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EXPLORING ENERGY SHARING MECHANISMS AND PROSUMER INTEGRATION IN ELECTRICAL AND THERMAL ENERGY COMMUNITIES

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Abstract

In recent years, energy community initiatives have gained significant momentum across Europe as a means to achieve energy transition goals, enabling citizen involvement in energy production, consumption, and distribution. In this context, the potential for sharing energy generated by production facilities represents a new paradigm for renewable energy generation and use.

Following the 2018 European RED II directive, projects focused on renewable energy communities and collective self-consumption have rapidly expanded across the continent, showcasing their potential to create sustainable local energy systems. This growth has been facilitated by regulations supporting the concept of shared energy, alongside incentive systems that deliver not only environmental and social benefits but also economic advantages to community members.

However, the breadth and complexity of this field make it challenging to grasp the various approaches that researchers take toward these new European entities. To address these challenges and explore the primary issues concerning these communities, a systematic literature review has been conducted. The goal is to provide a detailed and clarifying framework to help understand the features, potential, and limitations of these new entities within the European energy landscape and the scientific community.

The findings reveal several crucial insights, showing that these communities have been largely studied from a social and political perspective rather than a technological one, with a strong focus on the economic and financial aspects essential to their operation. Most studies have concentrated on electricity, especially linked to photovoltaic systems, due to national regulatory incentives, while research on thermal energy communities still remains limited. Another central challenge for energy communities is ensuring the equitable distribution of benefits from shared energy. Although many studies are country-specific, comparative analyses across regions are essential to understand commonalities and differences. The development of these models faces regulatory, financial, and management hurdles, with Italy leading in testing EU policies since their early adoption in 2020, resulting in a significant number of studies focused on the country.

Thanks to this experimental regulatory framework, it has been possible to analyze and test the practical application of an energy community in Italy, integrated with a district heating network. The study aimed to enhance both energy performance and economic benefits through internal energy sharing, showing significant reductions in energy demand and emissions without requiring additional investments. However, since the economic benefits of shared energy are assessed at the community level, tracking the specific advantages for individual prosumers remains challenging due to the virtual energy-sharing model in place.

The lack of clarity in energy sharing models has led to the development of four algorithms aimed at optimizing the allocation of shared energy benefits in energy communities: a consumption-proportional key, a Pearson correlation coefficient-based key to evaluate the correlation between electricity drawn from the grid and the surplus fed into the grid, a trend-based key that accounts for the difference between purchased and injected energy, and a combination of the previous two keys. A simulated energy community of eight users with real hourly energy profiles has been created to compare the algorithms and determine how shared energy is distributed, identifying strengths and limitations of each method.

The developed algorithms can be applied also to thermal energy communities, extending shared energy to thermal flows. While the REDII directive allows renewable thermal energy sharing, studies on this are limited, despite thermal energy making up a large portion of Europe's energy demand. Efficient district heating, as defined by the EED directive, offers a key opportunity for decarbonizing the thermal sector, enabling prosumers to consume, produce, and share locally generated thermal energy.

Therefore, this work proposes an innovative approach to retrofit traditional substations into bidirectional ones for district heating networks. These substations allow prosumers to consume thermal energy and share surplus with the network. Based on an existing network in northern Italy, a "supply-to-return" layout has been developed. To evaluate the performance and potential of the proposed bidirectional device, a detailed numerical model has been developed using Dymola. The model focused on simulating domestic hot water demand on a mid-season day and a summer day, using custom control logics to accurately reflect the substation's behavior. Experimental tests from EURAC Research provided crucial input data, supporting the energy validation of the model and enhancing its overall robustness.

The results show that most DHW demand is met by the DHN, due to a mismatch between demand and solar production. The bidirectional setup enables excess thermal energy to be fed into the network, especially in summer, improving energy performance and increasing the useful energy coefficient. The model validation showed good consistency with experimental data, with minor discrepancies in energy flows, particularly a 6.1% error in May and 0.6% in August.

This work examines the sharing of electrical and thermal energy within energy communities, crucial for decarbonization. By analyzing regulatory guidelines, case studies, and benefit distribution, the study addresses key knowledge gaps and highlights the potential of these communities. It further explores extending energy sharing to thermal flows, supporting the future growth of thermal energy communities in Europe.

Activities carried out and scientific publications

RESEARCH ABROAD

I completed my PhD research abroad from March 16, 2024, to June 16, 2024, at the IREC research center in Barcelona. During this collaboration, I evaluated the impact of implementing bidirectional substations in district heating networks in a Mediterranean climate, conducting an energy balance analysis using IREC's co-simulation tool. The technical challenges included integrating Dymola functional mock-up units (FMUs) into the co-simulation environment, defining the boundaries between the FMUs (building, solar thermal, substation, district heating), and managing the simulation workflow. However, some technical issues arose with the Python codes, particularly in integrating the building FMUs modelled in TRNSYS, while the substation FMU, modelled in Dymola, worked correctly even in the codes. The collaboration will certainly continue in the future, with the aim of resolving the technical issues encountered.

DISSEMINATION

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- F. Gianaroli, M. Pipiciello, P. Sdringola, M. Ricci, B. Di Pietra, D. Menegon, F. Melino. Empowering prosumers in district heating networks: experimental analysis and performance evaluation of a bidirectional substation. Proceedings 37th International Conference of ECOS 2024 (accepted and already submitted, awaiting inclusion in Scopus)
- F. Gianaroli, M. Ricci, P. Sdringola, M. Pipiciello, D. Menegon, F. Melino. Retrofit design and numerical modeling of bidirectional substations for the empowerment of thermal prosumers in district heating networks. Proceedings 16th International Conference of ICAE 2024. 10.46855/energy-proceedings-11467

STRUCTURE OF THE MANUSCRIPT

This thesis is organized into six chapters, and a detailed overview is provided below.

Chapter 1 INTRODUCTION

This section provides an overview of the current energy landscape, highlighting the role of energy communities as a key instrument in the energy transition, and the importance of efficient district heating in the decarbonization of the heating and cooling sector. Specifically, section 1.1 analyzes the global and European energy landscape, focusing on primary energy consumption, environmental impact, and the main energy policies adopted in Europe to increase the share of renewable energy. Section 1.2 explores how the transition to renewable energy and the decentralization of energy systems have led to the regulation of energy communities through the REDII and IEMD European directives. Finally, section 1.3 addresses the dependence of the heating and cooling sector on fossil fuels, introducing efficient district heating as a solution for decarbonizing this sector.

Chapter 2 THEORETICAL BACKGROUND

This section delves into the key aspects that influenced the research activities on energy communities during the PhD. Given the vastness and complexity of the field, which makes it difficult to understand the different approaches researchers take towards these new European entities, section 2.1 outlines the methodology used for a systematic literature review on energy communities, highlighting the results and findings that shaped the subsequent PhD activities. Section 2.2 focuses on a concept that is still underexplored in the literature: the efficient management of energy communities, particularly the distribution of benefits among members. It explores the concept of shared energy in communities that adopt a virtual model, often linked to incentive tariffs introduced by recent European directives. Finally, section 2.3 addresses another key issue that emerged from the review, namely the extension of shared energy to thermal energy communities. Active district heating is introduced as a strategy to promote these communities, enabling prosumers to share surplus energy with other network members via an already established infrastructure. This is achieved through the use of bidirectional substations, with a focus on numerical modeling as a tool to simulate and test the potential of these substations.

Chapter 3 REC DESIGN FOR DHN: ITALIAN CASE STUDY

This section examines the potential for creating an energy community connected to a district heating network, based on the provisional regulatory framework introduced by Italian legislation in 2020. The goal is to improve overall energy and economic performance by optimizing the internal sharing of energy from photovoltaic systems. Section 3.1 describes the case study and the methodology adopted, while section 3.3 presents and discusses the results of the techno-economic analysis of the proposed scenarios. Finally, section 3.4 concludes by summarizing the key points of the chapter, emphasizing that the economic benefits obtained refer to the entire community rather than individual members.

Chapter 4 ALGORITHMS FOR DYNAMIC ENERGY SHARING

This section addresses the distribution of shared energy in energy communities that adopt a virtual model, a relevant issue since this energy is often linked to incentive tariffs. Section 4.1 defines the concept of shared energy and introduces the four methods developed, which are applied to three hourly consumption profiles in section 4.2 to illustrate the logic followed in their development. Section 4.3 presents the case study selected to test the methods, based on real hourly consumption profiles from eight users. Section 4.4 presents and discusses the results of applying the methods to the case study. Finally, section 4.5 concludes by highlighting the key findings of the analysis, outlining the advantages and limitations of the proposed methods.

Chapter 5 NUMERICAL MODELLING OF BIDIRECTIONAL SUBSTATION FOR EXISTING DHN

Extending the concept of shared energy to thermal flows is crucial for the creation of thermal energy communities. In this section, this possibility is explored through district heating infrastructure and the active district heating model, presenting a new approach for transforming traditional district heating substations into bidirectional thermal exchange devices. This allows prosumers to use thermal energy for their needs and share any excess energy with other network users. Section 5.1 describes the existing network used as a reference and the current state of the substation under examination. Section 5.2 introduces the new bidirectional setup developed for the existing substation. Section 5.3 describes the experimental setup of the bidirectional substation prototype, which replicates the behavior of the bidirectional layout described in the previous section and tested by EURAC Research. The experimental data collected were essential for developing the numerical model in Dymola, presented in detail in section 5.4. Section 5.5 reports the results of the dynamic simulation of the substation model over two days, one in mid-season and one in summer, considering only domestic hot water demand. Section 5.6 presents the energy validation, highlighting the error percentage between the numerical and experimental models. Finally, section 5.7 concludes by summarizing the key points of the work.

Chapter 6 CONCLUSION

This section concludes the thesis by reviewing the main steps of the research conducted and the most significant findings. The work focused on energy communities, with particular attention to the role of the prosumer and the central importance of energy sharing within these communities, both electrical and thermal. The study highlighted that the prosumer is not only an active consumer but also a key player in optimizing shared energy, opening up new perspectives for the integration of renewable sources and the decarbonization of the energy system.

