hours with a lower environmental impact.

4.2 Environmental impact reduction of real residential and commercial end-users energy consumption

European policies aimed at reducing GHG emissions into the atmosphere primarily promote more efficient energy use at all stages of the energy chain: from the production, enhancing the share of energy from RES, to the transformation and distribution up to the final consumption. To address the latter, a twofold approach can be employed: to promote the adoption of devices with greater energy efficiency, minimizing the energy use for the same level of user demand, or boost energy consumption during periods linked to lower CO_2 emissions. As previously introduced, in recent years, the electricity generation system has undergone substantial changes mainly driven by the ever-increasing pervasiveness of plants based on RES, programmable and non-programmable. This leads to significant fluctuations in the corresponding PG CO_2 equivalent emission factor across different times and locations.

In this paragraph, the application of the previously proposed methodology, focused on shifting the electrical loads of end-users with a weighted approach with respect to the corresponding PG CO_2 emission factor, is presented. The energy consumption data come from real residential and commercial users of a Southern Italy municipality. The assessments are made with respect to the hourly variation of the CO_2 emission factor on a national scale. The outcomes result in decreased direct environmental impact associated with users' energy demand, not by reducing consumptions, but merely by shifting them to optimal hours of the day from an environmental viewpoint. Thus, the results of more efficient use of final energy consumption align with ambitious European targets.

4.2.1 Case study

The method described was implemented in a real case study involving a variety of end-users, both residential and commercial, located in a small municipality in Southern Italy, specifically in the province of Benevento. The methodology was applied to a total of eighteen residential users (RUs) and three commercial users (CUs). For each user, real consumption data was obtained for every consumption band, covering each month of an entire year, from electricity bills. The RUs usually have an engaged power of 3 kW, with a few exceptions. RU#15 has an engaged power of 4.5 kW, while RU#7 and RU#12 each have an engaged power of 6 kW. For CUs, the following details apply: CU#1 is a mechanic's shop with an engaged power of 11 kW, CU#2 is a bakery with an engaged power of 3 kW, and CU#3 is a small farm with an engaged power of 10 kW. The annual consumption details for each end-user and their respective engaged

power are shown in *Table 4.4*. The three consumption bands are considered according to the Italian tariff system [396].

Table 4.4 Annual energy consumption by consumption bands and engaged power of the considered users.

User	Engaged power [kW]	Yearly energy consumption [kWh]		
		F1	F2	F3
RU#1	3	440	381	521
RU#2	3	569	483	714
RU#3	3	554	720	814
RU#4	3	1376	1134	1361
RU#5	3	1614	1220	1513
RU#6	3	1025	1044	1435
RU#7	6	1068	833	1190
RU#8	3	855	525	712
RU#9	3	799	599	791
RU#10	3	413	440	572
RU#11	3	223	586	827
RU#12	6	2593	1111	1383
RU#13	3	506	306	410
RU#14	3	692	540	684
RU#15	4.5	1920	1550	1220
RU#16	3	1086	933	991
RU#17	3	1238	979	1067
RU#18	3	755	625	908
CU#1	11	1524	906	1048
CU#2	3	414	427	798
CU#3	10	13648	9569	15007

In order to effectively apply the proposed methodology, real consumption data have been profiled on an hourly basis. In particular, for the RUs, a profiling methodology was implemented utilizing data provided by ARERA for residential users. The corresponding province and engaged power were selected, and the consumption profiles of each month were considered for weekdays, Saturdays and Sundays, to proportionally allocate the consumption of each consumption band [528].

For CUs, a complementary approach has been adopted, starting from the trend of load profiles provided by the energy simulation software Homer Pro [74]. In particular, considering the corresponding climatic zone, typical commercial profiles have been assessed for CU#1 and CU#2, which, according to the type of commercial activity, it has been assumed that they are not operational on Sunday. In the case of CU#3, it was assumed that energy consumption

decreases on Sundays, but it doesn't drop down to just the base load. Therefore, a profile that reflects these conditions has been developed. *Figure 4.16* illustrates the weekly load profile for one RU and CU.

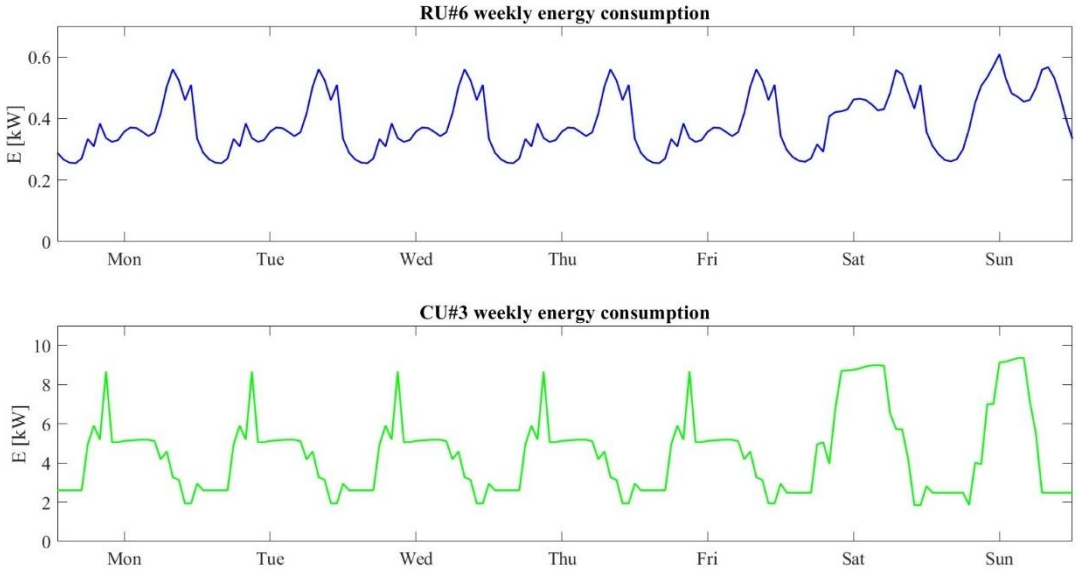

Figure 4.16 Weekly load profile of RU#6 and CU#3.