NOMENCLATURE

Abbreviations		Symbols and Greek Letters	
AC	Absorption Chiller	C	Consumption
BEP	Break Even Point	E	Energy
BESS	Battery Energy Storage System	En	Nth scenario
BIPV	Building Integrated Photovoltaic System	E_{DG}	Energy produced by DG
CC	Compression Chiller	$E_{DG\ toDHN}$	Energy produced and feed into the grid
CEC	Citizen Energy Community	$E_{DG\ to\ user}$	Energy produced by the DG to the end-user
CEP	Clean Energy Package	E_{inj}	Energy fed into the grid
CHP	Combined Heat And Power	E_{user}	Thermal load for end-user
COP	Coefficient of Performance	F	Fuel
CRE	Community Owned Renewable Energy	N	Total number of REC members
CSC	Collective Self Consumption	Q	Power
CS	Cooling System	r	Dynamic sharing key
DG	Distributed Generation	S	Surface
DH	District Heating	SC	Self-consumption rate
DHC	District Heating And Cooling	SH	Shared Energy
DHN	District Heating Network	SH_{lim}	Shared Energy Limit
DHW	Domestic Hot Water	SR	Sharing rate coefficient
DPP	Discounted Payback Period	SS	Self-sufficiency rate
DR	Demand Response	Uec	Useful energy coefficient
DSO	Distributor Network Operator	T	Temperature
EAC	Equivalent Annual Cost	V	Volume
EC	Energy Community	η	Efficiency
EER	Energy Efficiency Ratio	p	Daily Pearson coefficient remapped
ES	Energy Storage	α	Weights for Pearson correlation coefficient
EV	Electric Vehicle	β	Weights for sharing rate coefficient
HE	Heat Exchanger	ξ	Exponential decay constant
HP	Heat Pump	i	i-th member of the REC
ICE	Internal Combustion Engine	j	j-th hour
ICES	Integrated Community Energy System		
IEMD	Internal Electricity Market Directive		
IRR	Internal Rate Of Return		
iVN	Intelligent Virtual Network		
LP	Linear Programming		
MES	Multi Energy System		
MILP	Mixed Integer Linear Programming		
MOO	Multi Objective Optimization		
MPC	Model Predictive Control		
NPV	Net Present Value		
PCR	Percentage Cost Reduction		
PtG	Power to Gas		
PV	Photovoltaic		
REC	Renewable Energy Community		
RED	Renewable Energy Directive		
RES	Renewable Energy Sources		
RPV	Rooftop Photovoltaic		
SG	Smart Grid		
SH	Space Heating		
SME	Small And Medium-Sized Enterprise		
SOO	Single Objective Optimization		
SP	System Production		
SPP	Simple Payback Period		
SWH	Solar Water Heater		
TEC	Thermal Energy Community		
TES	Thermal Energy Storage		
WPP	Wind Power Plant		

INTRODUCTION

1.1. Energy contest & scenario

This section is essential for understanding the broader context in which the energy transition is taking place, laying the foundation for the subsequent discussion. An overview of the global energy landscape is provided, with section 1.1.1 focusing on key aspects such as total energy consumption, emissions, and the share of renewable energy utilized by major countries worldwide. These insights highlight the current state of energy use and environmental impact on a global scale. Section 1.1.2 then narrows down to the European context, discussing primary policies and initiatives aimed at addressing the energy transition and promoting sustainable energy practices within the region. This structure offers a clear and systematic analysis of both global and regional approaches to sustainability in the energy sector.

1.1.1 Global energy landscape: trends and consumption patterns

In recent decades, global energy demand has increased significantly, driven primarily by economic growth and the industrialization of emerging and developing countries. Energy needs are of crucial importance for both socioeconomic progress and the challenges related to environmental sustainability, reflecting disparities in resource access across different regions of the world. In this context, an analysis of global primary energy consumption reveals a diverse landscape, with wide geographical differences both in absolute volumes and per capita consumption, as shown in Figure 1. 1 and Figure 1. 2. Each region analyzed includes the following countries:

- North America: Canada, Mexico, United States;
- Central & South America: Argentina, Brazil, Chile, Colombia, Ecuador, Peru, Trinidad & Tobago, Venezuela, Central America, Other Caribbean, and Other South America;
- Europe: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, and United Kingdom;
- CIS: Azerbaijan, Belarus, Kazakhstan, Russian Federation, Turkmenistan, and Uzbekistan;
- Middle East: Iran, Iraq, Israel, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates;
- Africa: Algeria, Egypt, Morocco, South Africa, Eastern Africa, Middle Africa, Western Africa, Other Northern Africa, and Other Southern Africa;
- Asia-Pacific: Australia, Bangladesh, China, China Hong Kong SAR, India, Indonesia, Japan, Malaysia, New Zealand, Pakistan, Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand, Vietnam, and Other Asia-Pacific.

In particular, Figure 1. 1 shows that, currently, the Asia-Pacific region is the largest consumer, driven by the high demand from China and India. Next is North America, with the United States as the main consumer, followed by Europe, where Germany, France, the United Kingdom, Italy, and Spain account for the highest usage. Africa, with South Africa as a notable exception, is the region with the lowest primary energy consumption, reflecting limited access to energy resources in many areas of the continent. Finally, looking at per capita consumption data in Figure 1. 2, the scenario changes: North America ranks first, with Canada making a significant contribution. The CIS region follows, then Europe and the Middle East. In this context, the Asia-Pacific region ranks lower in per capita consumption, with notable usage only in countries like South Korea, Australia, and Japan. The differences between absolute primary energy consumption and per capita consumption highlight the influence of various economic, demographic, and climatic factors. Countries with large populations, such as China and India, dominate absolute energy consumption but have relatively low per capita levels, as their energy demand is spread over vast numbers. In contrast, nations with smaller populations and a high standard of living, such as Canada or the United States, have high per capita consumption, underscoring how lifestyle and environmental conditions impact individual energy needs.

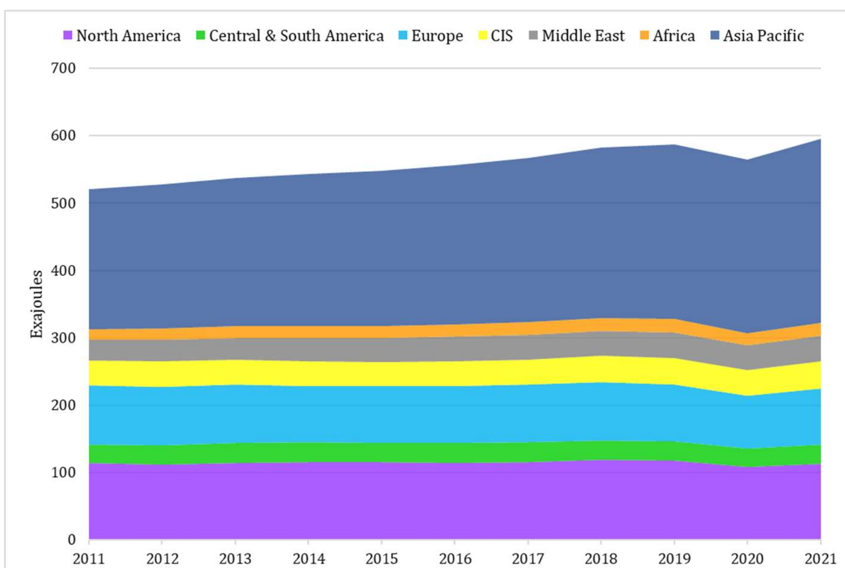


Figure 1. 1 Trend of primary energy consumption across major global regions from 2011 to 2021 (data from [1])

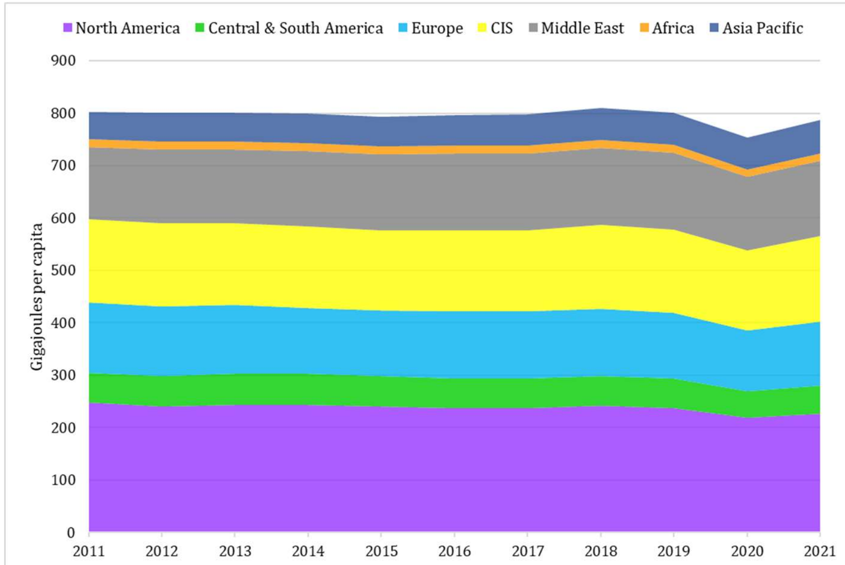


Figure 1. 2 Trend of primary energy consumption per capita across major global regions from 2011 to 2021 (data from [1])

After analyzing primary and per capita energy consumption, it is essential to consider the associated environmental impact and the evolution in the use of renewable sources. CO_2 emissions and the increase in renewable energy usage provide a comprehensive view of the environmental consequences of energy consumption and the sustainability strategies adopted globally. The following charts highlight the link between energy demand and emissions and show how interest in renewables is rising in various regions of the world. Figure 1. 3 focus on CO_2 emissions and shows that the Asia-Pacific region has the highest emission levels, mainly due to China, which holds the global record for emissions. North America follows, with Europe close behind. A clear correlation is evident between primary energy consumption, as seen in the first figure, and CO_2 emissions, as areas with higher energy demand also tend to produce higher emission volumes. Figure 1. 4, focused on renewable energy consumption in North America, Central and South America, Europe, and the Asia-Pacific region, shows a clear increase in these sources across all areas analyzed, especially in recent years. Although data for other regions is unavailable, the overall trend reflects the growing adoption of renewables within the global energy mix. This progress aligns with efforts to reduce CO_2 emissions and represents a critical step toward a more sustainable energy system, reducing the environmental impact of rising energy consumption.

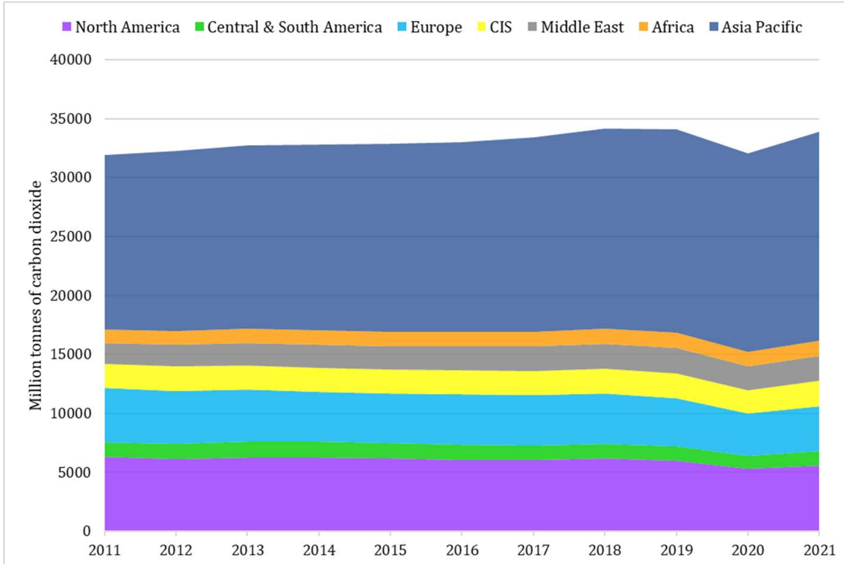


Figure 1. 3 Trend of CO_2 emissions across major global regions from 2011 to 2021 (data from [1])

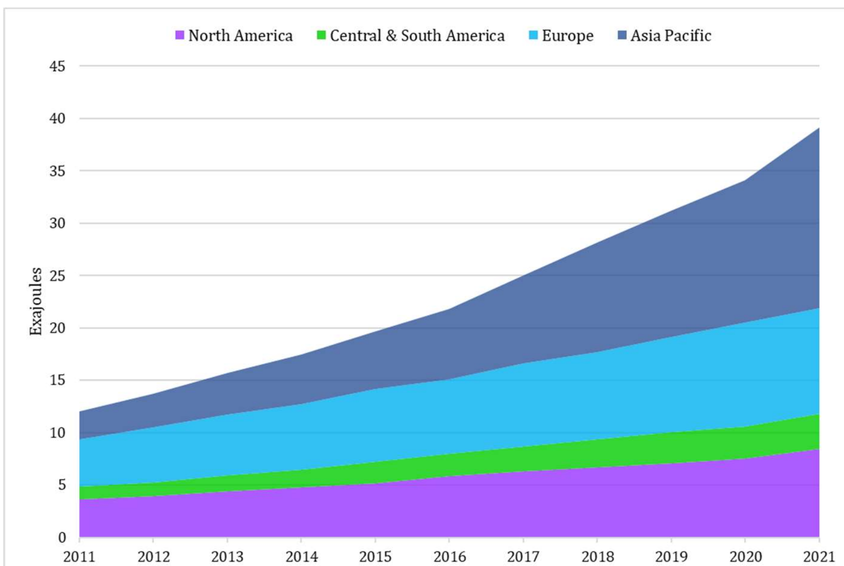


Figure 1. 4 Trend of renewable energy consumption across some global regions from 2011 to 2021 (data from [1])

Figure 1. 5 representing the trend in global total primary energy consumption and CO_2 emissions from 2011 to 2021, showing a parallel increase in both values. It is interesting to note the significant decline in primary energy consumption in 2020, during the COVID-19 pandemic, which stands in contrast to previous years' growth. This decline also led to a considerable reduction in CO_2 emissions for the same year, highlighting the impact of changes in economic

activity and energy consumption on global emissions. This phenomenon reflects the widespread use of fossil energy sources in many of these regions, where the contribution of renewable sources remains limited—otherwise essential for a meaningful reduction in emissions. Table 1. 1 summarizes key data on primary energy consumption, per capita consumption, CO_2 emissions, and the share of renewable energy for major global regions in 2021. The reported values confirm the trends discussed: the Asia-Pacific region stands out as the main consumer and emitter, while North America and Europe show high per capita consumption. The share of renewable energy varies significantly, with steady growth across all areas, in line with the commitment to a global energy transition.

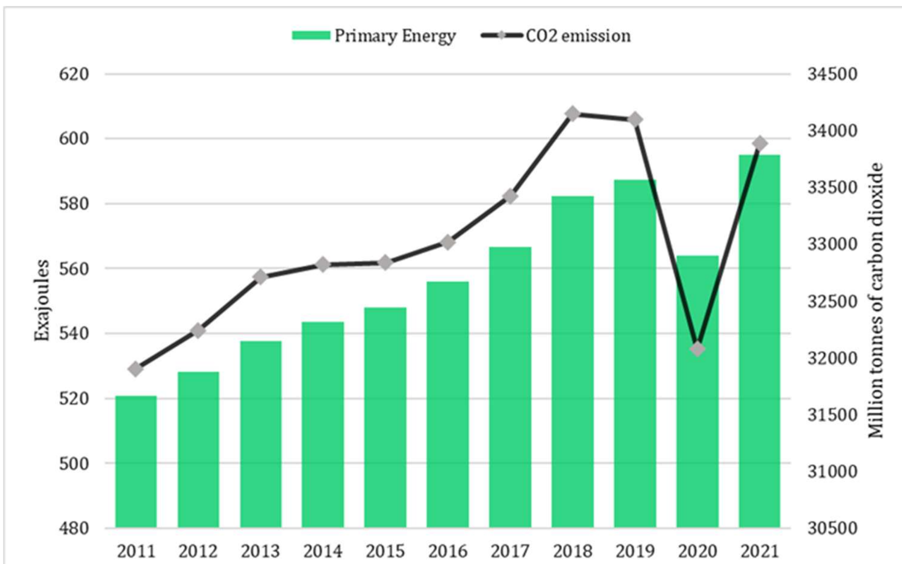


Figure 1. 5 Global primary energy consumption and CO_2 emissions trends, 2011-2021 (data from [1])

Table 1. 1 Key data on major world regions in 2021 [1]

	Primary energy consumption [EJ]	**Gigajoules per capite**	**Carbon emission [$MtCO_2$]**	**Renewable consumption [EJ]**
North America	113.7	227	5602.2	8.44
Central & South America	28.46	53.7	1213.1	3.35
Europe	82.38	122	3793.7	10.14
CIS	40.32	163	2132.5	0.1*
Middle East	37.84	143	2117.2	0.18*
Africa	19.99	14.6	1290.7	0.47*
Asia Pacific	272.45	63.6	17734.6	17.22

*lack and uncertainty of data for effective evaluation of the renewable contribution

1.1.2 European energy goals and consumption patterns in transition

After analyzing the global context, for the present work is relevant to focus on Europe, one of the most active regions in energy transition and CO_2 emission reduction. Despite being among the areas with the highest primary energy consumption worldwide, Europe stands out for its growing share of renewable energy and a constant commitment to reducing its carbon footprint. Countries like Germany, France, the United Kingdom, Italy, and Spain contribute significantly to Europe's energy demand. A more specific analysis of primary energy consumption in Europe, as highlighted in the Figure 1. 6, shows the distribution of main energy sources and usage trends. Overall primary energy consumption has not seen significant increases in recent years, but oil remains the primary source, with Germany as the leading consumer. Germany is also notable for its consumption of natural gas, the second most used energy source in Europe, followed by the United Kingdom. Coal ranks as the third most used energy source, with Germany again as the largest consumer, alongside Poland. As for nuclear energy, France is the undisputed leader in consumption, followed by other countries, though at lower volumes. Renewable sources, divided between hydropower and other renewables, show a different dynamic: renewables have seen constant growth, with Germany as the primary user, followed by the United Kingdom, Spain, and Italy. This growth trend is further highlighted in the Figure 1. 7, which shows an increase in renewable energy production and consumption on a global level. The relationship between renewable production and consumption confirms the growing commitment toward more sustainable energy sourcing, aligning with the trends discussed in the previous paragraph.

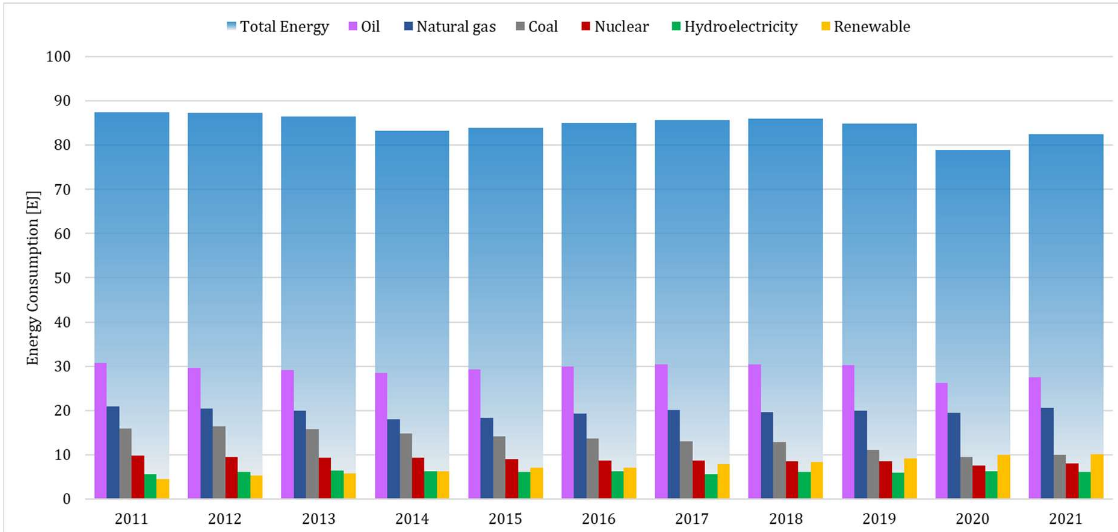


Figure 1. 6 Trend of total primary energy consumption by source in Europe (data from [1])