Depending on the type of considered user, the methodology was applied considering that for RUs the allowable period for moving loads goes from 6 am to midnight ($H^{(0)}$=7,8,…,24). In contrast, for CUs it ranges from 6 am to 9 pm ($H^{(0)}$=7,8,…,21). For all users considered, the methodology was implemented for each day of a whole year.

Regarding the value of PG CO_2 emission factor, Ceglia, et al. [353] showed considerable differences in the CO_2 emission factor for Italian PG, attributed to the varying presence of RESs during the years and during the day and hours of the same year. The presented approach calculates it as the ratio of the total product of the individual emission factor of each fossil fuel [529] and its respective energy output, which signifies the total CO_2 emissions from burning fossil fuels in thermoelectric plants for electricity generation, to the hourly net electricity output from each source (fossil fuels and RESs) after reducing for pumped storage hydroelectricity demand and T&D losses using a reduction factor. Using the approach outlined in [353], hourly α values for Italy have been assessed for the year 2022. Results on an hourly basis are presented in *Figure 4.17*.

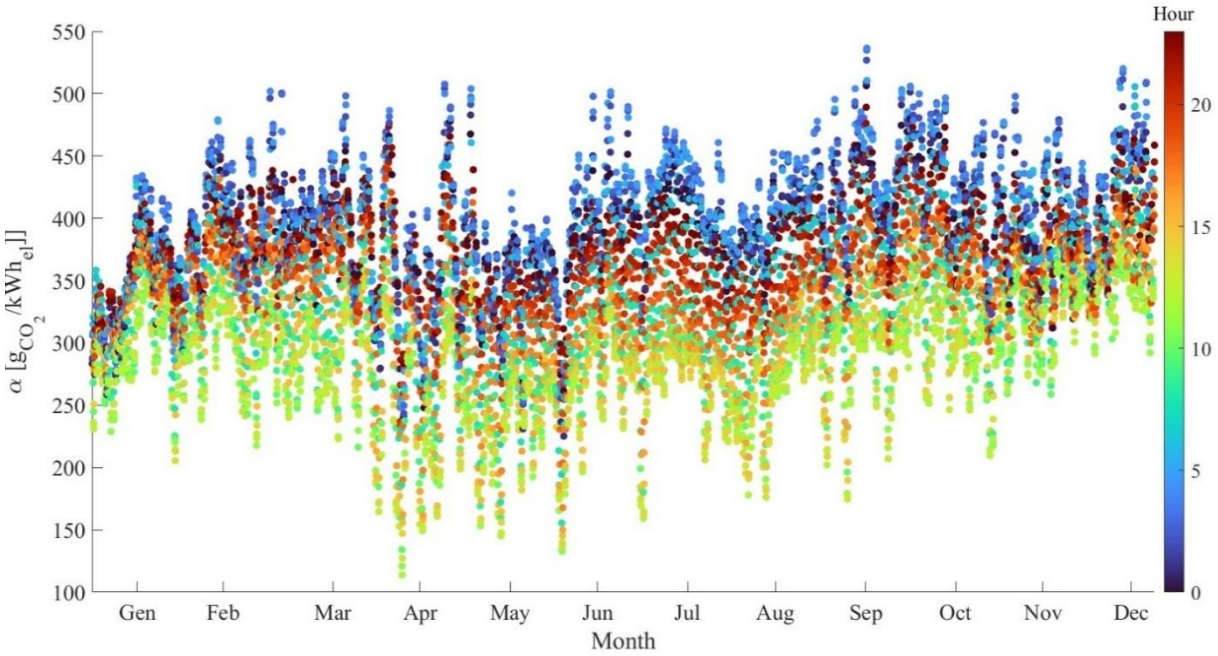

Figure 4.17 Variation of Italian power grid CO_2 emission factor for 2022.

The hourly fluctuation of the CO_2 emission factor displays a similar trend daily, with the lowest values during the central hours. This pattern is attributed to the contribution of programmable RESs alongside solar PV technology, with productivity taking place only during daylight hours, and which has seen the most significant increase in capacity installed in Italy over the past years [523]. The comparison of seasons shows higher α values in winter and autumn within the same hour range, significantly affected by the characteristics of the solar source.

4.2.2 Results and discussion

This section thoughtfully presents the results of the proposed methodology applied to electricity consumption loads, illustrating the potential benefits of load shifting and the accompanying reduction in CO_2 emissions. *Figure 4.18* and *Figure 4.19* illustrate the load profile, both initial (continuous line) and modified (dotted line), in relation to the hourly variation of α for a typical day in summer, winter, and the intermediate season. Results are presented for a RU (*Figure 4.18*) and a CU (*Figure 4.19*). In each of the presented cases, it is emphasized that the load profile shifts towards the central hours of the day. This shift occurs during a period when α values are lower due to the significant presence of electricity generation by PV plants. This variation is most significant for RUs which normally have peak demand in the evening hours (between 6 pm and 10 pm). For the CUs, the shift is less noticeable since their activities are primarily already concentrated in the middle hours of the day, although a

shift relative to some hours can be observed. Additionally, the results presented on a seasonal basis indicate that summer is associated to lower α values.

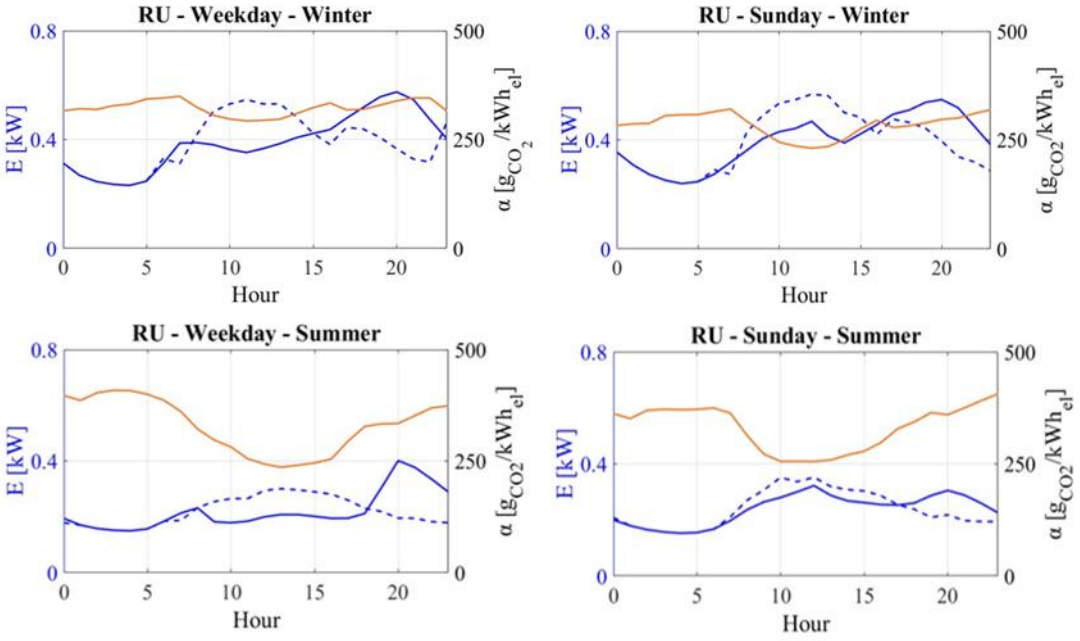

Figure 4.18 RU initial (continuous line) and modified (dotted line) energy consumption for typical summer and winter weekday and Sunday with respect to corresponding hourly α.

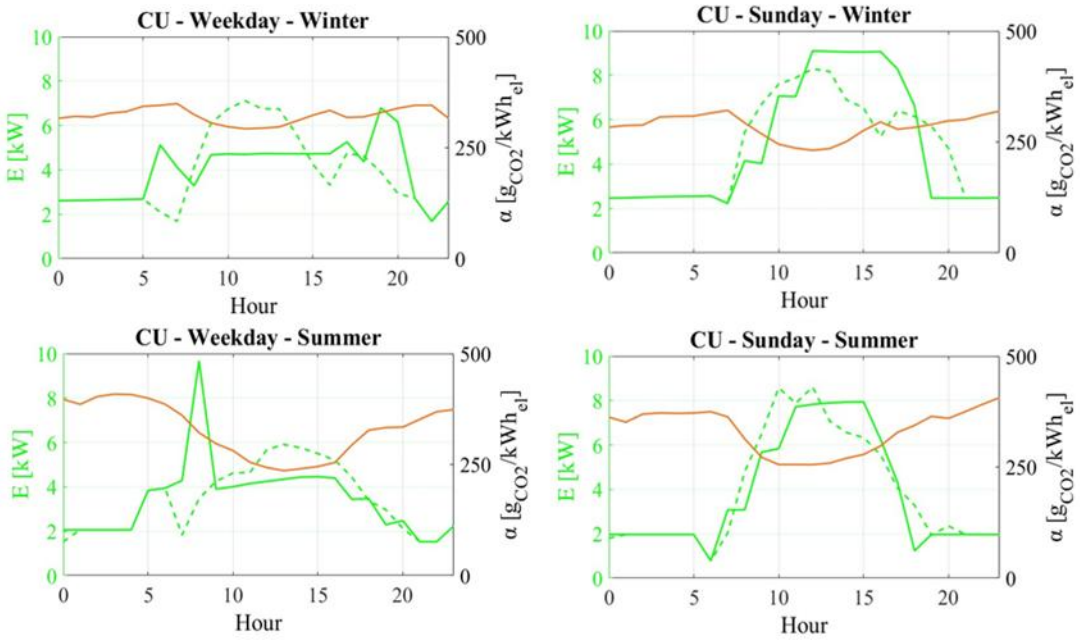

Figure 4.19 CU initial (continuous line) and modified (dotted line) energy consumption for typical summer and winter weekday and Sunday with respect to corresponding hourly α.

Figure 4.20 shows the variations in CO_2 emissions relative to the initial and modified energy load for each considered user. On average the percentage change for users is 3.00 %, with a maximum value of 5.39 % for RU#5. The CUs, on the other hand, show an average variation

of 2.22 %, mainly due to the fact that commercial activities have a reduced load of the evening hours therefore the shift from this period to the central hours of the day which have a lower α value is less significant.