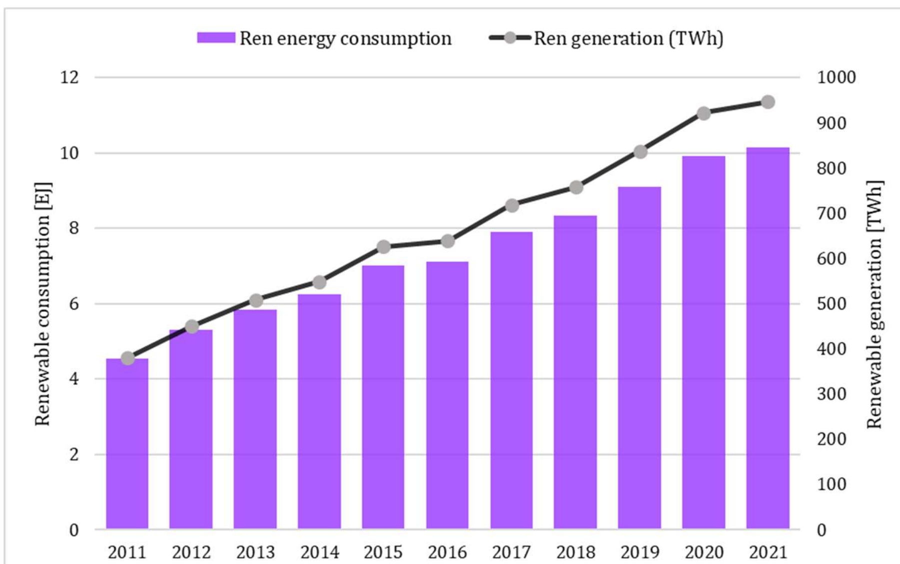


Figure 1. 7 Trend of renewable generation and consumption in Europe (data from [1])

1.1.3 EU's path to decarbonization: emission targets and energy transition

The energy transition in Europe is driven by growing concerns over the climate crisis and the urgent need to strengthen energy autonomy. In response, the European Union has adopted a comprehensive set of policies and regulations aimed at promoting clean energy technologies, enhancing energy efficiency, and accelerating investments in renewable sources like wind and solar power. The EU's long-term vision is to create a resilient and sustainable energy system that supports economic growth while reducing dependency on fossil fuels. At the heart of this transformation are two key objectives: a 55% reduction in greenhouse gas emissions by 2030, and the achievement of climate neutrality by 2050, both of which are enshrined in the European Climate Law. To meet these ambitious targets, the EU has developed strategic frameworks and action plans designed to shift the continent's energy mix toward renewable sources, thereby significantly lowering its environmental impact. Central to this is the "Clean Energy for All Europeans" package, which includes two important directives: RED II (Renewable Energy Directive II) and IEM 2019 (Internal Electricity Market Directive). The 2018 RED II Directive set a target for renewable energy to account for 32% of Europe's energy consumption by 2030, encouraging sustainable production and promoting energy self-consumption. On the other hand, the 2019 IEM Directive aims to complete the integration of the European electricity market, fostering competition and ensuring fair access for all energy producers, including small renewable energy providers. A critical component of the energy transition is the decarbonization of the heating and cooling sector, which represents nearly half of Europe's total energy demand—exceeding the requirements for transport and electricity. Despite progress, global heating and cooling systems remain heavily reliant on fossil fuels. In 2022, only 24.8% of the heat generated globally came from renewable sources. This underscores the need to prioritize the decarbonization of this sector to achieve the EU's climate and energy goals. To support its emissions reduction targets, the EU launched the "Fit for 55" package, which serves as the strategic blueprint for reducing emissions by 55% by 2030 compared to 1990 levels. In line with this plan, the European Council approved the new Directive 2023/1791 on energy efficiency in July 2023. This directive requires Member States to collectively reduce final energy consumption by at least 11.7% relative to the 2030 projections established in 2020. Between 2024 and 2030, Member States will need to achieve gradual increases in energy savings, with an annual average reduction of 1.49%, culminating in a 1.9% reduction by the end of the decade. Efficient district heating systems are expected to play a crucial role in this process. These systems, which leverage recovered thermal energy and renewable-based technologies, offer significant potential for reducing primary energy demand. Their widespread adoption is seen as essential to achieving both energy efficiency and emissions reduction goals across Europe.

1.2. Energy Communities

With the advancement of the energy transition and the growing need to move towards renewable sources, the concept of decentralization of energy systems and promotion of renewable initiatives led by energy communities has gained importance in Europe. In this section, a comprehensive overview of energy communities within the European context is provided, examining their structure, purpose, and regulatory underpinnings. Section 1.2.1 focuses on the RED II and IEMD EU directives, which have been instrumental in defining the formal configurations and operational guidelines for energy communities, establishing a foundational framework to facilitate their growth and integration throughout Europe. Section 1.2.2 provides a brief overview of the Italian regulation framework on ECs.

1.2.1 Energy Community configurations in European directives

The shift in power systems, driven by the widespread adoption of distributed generation through renewable energy sources and the rise of prosumers, has brought significant challenges and opportunities to global energy landscapes [2]. Within this evolving context, the concepts of energy sharing and prosumer involvement have gained considerable attention, as users are increasingly able to participate in energy distribution through both electrical grids and decentralized systems. This paradigm shift allows individuals to manage energy production and consumption according to their needs and capabilities, paving the way for "Energy Communities" (ECs), which promote local-level engagement and sustainable practices [3]. ECs, in particular, have gained prominence in Europe as essential instruments in the transition from traditional, centralized energy systems—largely dominated by fossil fuels—to a more decentralized, democratized, and renewable-oriented market. Their emergence reflects a fundamental shift in governance models within the European Union, empowering citizens to actively engage in the energy transition by producing, consuming, and sharing renewable energy sustainably. Consumers who adopt renewable energy systems transition into prosumers, sharing part of their generated energy within local ECs [4]. Within these communities, prosumers can engage in various energy transactions, such as trading energy with the public grid at real-time prices (RTP), engaging in local trading, and utilizing peer-to-peer (P2P) mechanisms through bilateral agreements [5,6]. Furthermore, recent technological advancements have facilitated a convergence between the energy sector and sharing economy models, particularly with smart grid technologies [7], reducing costs and peak loads through sophisticated energy-sharing algorithms [8] and optimization models [9]. In light of these developments, the European Union introduced the (*Clean energy for all European packages*) in 2016. This initiative marked a transformative step in formally recognizing energy-sharing projects and promoting collective self-consumption and the establishment of energy communities within European legislation. The Clean Energy Package culminated in two directives that provide a legal basis for these new energy models:

- the EU Renewable Energy Directive 2018/2001 (RED II)
- EU Internal Electricity Market Directive 2019/944 (IEMD)

The RED II directive outlines two configurations for energy sharing in Article 2: "jointly acting renewables self-consumers" or "Collective Self Consumption" (CSC) in paragraph 15 and "Renewable Energy Communities" (REC) in paragraph 16. A REC represents a collective initiative where various stakeholders—such as citizens, SMEs, and local authorities—collaborate to produce renewable energy, prioritizing consumption and sharing within the community to support self-sufficiency and sustainability. Aligning with REC principles, CSC is limited to a specific geographic area, typically where users are located within the same building or multi-apartment complex. Thus, both REC and CSC differ from individual self-consumption, where a single user independently generates and consumes renewable energy for their own needs. Under RED II, the main purpose of RECs is not to generate financial profit but rather to bring environmental, economic, and social benefits to their members or local areas. Furthermore, the directive requires EU Member States to integrate the REC framework into national legislation by June 2021, as outlined in Articles 21 and 22, which specifically detail the role of Member States in supporting the development and operation of RECs and CSCs. These articles mandate that Member States ensure these energy communities have adequate access to energy networks and can participate in energy markets on a non-discriminatory basis. The Table 1. 2 highlights the key distinctions between 'Jointly Acting Renewables Self-Consumers' and 'Renewable Energy Communities,' as defined by the EU directive, focusing on their organizational structure, operational scope, and primary objectives.

Table 1. 2 Main differences between the two configurations introduced by REDII directive

Characteristics	Jointly Acting Renewables Self-Consumers	Renewable Energy Community
Base Definition	A group of at least two "renewables self-consumers" (as per directive definition) who are located in the same building or multi-apartment block.	A legal entity based on open and voluntary participation, autonomy, and local control over renewable energy projects.
Composition	Group of individual consumers, each generating and consuming renewable energy primarily for their own use.	Legal entity composed of natural persons, SMEs, or local authorities (e.g., municipalities) as members or shareholders.
Operating Scope	Restricted to the same building or residential complex (multi-apartment block).	In proximity to renewable energy projects that are owned and operated by the community entity.
Primary Purpose	To facilitate self-consumption and energy sharing among individual consumers within confined premises.	To provide environmental, economic, or social benefits to its members or the local area, rather than financial profits.
Main Goal	Meet the energy needs of individual consumers within a confined space.	Promote community benefits through a locally controlled and inclusive governance model.

Similarly, the IEMD defines in the article 2, paragraph 2 the "Citizen Energy Communities" (CECs) and expands on their function by promoting participation in various energy markets, including day-ahead, balancing, and ancillary service markets. CECs prioritize user involvement, even from small or domestic consumers, enabling them to engage in energy markets under a collective framework that mirrors the sustainability and self-sufficiency objectives of RECs. The main distinction between Citizen Energy Communities (CECs) and Renewable Energy Communities (RECs) lies in their scope and energy sources. While CECs may operate with various types of energy, including non-renewable sources, RECs are exclusively focused on renewable energy production and local consumption. Additionally, RECs emphasize environmental sustainability, aiming to provide direct benefits to their local communities, whereas CECs support broader market participation. These differences are summarized in Figure 1. 8, providing a clear comparison of their core objectives and operational frameworks.