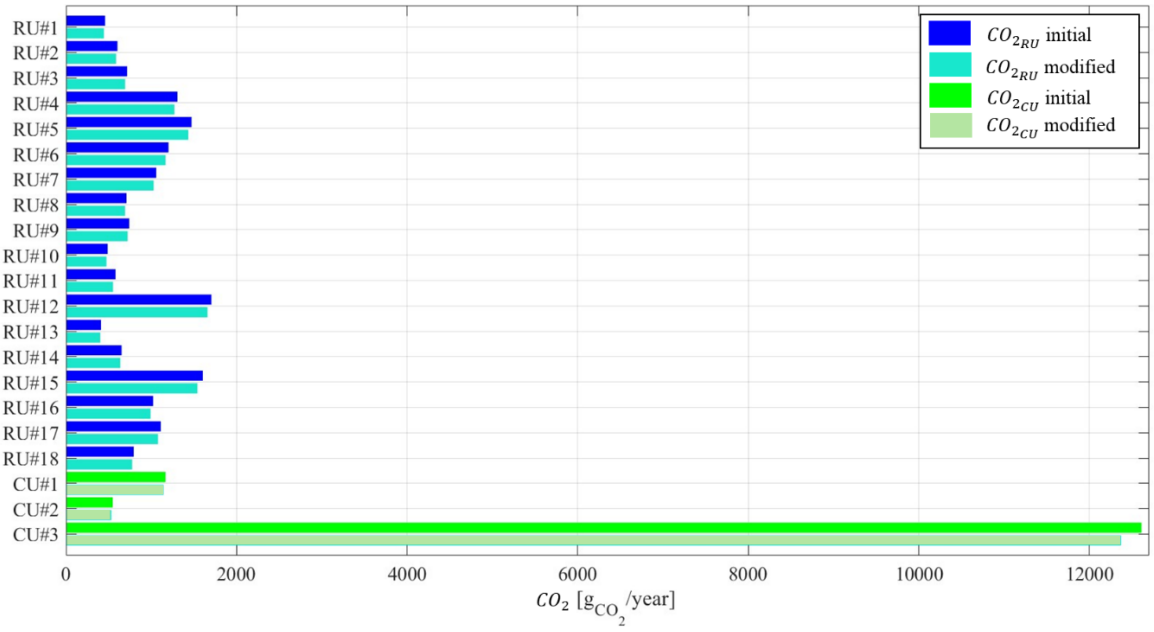

Figure 4.20 CO_2 emissions on an annual basis evaluated for initial and modified energy consumption, for each considered RU and CU.

Note that the methodology is designed to maintain constant daily energy consumption. This indicates that reducing emissions is only associated with shifting energy demands to times when they have a lower environmental impact, influenced by the technology mix of the PG production subsystem. By integrating this shift with energy-efficient behaviours, users can meet their needs while reducing the amount of electricity drawn from the PG and, consequently, lowering CO_2 emissions. Furthermore, the recent decline in α values, primarily attributed to the increasing presence of RES-based plants, presents a favourable opportunity to implement methodologies similar to the one proposed in this study. To encourage end-users to adopt energy consumption behaviours that aim to minimize associated environmental impact, dedicated energy policies could be introduced. Specifically, economic incentives could be recognized for users who shift their energy consumption to time periods when the respective α value of the PG is lower. To facilitate this, current tariff structures could be revised to offer lower rates during hours when the α value is typically lower. However, a significant shift in end-users' behaviour could substantially impact the electricity system in terms of production and transmission, potentially necessitating a new balance for effective operation.

In conclusion, end-user electricity consumption serves as a direct reflection of the environmental impact associated with the PG technology mix. Since this is neither constant over time nor uniform across locations, the temporal and spatial characteristics of user load profiles can significantly influence overall CO_2 emissions. The role of end-users in the energy transition is therefore increasingly recognized as both strategic and transformative. By enhancing awareness through targeted policies, real-time information, and behavioural or economic signals, users can better understand the environmental consequences of their energy demand and make informed decisions. This evolution of the end-user, from a passive consumer to an active participant, offers multiple benefits. It strengthens the effectiveness of energy efficiency measures, complements the diffusion of renewable energy technologies, and enables more responsive and flexible electricity systems. Furthermore, it provides a framework for aligning bottom-up actions, such as individual demand management and lifestyle choices, with top-down energy-sector transformations, including policy-driven decarbonization and smart grid development. Overall, the growing engagement of end-users confirms their pivotal role in achieving environmental sustainability, optimizing energy efficiency, and supporting the broader objectives of a low-carbon and resilient energy system. By integrating user-driven flexibility and awareness into energy planning, the sector can leverage distributed actions to maximize the societal and environmental benefits of the energy transition.

Conclusions

In the current energy landscape, energy sharing-based configurations are emerging as innovative models for end-user engagement, enabling consumers to play an active role in the energy transition, delivering both energy and economic benefits while reducing environmental impacts and addressing social challenges such as energy poverty. Among the various models proposed, Renewable Energy Communities (RECs) offer a particularly promising pathway for practical implementation, supported by national legislative frameworks adopted across several European countries. In parallel, Positive Energy Districts (PEDs) represent a new frontier in the evolving energy paradigm, with a specific emphasis on the environmental impact of districts that, in addition to promoting the installation of RES-based plants, aim to achieve carbon neutrality. Within these configurations, end-users assume a central role: their energy-related decisions can generate tangible impacts, and increased energy awareness emerges as a key factor in enhancing overall environmental sustainability. Beyond specific configurations, this approach can be generalized through the definition of methodological frameworks and evidence-based guidelines aimed at influencing end-user behaviour. By promoting informed decision-making and more conscious energy consumption patterns, such guidelines can support broader improvements in environmental sustainability, extending the benefits of energy-sharing models to contexts outside formal community-based configurations.

The studies presented in this thesis focus on the methodological and numerical analysis of the aforementioned topics, namely RECs, PEDs, and end-users energy consumption, with the aim of assessing their role in enhancing energy efficiency and environmental sustainability.

With specific reference to RECs, the first chapter of this thesis addresses their conceptual, methodological, and applied dimensions through three complementary studies. Starting from the regulatory framework introduced at the European level by the RED II, the analysis highlights how its transposition into national legislation has led to heterogeneous implementation pathways across EU Member States, shaped by geographic, economic, cultural, and political factors. In this context, the first study proposes a standardized and generalizable roadmap for the establishment of a REC, aimed at supporting its practical implementation. The roadmap adopts a multidisciplinary perspective, integrating energy, economic, and legal aspects, and is structured into four main phases: feasibility study, aggregation, operating phase and management. This framework provides a systematic approach for assessing technical

performance, environmental impacts, economic viability, and social implications, offering a replicable reference for REC development within the European context. The study highlights potential future developments, including the extension of the roadmap to wider contexts, the integration of uncertainty analyses related to dynamic community membership, and the explicit consideration of energy storage systems and thermal energy sharing through district heating and cooling networks. The successful implementation of RECs depends on the interplay of technical, regulatory, and organizational dimensions. To provide a structured understanding of these configurations, ten main aspects have been investigated. With regard to membership, RECs can involve a wide range of stakeholders, whose participation directly influences governance structures, democratic decision-making, and social cohesion. The level of REC development remains highly heterogeneous, reflecting significant differences in regulatory maturity and incentive schemes across countries and regions. Understanding this variability is essential for adapting implementation strategies and identifying practices with high replication potential. From a technological perspective, PV systems currently represent the dominant solution due to their modularity and scalability, while other renewable and hybrid systems are increasingly adopted to enable multi-sector integration. Planning, optimization, and simulation tools play a key role in supporting REC design and operation, enabling multi-objective performance evaluation and interaction with energy markets. At the same time, advanced monitoring and energy management infrastructures are required to ensure effective real-time control of energy flows. In this framework, flexibility strategies, including demand response, storage integration, sector coupling, and peer-to-peer energy trading, are crucial for aligning variable generation with dynamic demand, enhancing autonomy and reducing grid dependency. The growing adoption of digital solutions, including AI and predictive analytics, is expected to further expand the capability of RECs to provide grid-supportive services. Additionally, RECs can significantly contribute to the achievement of the Sustainable Development Goals, especially with respect to energy poverty reduction, clean energy access and climate change mitigation. Despite existing technical and regulatory constraints, these characteristics highlight the potential of RECs to scale from building-level applications to neighbourhood or district-level systems, paving the way toward Positive Energy Districts. In this perspective, the development of robust and socially inclusive business models, supported by more harmonized enabling conditions, remains a key requirement for fully unlocking the potential of RECs. A specific study has been conducted to investigate the benefits of RECs through the analysis of three representative case studies, referring to residential, industrial, and office applications with EV integration. Since REC configurations are not uniquely defined, the selected cases reflect

different operational and organizational arrangements, allowing a comparative evaluation across application fields. The analysis assesses the performance of REC-based systems in comparison with conventional energy supply configurations, considering energy, environmental, and socio-economic indicators. RECs also generate correlated benefits as enhanced affordability of energy services, mitigation of energy poverty for vulnerable users, and the provision of additional energy-related services that increase local attractiveness and territorial resilience. Overall, these aspects confirm that REC-based configurations offer superior performance compared to traditional end-user energy systems, regardless of the sectoral context or the typology of involved stakeholders, reinforcing their role as a scalable and inclusive instrument for the energy transition.

Accordingly, the second chapter of this thesis focuses on numerical analyses of RECs, aimed at evaluating in-depth their potential across diverse application contexts and assessing the influence of different configurations, technologies, and regulatory frameworks. The studies encompass a range of scenarios, including the integration of EV based car-sharing systems, energy storage systems and industrial users within a REC, and cross-country comparisons of energy-sharing and economic remuneration mechanisms. These numerical investigations provide a systematic assessment of the energy, environmental, economic, and social outcomes achievable under varying conditions, offering valuable insights into the replicability, scalability, and broader applicability of REC-based solutions. In line with European targets to reduce fossil fuels use in favour of RESs, the first study focuses on an application in the transport sector, which, despite a strong push towards electrification, remains heavily dependent on fossil fuels and accounts for approximately 25 % of global GHG emissions. To pursue real benefits of e-mobility in urban context and facilitate access to a wide share of the population, an EV car-sharing system integrated into a REC is investigated. The system is sized starting on real traffic flow data for the municipality of Lioni (Italy), and 3-E benefits are evaluated by comparing it with an EV car-sharing system, whose energy demand is met by the PG, and with an ICE vehicle car-sharing system, considering the same fleet size and distance travelled. The simulation model developed for the case study of a small municipality is designed to compare a REC relying on diffuse PV installation, considering the virtual electricity self-consumption, with the case based on the REC adopting a lithium-ion battery, in addition to the RES-based plant. In this context, the implications of incentives on investment costs of the plant and consequent tariff reduction are evaluated. The further REC case study is focused on assessing the performance of a configuration including two members located in the industrial area of a Southern Italy city,

namely a mixed-use building and an industrial wastewater treatment plant. Moreover, the traditional single end-users' configuration has been investigated as an additional scenario in order to further emphasize the benefits owing to energy sharing. In both proposed scenarios, the users have been equipped with PV plant. The analyzed case studies enable the investigation of RECs within a multi-sectoral perspective, proposing configurations that are both practically feasible and capable of delivering tangible benefits. This approach highlights how the inherently multidisciplinary nature of RECs allows for an expansion of their scope, integrating different energy uses and sectors under a common framework. Such integration enhances the potential to achieve shared energy, environmental, and economic benefits, while also supporting more efficient resource utilization and system optimization. Overall, the results demonstrate that broadening REC applications beyond single-sector boundaries can significantly strengthen their contribution to the energy transition and to sustainability objectives.