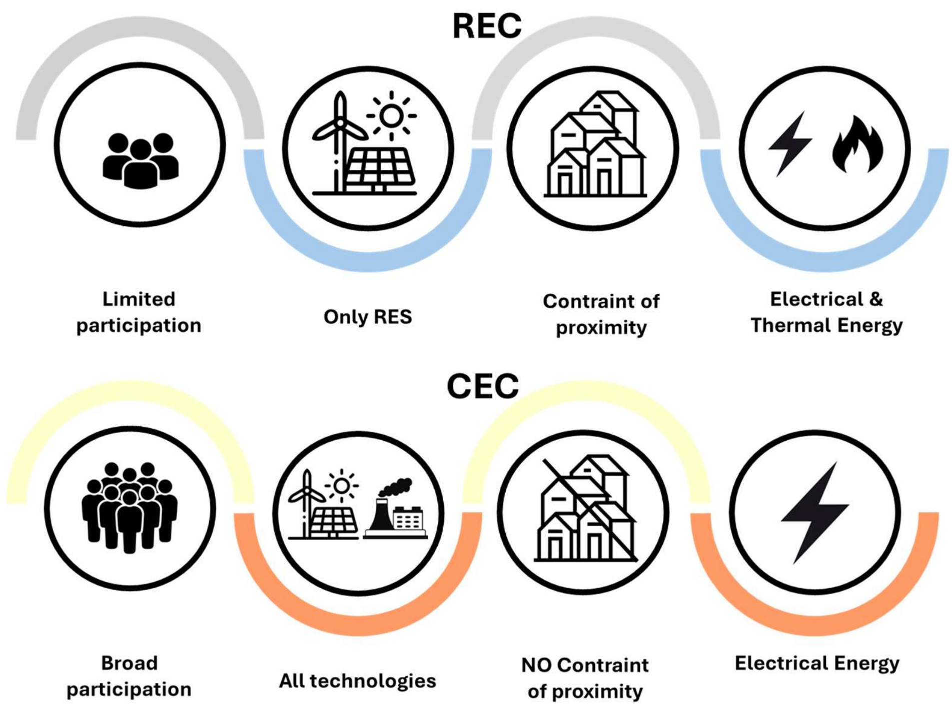


Figure 1. 8 Main differences between REC and CEC configuration

ECs represent a shift from individual self-consumption—where a single user generates renewable energy for personal needs—to collective self-consumption, where groups collaborate within shared geographical or physical spaces (e.g., buildings or communities) to optimize resource use. Through configurations such as RECs and CECs, energy users can become "prosumers," actively producing and consuming energy, and exchanging surplus within their communities or with the public grid. This transition is supported by recent technological advancements like smart grids and peer-to-peer (P2P) energy trading, which help streamline energy flows and encourage participation from diverse actors in the energy market. By fostering local energy generation and promoting a sense of ownership, energy communities also contribute to greater public awareness and engagement in sustainable practices. As a result, individuals shift from being mere consumers to prosumers who actively manage their energy needs and contribute surplus energy back into the community. The role of prosumers is central to the success of energy communities, as they benefit from increased autonomy, economic savings, and active involvement in the transition to a low-carbon economy. The regulatory frameworks for energy communities set forth by the European Union mark a significant step in aligning energy policy with sustainable development goals. With the EU's mandate for Member States to establish supportive legislation for these entities, energy communities are poised to play a central role in Europe's energy future, supporting environmental and social objectives while enhancing the security and resilience of the energy system.

1.2.1 Overview of the regulatory framework for Energy Communities in Italy

Italy was one of the first EU member states to begin transposing the European REDII directive and regulating energy communities. On February 28, 2020, a provisional regulatory framework was introduced, setting the main guidelines for subsequent regulatory measures from ARERA, MiSE, and GSE, the primary national authorities responsible for energy regulation, oversight, and promotion in Italy. This framework, initiated through Article 42-bis of Decreto-Legge 162/19 [11], came into force on March 1, 2020. This article introduced for the first time in Italy the concepts of "collective renewable energy self-consumers" and "Renewable Energy Communities" and formally defined "Shared Energy." The primary goal was to encourage the adoption of renewable energy sources, particularly decentralized solutions, to improve energy efficiency, foster consumer participation in the energy market, ensure affordable energy, and tackle energy poverty. On April 1, 2020, ARERA issued consultation document 112/2020/R/eel [12], outlining guidelines for the regulation of electricity used for collective self-consumption and shared energy within Renewable Energy Communities. This document detailed how ARERA intended to implement Article 42-bis, defining energy communities, the role of the GSE, and the framework for accessing the new regulatory environment, while also addressing the tariff components of shared electricity and potential incentives. On August 4, 2020, ARERA released Resolution 318/2020/r/eel [13], considering feedback from the consultation and issuing the final regulations governing the economic aspects of shared energy for both collective self-consumption and Renewable Energy Communities. On September 15, 2020, the MASE enacted a decree establishing a 20-year incentive tariff for shared renewable energy produced by plants within the framework of collective self-consumption and Renewable Energy Communities [14]. On December 22, 2020, GSE published the "Technical Rules for Accessing the Shared Electricity Valorization and Incentive Service," detailing the criteria and procedures for accessing financial incentives for renewable electricity production and sharing. These rules outlined the methods for selling energy, the technical requirements for plants, and the procedures necessary to access the service. On November 8, 2021, legislative decree 199/21 [15] was published in the Gazzetta Ufficiale, completing the implementation of the RED II directive. It introduced significant changes to the pilot framework, such as increasing the maximum capacity for plants from 200 kWp to 1000 kWp and expanding the geographical scope from secondary to primary substations. On the same day, legislative decree 210/21 was published [16], transposing the IEM directive, which introduced "active customers," "collective active customers," and "Citizen Energy Communities" into the Italian regulatory framework. On April 4, 2022, GSE published updated technical rules for groups of renewable energy self-consumers and renewable energy communities, extending the pilot framework's validity until the final implementing measures are adopted by MASE and ARERA. On November 28, 2022, the MASE initiated a public consultation on a draft decree for energy communities, inviting suggestions and feedback until December 12. On December 27, 2022, ARERA issued Resolution 727/2022/r/eel [17], approving the Integrated Text for Diffused Self-Consumption (TIAD). This document completed the rules for different self-consumption configurations, streamlining the procedures introduced during the 2020 transitional framework and implementing legislative decrees 199/21 and 210/21. On November 22, 2023, the European Commission approved the Italian decree introducing incentives to promote renewable energy self-consumption. Finally, on January 23, 2024, MASE issued the implementing decree to promote the creation and development of Renewable Energy Communities and Diffused Self-Consumption in Italy, introducing a new incentive tariff for shared energy. On February 23, 2024, GSE published updated operational rules for accessing the diffused self-consumption service, which were later approved by MASE on April 22, 2024.

1.3. District Heating Network

While energy communities have primarily focused on renewable electricity, the heating and cooling sector remains heavily dependent on fossil fuels, representing a significant share of energy demand. To fully decarbonize the energy system, efficient district heating offers a promising solution, thanks to its infrastructure. This system not only reduces the carbon footprint of heating and cooling but also enables the sharing of thermal energy within communities. Section 1.3.1 provides an in-depth overview of heating and cooling sector within the European context, analyzing the primary energy consumption patterns and the rising contribution of renewable energy sources over recent years. Section 1.3.2 expands on the geographic distribution and adoption of district heating across Europe, illustrating regional trends and highlighting the factors that have influenced its growth in various countries. Section 1.3.3 delves into the key European regulations and policy measures supporting efficient district heating, aimed at accelerating the transition to low-carbon solutions in heating and cooling. Together, these sections underscore the role of efficient district heating as a strategic pathway toward achieving Europe’s ambitious climate goals. Section 1.3.4 provides an overview of district heating adoption at Italian level.

1.3.1 Trends in renewable energy use for heating and cooling in EU countries

Energy used for heating and cooling accounts for approximately half of the gross final energy consumption in the European Union. Despite a slight increase in fossil fuel consumption in 2021, linked to the post-pandemic economic recovery as shown in the Figure 1. 9, the share of renewable energy used for heating and cooling has continued to grow in the following years.

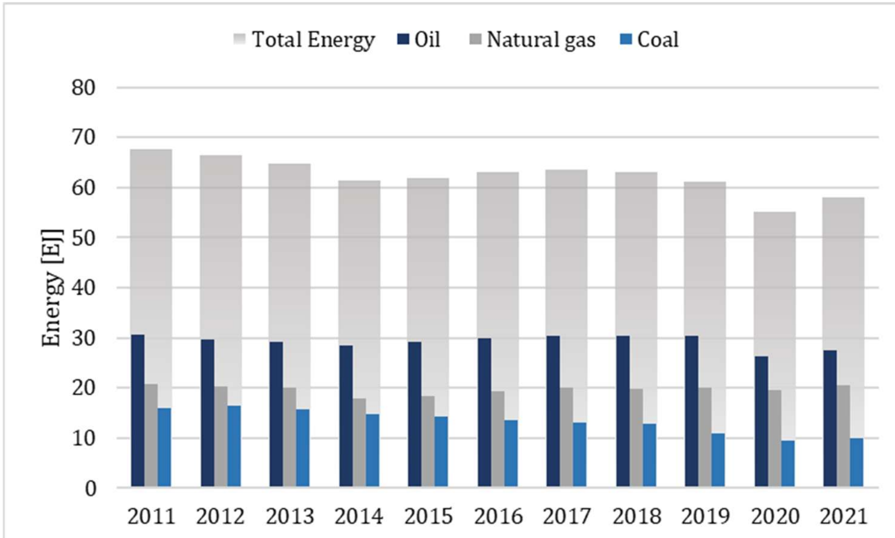


Figure 1. 9 Trend of primary energy consumption by fossil fuel source in Europe (data from [1])

Analyzing Figure 1. 10 and Figure 1. 11 it emerges that from 23.0% in 2021, the share increased to 24.8% in 2022, marking a rise of 1.8 percentage points. Sweden remains the leader in Europe for the use of renewable sources for heating and cooling, with a share of 69.3%, followed by Estonia (65.4%) and Latvia (61.0%), countries that rely heavily on biomass and heat pumps. On the opposite end, Ireland (6.3%), the Netherlands (8.6%), and Belgium (10.4%) record the lowest percentages of renewables used for heating and cooling. Compared to 2021, the largest increases were observed in Malta (+5.2 percentage points), Luxembourg (+2.5 points), and Ireland (+1.4 points). Conversely, some nations, such as Austria (-2.4 points), Slovenia (-1.2 points), and Cyprus (-1.0 points), experienced a slight decrease in the renewable share within their heating and cooling energy mix. In absolute terms, renewable energy use for heating and cooling has shown a long-term upward trend, largely due to the contribution of biomass and heat pumps; in fact, over ten years, the EU average rose from 18.6% to 24.8% (+6.2 percentage points). Developments in the industrial, services, and residential sectors, along with the growing electrification of heating through heat pumps, are key factors in the growth of renewables for heating and cooling.