The main findings concern:

- among the investigated configurations, the REC based layouts consistently achieve the best results from both energy and environmental perspectives, particularly as the size of the RES plant increases and the energy sharing is maximized;
- regarding the car-sharing system study, the economic analysis shows that conventional vehicles configuration exhibit a shorter payback period, whereas in the REC configuration, revenues from shared energy and electricity fed into the PG are not sufficient to rapidly recover the investment costs associated with the PV system, EV fleet, and charging infrastructure. However, the inclusion of EV purchase incentives significantly improves the overall economic performance of the REC scenario;
- the integration of energy storage system with a PV based REC enhances the level of shared energy, leading to additional energy and environmental benefits. Nevertheless, these improvements remain limited in the cases of undersized storage system. Furthermore, the REC Italian policy characterized by partial coverage of PV plant investment cost and a consequent reduction in energy sharing economic incentives, results in a significant improvement in the SPB for the configuration without storage, while leading to less favourable economic outcomes in the case with storage, where the marginal increase in shared energy does not compensate for the reduced economic incentives;

- for the industrial REC, energy sharing increases users' self-sufficiency and renewable energy on-site consumption compared to the single self-consumers' configuration, while also enhancing annual operative costs savings. As a results, the REC scenario is characterized by higher overall investment profitability.

Future developments of this work will include the integration of additional RES-based technologies capable of meeting community energy demand as a means of further reducing carbon dioxide emissions. However, their economic feasibility will need to be carefully assessed, as these technologies are generally less mature than PV systems. Furthermore, the inclusion of additional members in energy sharing schemes will be investigated, with the aim of promoting the adoption of such configurations across other sectors, in light of their demonstrated technical, economic, and social advantages.

Since the case studies analyzed involved numerical analyses on RECs carried out in accordance with the sharing mechanism provided for by Italian legislation, in order to explore its strengths and limitations, aspects of energy and economic sharing were compared with those provided for by the legislative framework of another European country in a dedicated study. In particular, various energy sharing models and economic remuneration schemes for shared energy, drawing on the Italian and Spanish regulatory contexts regarding RECs have been examined. Several scenarios are proposed, incorporating different combinations of these two aspects. For the sharing model based on the Spanish framework, both static and optimized static/dynamic allocation coefficients determined through an economic optimization model for the REC, are considered. The scenarios are applied to a PV-based REC consisting of ten residential users, whose real hourly loads are used as input data. For each scenario, different system sizes are considered. The energy results indicate that considering the different energy sharing mechanisms, the highest values of shared energy are achieved under the optimized dynamic allocation coefficients mechanism and, equivalently, under the energy sharing model based on the Italian regulatory framework. Regarding the variation in REC plant size, it is observed that as the size of the REC plant increases, the shared energy rises more slowly than production, since the REC's demand limits potential improvements. In this framework, it is highlighted that only the correct sizing of the RES plants allows for maximising the results. From an economic perspective, the operating cost outcomes show that joining a REC is always financially beneficial for individual users compared to a no-sharing configuration. The comparison between different remuneration mechanisms application shows that direct bill reduction yields slightly higher annual savings for end-users than incentive-based schemes, and

similarly, for the REC as a whole. In conclusion, the adoption of RECs hinges on the development of effective energy sharing models and economic remuneration schemes, which not only foster energy transition but also deliver a range of co-benefits. This emphasizes the importance of designing schemes that maximize these benefits.

Together with RECs, the Positive Energy District concept is emerging as a globally recognized approach to support the energy transition of cities, which represent the core of the energy transition claimed for achieving carbon neutrality by 2050. PEDs represent a natural evolution of RECs, expanding both operational scale and governance. By integrating electricity, thermal, and mobility demands, they adopt a multi-sectoral, flexible approach that maximizes local resource efficiency, demand-side flexibility, and infrastructure use. Beyond balancing consumption and renewable generation, PEDs aim for net-positive energy, enhancing self-sufficiency, economic performance, emissions reduction, and system resilience, while enabling multi-actor collaboration across energy systems. The research conducted on the topic includes a novel methodology for the energy and environmental analysis of districts and communities aimed at verifying the accomplishment of the goals of PEDs. The detailed mathematical model proposed in the third chapter has been transposed in a user-friendly tool designed to assist in defining the optimal plant configuration of a district, with focus on Mediterranean area. The tool incorporates a variety of RES-based plants, alongside conventional backup systems. To ensure real applicability, input data on district-level energy demand and the location among various provinces in Southern Italy, from which real renewable sources availability is considered, are required. The operation of all energy conversion systems is modelled by combining location-based renewable resource data with corresponding performance characteristics of plants. The size of the selected plants is evaluated in order to meet the district energy demand, by achieving energy balance and verify the annual carbon neutrality. The tool has been designed with the aim not only to support the design of more sustainable districts but also to provide practical outputs for the technological development required to achieve PED status.