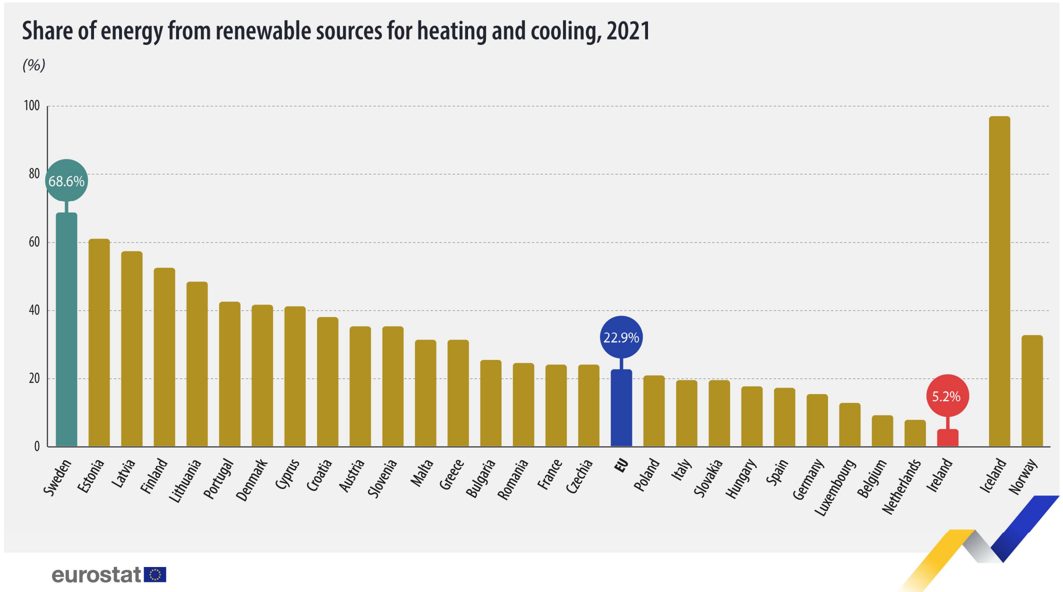


Figure 1. 10 Share of energy from RES for heating and cooling in Europe in 2021 [18]

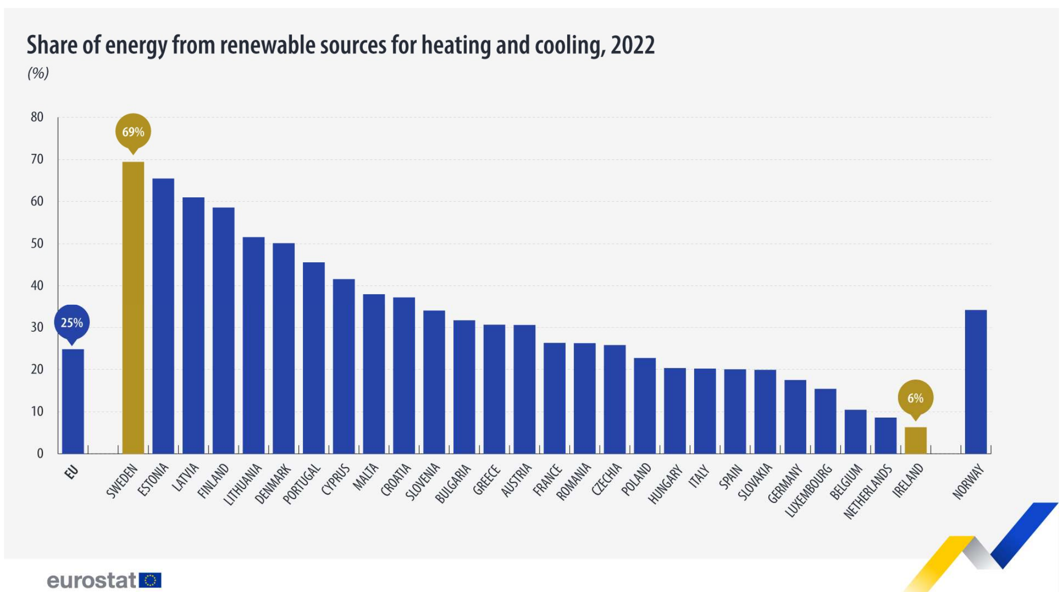


Figure 1. 11 Share of energy from RES for heating and cooling in Europe in 2022 [18]

1.3.2 The role of district heating in the decarbonization process

Addressing the challenge of decarbonizing heating and cooling systems is an urgent priority. In this context, district heating networks (DHN) play a fundamental role, enabling a broader and centralized integration of renewable energy sources and waste heat. In contrast, decentralized decarbonization solutions face significant limitations, particularly in urban areas [19,20].

District heating networks saw substantial development after the Second World War, with their primary advantages being the reduction of pollutant emissions and heat waste in cities. Additionally, the extensive use of these networks increases safety by eliminating the need to install combustion systems at the end-users of thermal energy. This also leads to a drastic reduction in fuel transport within urban areas. Furthermore, district heating enables high levels of energy conversion efficiency, thanks to the centralization of thermal energy production in a few large plants that meet residential sector demands. Typically, these plants operate in a cogeneration setup, ensuring optimal resource use. In Europe, approximately 6,000 district heating and cooling systems supply thermal energy to 100 million people across 32 countries, with significant variations between nations [21]. In 2015, over 60% of the population in Denmark and Estonia was served by district heating networks (DH), while in Switzerland and the Netherlands, this percentage dropped below 5%. Similar differences are observed in the capacity of district cooling (DC) systems. The energy sources used for district heating are also highly varied, each with a different impact on greenhouse gas emissions generated by DHC systems. The map in Figure 1. 12 provides an overview of the spread of district heating and cooling across Europe, based on various datasets covering the period from 2015 to 2020.

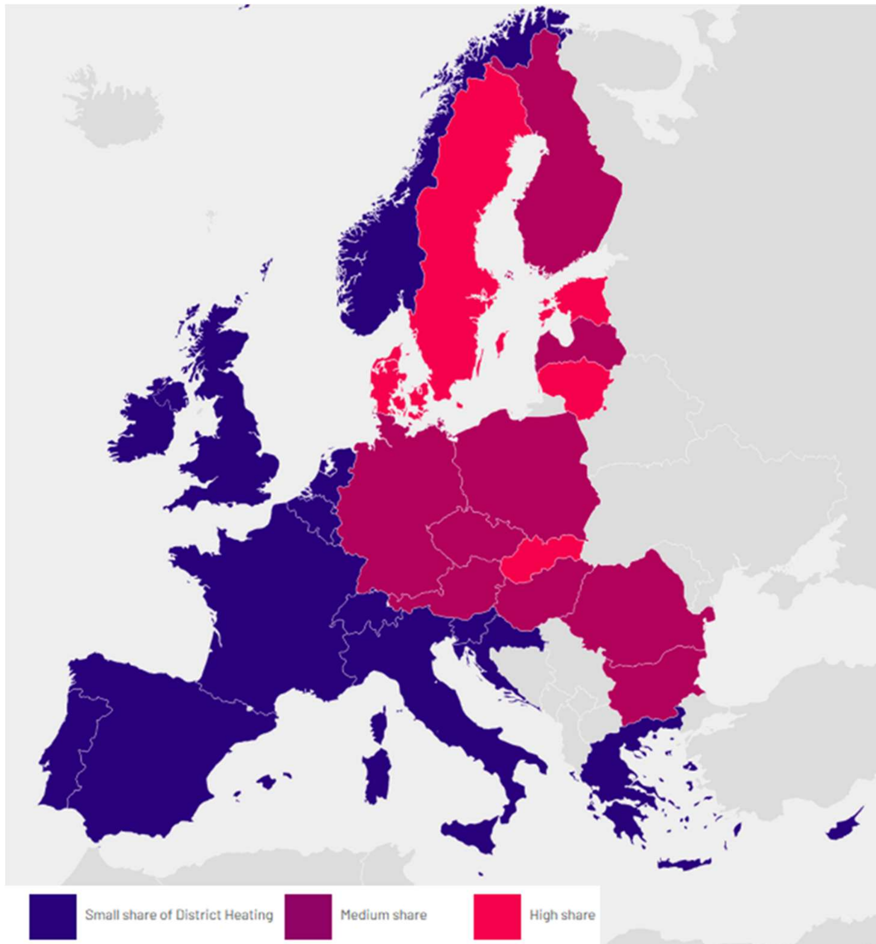


Figure 1. 12 Geographic distribution of District Heating Networks in Europe [22]

1.3.3 European regulations and policies for decarbonizing heating and cooling through efficient district heating

The European Commission highlights the importance of energy efficiency as a key element in reducing overall energy consumption and achieving the EU's climate targets, while simultaneously strengthening energy security and sustainability for the present and future. To support the EU's goal of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, the Commission has updated the Energy Efficiency Directive along with other energy and climate-related regulations. The revised [23] marks a significant advancement for the EU in the realm of energy efficiency. Practically, this means that EU member states will need to prioritize energy efficiency in major policy decisions and investments, both in energy-related sectors and those not strictly related to energy. The October 18, 2023, update follows the proposal to recast the Energy Efficiency Directive presented by the Commission in July 2021, a core component of the European Green Deal. Full implementation of the Energy Efficiency

Directive will be crucial for the EU to meet the Global Pledge, which aims to double the global rate of energy efficiency improvement from 2% to over 4% by 2030. Figure 1. 13 shows the timeline of the main European regulatory provisions on energy efficiency.

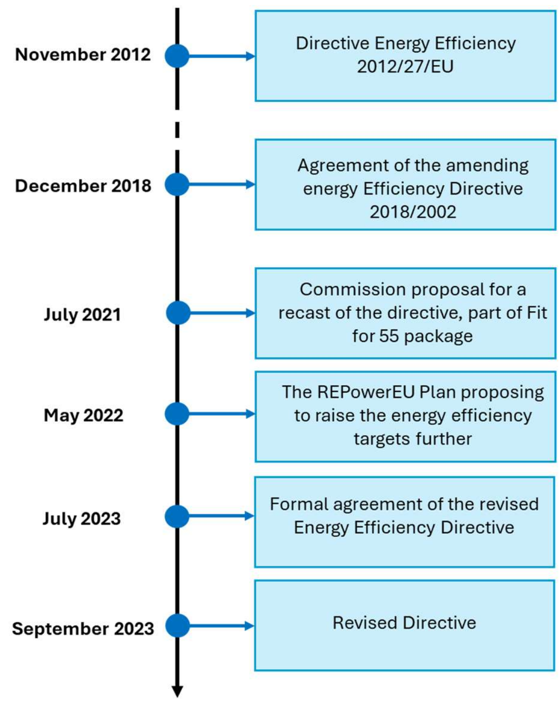


Figure 1. 13 EU provisions timeline in energy efficiency

Within the context of this work, the section of the European Energy Efficiency Directive relevant to efficient district heating and cooling is particularly important. To facilitate the decarbonization of district heating and cooling supply by 2050, the directive updates the definition of "efficient district heating and cooling." Specifically, paragraph (46) outlines the criteria these systems must meet, as specified in Article 26 of the directive. This article sets progressive criteria to improve energy efficiency and increase the use of renewable sources in centralized heating and cooling systems. The requirements establish rising percentages of energy from renewable sources, waste heat, and high-efficiency cogeneration, with a target of achieving 100% renewable energy by 2050. Alternatively, member states may adopt greenhouse gas (GHG) emission-based criteria per unit of heat or cooling supplied, with emission limits progressively reduced to reach zero emissions by 2050. The remaining points of Article 26 are summarized below:

- States must ensure that centralized heating and cooling systems comply with updated energy efficiency criteria in cases of construction or renovation, limiting the use of fossil fuels (only natural gas is permitted until 2030).
- Starting in 2025, every five years, systems with a capacity exceeding 5 MW that do not meet the standards must present plans to reduce energy consumption and distribution losses, promoting the use of renewable energy.
- Data centers with energy consumption exceeding 1 MW must recover and reuse waste heat.
- States must conduct cost-benefit analyses to improve energy efficiency in thermal generation plants, industrial facilities, water treatment plants, and data centers.
- States must collect and publish the results of energy efficiency analyses, including data on heat consumption and demand.

Additionally, paragraph (101) of the directive highlights the potential of efficient district heating not only for primary energy savings but also for integrating renewable energy sources and recovering hot water from facilities, which can be distributed through these networks. Specifically, the directive states:

"[…] *High-efficiency cogeneration and efficient district heating and cooling have significant potential for saving primary energy in the Union. Member States should carry out a comprehensive assessment of the potential for high-efficiency cogeneration and efficient district heating and cooling. Those assessments should be consistent with Member States' integrated national energy and climate plans and their long-term renovation strategies and could include trajectories leading to a renewable energy and waste heat based national heating and cooling sector within a timeframe compatible with the achievement of the climate neutrality objective. New electricity generation installations and existing installations which are substantially refurbished or whose permit or licence is updated should, subject to a cost-benefit analysis showing a cost-benefit surplus, be equipped with high-efficiency cogeneration units to recover waste heat stemming from the production of electricity. Similarly, other facilities with substantial annual average energy input should be equipped with technical solutions to deploy waste heat from the facility where the cost-benefit analysis shows a cost-benefit surplus. This waste heat could be transported where it is needed through district heating networks. The events that trigger a requirement for authorisation criteria to be applied will generally be such as to also trigger requirements for permits under Directive 2010/75/EU and for authorisation under Directive (EU) 2019/944* [...]".

The minimum requirements for energy use in heating and cooling systems will be gradually updated to encourage the integration of renewable energy and waste heat. Until 2030, support for new high-efficiency cogeneration units using natural gas will only be possible if these units are connected to efficient district heating systems, while the use of other fossil fuels will be prohibited for new heat generation capacity. Additionally, EU Member States are encouraged to promote local heating and cooling plans in municipalities with over 45,000 inhabitants.

1.3.4 The current landscape of district heating in italy

According to the latest reports from GSE [24] and AIRU [25], district heating systems have become well-established in Italy, with steady growth in both network coverage and installed thermal capacity. Currently, approximately 429 district heating networks are operational, including 279 medium-to-large systems and over 150 small or very small networks. The total network length exceeds 5,000 km, marking a 2.5% increase from the previous year and reflecting a continual expansion in the number of thermal substations, which now total around 90,000 units, as shown in Figure 1. 14. District heating systems are active in over 290 municipalities, primarily in northern regions, as illustrated in Figure 1. 15. In recent years, district cooling services have also expanded, provided either through dedicated chilled water networks or absorption units installed at user sites and powered by the district heating system. Figure 1. 16 highlights the growth in heated volume, which has reached nearly 400 million cubic meters, serving large cities like Turin, Milan, and Rome, as well as numerous smaller urban centers.

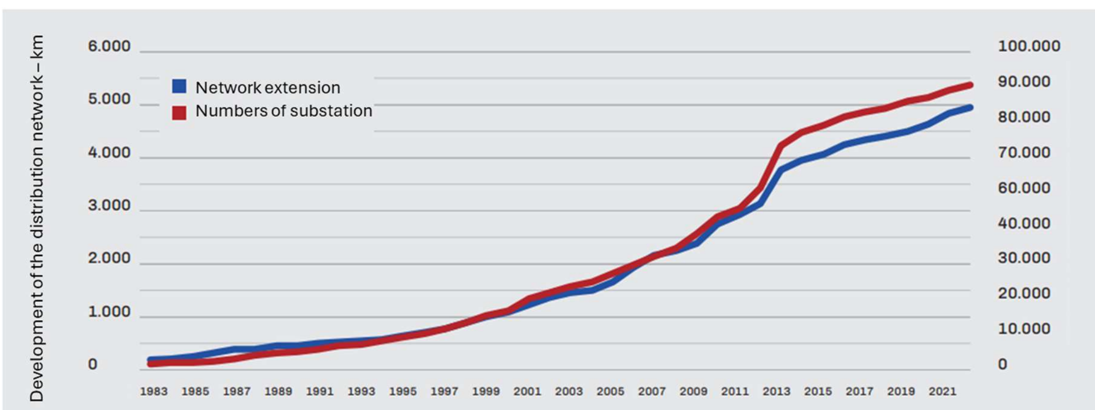


Figure 1. 14 Development of network and substations [25]

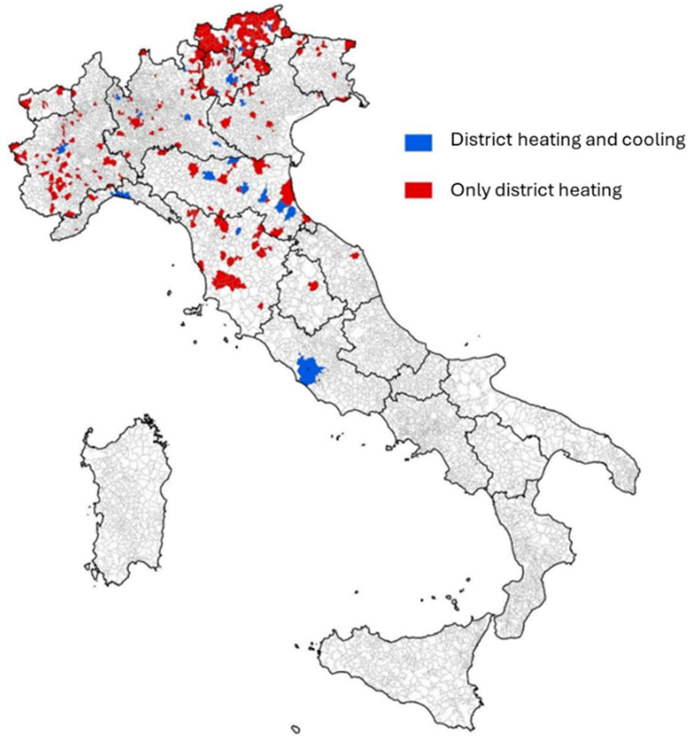


Figure 1. 15 Map of Italy showing the distribution of district heating and district cooling networks [24]

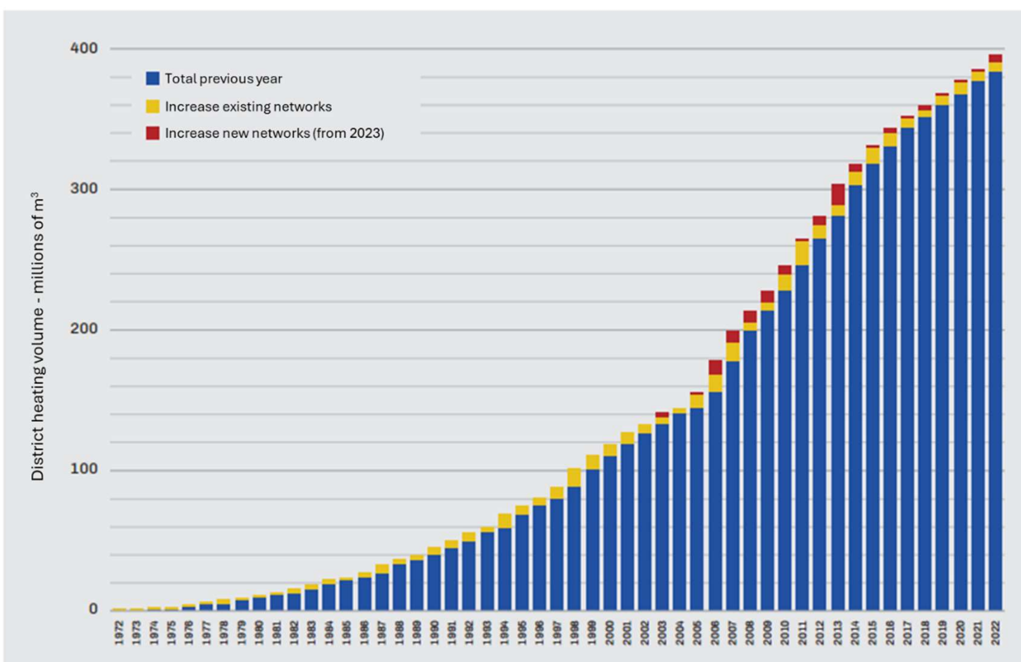


Figure 1. 16 Total trend of the total heated volume [25]

In the residential sector, district heating meets approximately 2% of the total energy demand for space heating and domestic hot water production, as shown in Figure 1. 17. Residential users are the primary recipients of this service, with substations that supply both heating and hot water, primarily using hot water as the carrier fluid.