Finally, the fourth chapter focuses on the evaluation of end-users energy consumption and the associated environmental impact. The latter is assessed by considering the load profile and respective CO_2 emissions of the PG, which depends on the technologies' mix for electricity generation. The assessment is framed within a broader consideration of the central role of end-users, who, in addition to being key actors in the energy transition, particularly within energy-sharing configurations such as those analyzed, can also contribute individually to

environmental sustainability through informed choices. In this context, end-users are positioned at the core of achieving environmental objectives within the ongoing energy transition. The analysis builds on the observation that, in recent years, the increasing presence of RES-based plants has significantly affected the trend of PG CO_2 emissions factor, which shows a pronounced daily variations, reaching minimum values in the central hours of the day. End-users' energy consumption has been evaluated in relation to the temporal variation of this emission factor, revealing that residential users concentrate their highest consumption during hours characterised by the greatest environmental impact. Based on this, an innovative methodology is proposed for the environmental impact reduction of individual end-users by redistributing the same daily energy consumption in order to minimise the associated emissions. This approach involves shifting higher consumption to hours with lower PG CO_2 emission factors. The application of this methodology to residential users' load profiles results in a shift of peak demand from evening to midday hours. The residential sector therefore plays a pivotal role in reducing environmental impact by directly involving end-users, who are central actors in the energy transition. Conversely, the application to commercial users yields less significant results, as the potential for load shifting is constrained to operating hours, which generally already coincide with the central hours of the day. Furthermore, by considering consumption time slots defined by the Italian national authority and aligned with electricity tariff structures, it emerges that current tariffs do not economically incentivise energy consumption during periods with lower CO_2 emissions from the generation subsystem. On the contrary, the lowest tariffs typically apply during the evening hours. To encourage users to adopt consumption profiles that minimise GHG emissions, several dedicated energy policies are proposed, including CO_2-oriented tariffs, the introduction of certificates for avoided emissions, and reductions in electricity bill taxes. The latter emerged as the most advantageous option for end-users. Nevertheless, different strategies should be implemented for different user typologies. Future developments of the study could include the detailed assessment of shiftable loads associated with household appliances, the application of the proposed methodology to prosumers with an evaluation of impacts on the PG, and analyses considering higher penetrations of RES-based plants.

The ongoing energy transition, which is expected to intensify in the coming years, places end-users at the very center of the transformation. Acting either collectively within energy-sharing configurations, such as RECs and PEDs, or individually in their daily consumption choices, end-users play a decisive role in achieving the established energy and environmental

targets. Their active participation is essential not only for adopting more conscious energy consumption practices but also for fostering a culture of efficiency, sustainability, and environmental responsibility. By aligning individual and collective behaviours with broader system objectives, end-users can directly influence energy demand patterns, reduce greenhouse gas emissions, and enhance the resilience and sustainability of local and regional energy systems. In this sense, empowering end-users through information, incentives, and innovative energy management strategies represents a cornerstone for the successful realization of the energy transition.

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** Conference speaker

Nomenclature

Acronyms

3-E	Energy, environmental and economic
A/W	Air-to-water
ABM	Agent-based models
AI	Artificial Intelligence
ARERA	Italian Energy Regulatory Authority
BEI	Baseline Emission Inventory
BER	Biomass Energy Ratio
BESS	Battery Energy Storage System
CBS	Centralized biomass-based system
CD	Child
CEC	Citizen energy community
CEP	Clean Energy Package
CEU	Characterization of energy users
CHP	Combined Heat and Power
CP	Cooling Energy Production Plant
CS	Conventional system
CSC	Collective services center
CU	Commercial user
DCN	District Cooling Network
DHN	District Heating Network
DHW	Domestic Hot Water
DR	Demand response
DSF	Demand-side flexibility
DSM	Demand Side Management
DSO	Distribution System Operator
EF	Emission Factor
EHP	Electric Heat Pump
EP	Electric Energy Production Plant
ESS	Energy Storage System
EU	European Union

EV	Electric vehicle
G2V	Grid-to-Vehicle
GHG	Greenhouses Gas
GSE	Italian Energy Services Manager Company
HP	Heat Pump
HV	High Voltage
IC	Investment cost
ICE	Internal Combustion Engine
IEMD	International Market Energy Directive
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LPG	Liquefied Petroleum Gas
LV	Low Voltage
MASE	Italian Ministry of Environment
MILP	Mixed-integer linear programming
MV	Medium Voltage
ND	No working day
NLP	Non-linear programming
NW	No-Worker
ORC	Organic Rankine Cycle
P2G	Power-to-gas
P2H	Power-to-heat
P2P	Power-to-power
P2V	Power-to-vehicle
P2X	Power-to-X
PED	Positive Energy District
PG	Power grid
POD	Point of Delivery
PV	Photovoltaic
PVT	Photovoltaic thermal
REC	Renewable Energy Community
RED II	Renewable Energy Directive
RES	Renewable energy source
RT	Retired

RU	Residential users
SD	Student
SDG	Sustainable Development Goal
SEC	Smart Energy Community
SECAP	Sustainable Energy and Climate Action Plan
SEU	System of Efficient Users
SME	Small and medium enterprise
ST	Saturday
STh	Solar Thermal Collector
T&D	Transmission and distribution
TOU	Time-of-use
TP	Thermal Energy Production Plant
TSO	Transmission System Operator
UBEM	Urban Building Energy Modelling
V2G	Vehicle-to-Grid
WD	Weekday
WR	Worker
WWTP	Wastewater treatment plant

Symbols

10%	10% index	[-]
α	CO_2 emission factor for electric energy	[kg_{CO_2}/kWh$_{el}$]
β	CO_2 emission factor for primary energy	[kg_{CO_2}/kWh$_p$][kg_{CO_2}/kg$_{fuel}$]
γ	Allocation coefficient	[-]
δ	Temperature coefficient (solar thermal collector)	[%/°C]
σ	Economic allocation coefficient	[-]
θ	Timestep	[h] [day]
η	Efficiency	[-]
a	Discount rate	[%]
a_0	Absorber optical efficiency	[-]
a_1	Thermal loss coefficients of the absorber	[W/m^{2}K]
a_2	Thermal loss coefficients of the absorber	[W/m^{2}K^2]
A	Area	[m^2]
AR	ARERA incentive for shared energy	[€/MWh]

c	Unitary average cost	[€/kWh] [€/l] [€/km]
C	Unitary fuel consumption	[l/km]
CF	Annual cash flow	[€/year]
CGP	Community Grid Perturbation	[-]
CO_2	Carbon Dioxide Emissions	[kg_{CO_2}/year]
COP	Coefficient of Performance	[-]
COST	Annual Electricity bill	[€/year]
dis	Distance	[km]
DPB	Discounted Pay back	[year]
DWR	Dedicated withdrawal rate	[€/kWh]
E	Energy	[kWh] [kWh/year]
EER	Energy Efficiency Ratio	[-]
f_{FIX}	Fixed share of incentive tariff	[€/MWh]
f_{GEO}	Location dependent share of incentive tariff	[€/MWh]
f_{VAR}	Variable share of incentive tariff	[€/MWh]
g	Percentage value of hourly energy consumption	[%]
G	Global irradiance	[W/m^2]
I	Economic incentive	[€/kWh]
IC	Investment cost	[€]
IN	Income	[€/year]
IRR	Internal Rate of Return	[%]
ISEE	Equivalent economic situation indicator	[€/year]
LHV	Lower Heating Value	[MJ/kg] [kWh/l]
losses	Losses factor	[-]
MC	Maintenance costs	[€/year] [€/km]
NOCT	Nominal Operating Cell Temperature	[°C]
NPV	Net Present Value	[€]
OC	Operating cost	[€/year]
OPEX	Management Costs	[€/year]
P	Power	[kW]
P_{cont}	Contracted power	[kW]
p	Percentage value of monthly energy consumption	[%]
P_z	Electricity market zone price	[€/MWh]
PER	Primary Energy Ratio	[-]

PLF	Partial Load Factor	[-]
T	Temperature	[°C]
$T_{air,ext}$	External air temperature	[°C]
TIP	Feed-in tariff for shared energy	[€/MWh]
RSC	Renewable self-consumption	[-] [%]
RSE	Renewable share of electricity	[-] [%]
SPB	Simple Pay Back	[years]
VAT	Value added tax	[%]

Superscripts and subscripts

*	Reduced
**	Not accounting primary energy request for RES
¯	Normalized
AM	Autumn
B	Referred to the boiler
BM	Biomethane
Cen	Centralized
CH	Referred to the chiller
CHP	Referred to the combined heat and power unit
co	Referred to cooling energy
CP	Cooling Energy Production Plant
d	day index
DCN	Supplied by the district cooling network
Dec	Decentralized
DHN	Supplied by the district heating network
Dis	Referred to the district
EHP	Referred to the electric heat pump
el	Referred to electric energy
EP	Electric Energy Production Plant
ESS	Referred to the electric storage system
EV	Referred to electric vehicle
EV-PG	Referred to electric vehicles fed by the Power Grid
EV-REC	Referred to electric vehicles integrated into a REC
exp	Export

Ext	External to the boundaries of the district
extr	Referred to extraordinary maintenance
f	Time slots index
FF	Fossil Fuel
fromESS	Referred to energy drawn from the electric storage system
gift	Gifted
gross	Gross energy
h	Hour
i	Plant index
ICE	Referred to Internal Combustion Engine
imp	Import
INC	Referred to plant incentive based scenario
Int	Internal to the boundaries of the district
ISEE	Referred to Equivalent economic situation indicator
j	User index
k	Iteration index
loss	Energy losses
m	Month index
MAX	Maximum
MIN	Minimum
n	Timestep index
NG	Natural gas
ND	No-working day
net	Net energy
nom	Nominal
op	Optimized
p	Referred to primary energy
PG	Referred to the Power Grid
PG-REC	Referred to electric energy drawn from the Power Grid by the REC (not shared)
PV	Referred to the photovoltaic plant
REC	Referred to the Renewable Energy Community
REC-PG	Referred to electric energy fed into the Power Grid by the REC (not shared)
rent	Referred to rental
RES	Referred to a Renewable Energy Source based plant

s	Season index
SC	Self-consumed
SH	Referred to shared energy
SM	Summer
SR	Spring
st	Referred to the charging station
ST	Saturday
STh	Referred to the Solar Thermal Collector
surp	Surplus
t	Typology of day
T&D	Transmission and distribution losses
th	Referred to thermal energy
toESS	Referred to energy fed into electric storage system
tot	Total
TP	Thermal Energy Production Plant
TS	Referred to the Traditional System
US	Referred to the user
W	Weighted
WD	Weekday
WN	Winter
Wt	Referred to the Wind turbine
Y	Referred to yearly value

Sets

A	Set of weighted α values
H	Set of hours
J	Sets of all users
N	Total number of timestep
NCP	Total Number of Cooling Energy Production Plants
NEP	Total Number of Electric Energy Production Plants
NTP	Total Number of Thermal Energy Production Plants
T	Sets of all timesteps

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