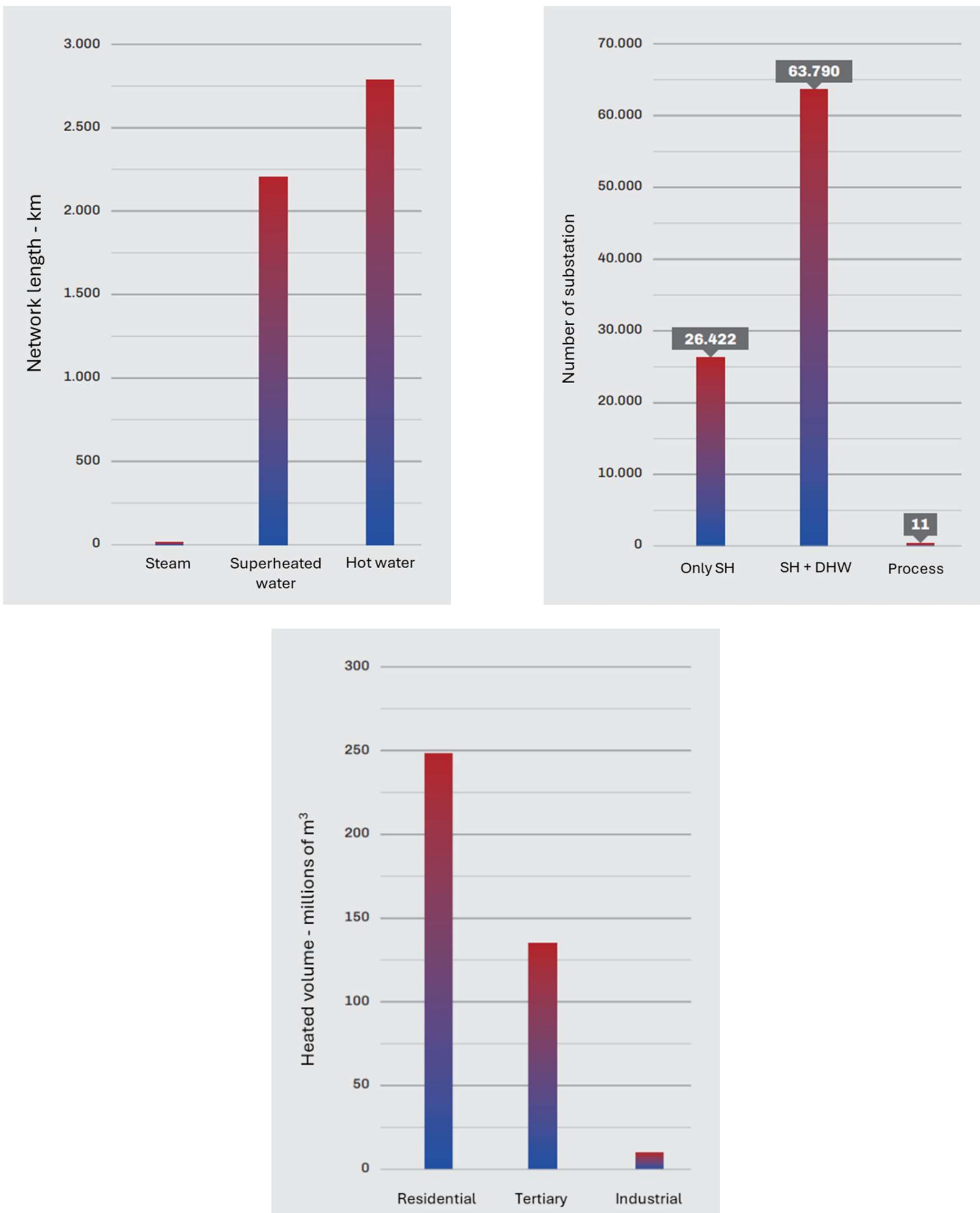


Figure 1. 17 Type of heat transfer fluid, substations and type of user served by the district heating [25]

Most district heating networks in Italy are powered by cogeneration plants that use both fossil fuels and bioenergy. The total thermal capacity of these plants is around 1,204 MWt, with a 49.2 MW increase recorded in 2022. This capacity growth reflects a commitment to improving energy efficiency and reducing emissions while encouraging the integration of renewable sources into urban heating. However, as shown in Figure 1. 18, natural gas remains the predominant energy source.

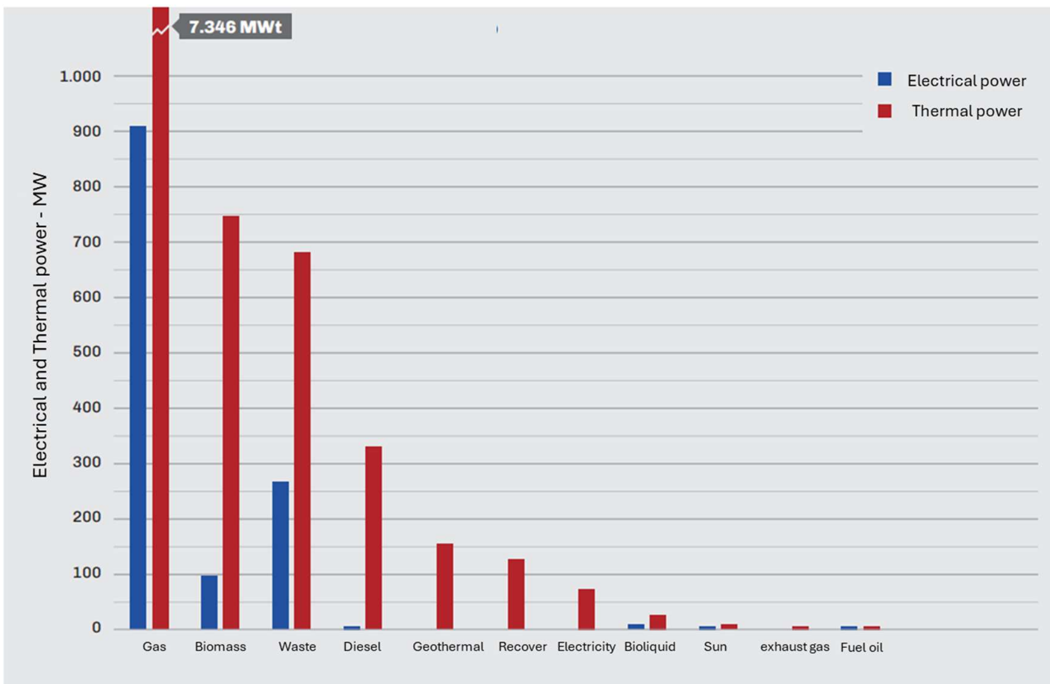


Figure 1. 18 Energy sources and installed powers [25]

THEORETICAL BACKGROUND

2.1 How do scholars approach Energy Communities in the European contest?

This section explores the topic of energy communities in the European context through a systematic review of the existing literature, with the aim of providing a comprehensive overview of the approaches adopted by researchers in addressing this issue. Specifically, section 2.1.1 outlines the objectives of the review and formulates the key research questions. Section 2.1.2 describes the methodological approach used to conduct the review. Sections 2.1.3 and 2.1.4 present the results obtained from the analysis. Following this, section 2.1.5 summarizes the main findings and the most relevant insights. Finally, section 2.1.6 discusses how the results and discoveries have influenced and guided the research activities carried out during the doctoral work.

2.1.1 Objectives of the review and development of research questions

Several scholars have reviewed publications on the subject of energy communities (ECs). The development of ECs varies significantly across countries both in pace and scope; [26] investigated the determinants influencing this development and suggested future research paths to support their expansion. Additionally, other research has focused on identifying the concepts and definitions related to Energy Communities and Collective Self-Consumption. For instance, [27] examined 183 definitions, categorized based on three focal points: meaning, activity, and purpose within the community. [28] explored the occurrence of EC concepts in the literature, while [29]highlighted the considerable overlap in definitions and terminologies associated with ECs, which often leads to confusion among researchers. Other investigations addressed more specific aspects of ECs. For example, [30,31] explored the rise of Thermal Energy Communities (TEC), [32,33] reviewed the recent advancements in Smart ECs literature, while [34] focused on the political, economic, and social factors influencing PV ECs. In contrast, [35] identified strategies to understand the local impacts of community-owned renewable energy (CRE), and [36] examined the energy trends that are shaping the future development of integrated community energy systems (ICES). A separate body of research delved into government and policy dimensions: [37,38] examined the intersection of ECs with governmental frameworks, while [39] analyzed the new peer-to-peer (P2P) energy markets from a consumer-centric perspective, particularly regarding energy sharing practices. [40] investigated the technical design aspects of local energy systems, assessing their economic, environmental, and social impacts. In terms of geographic focus, various studies analyzed specific regions: [41] concentrated on the growth of ECs in Italy, [42] focused on developments in Africa, and [43] studied EC initiatives in the USA. Moreover, [44] highlighted that EU energy research, which has only recently gained traction, tends to concentrate on "developed" nations, especially the United Kingdom, United States, Germany, and the Netherlands. Several studies also homed in on the European context: [45] gathered and mapped EC initiatives across Belgium, France, Germany, Italy, Poland, Spain, Sweden, and the United Kingdom. [46] examined business models for both established and emerging ECs, analyzing case studies from across Europe, while [37] provided a policy-focused review of scientific literature on ECs in Europe. Lastly, [47] explored the concept of Citizen Energy Communities (CEC) as introduced by the IEMD.

The works mentioned above are detailed in Table 2. 1, which outlines the primary characteristics of literature reviews on ECs from recent years, all conducted using systematic approaches and rigorous search criteria. Within this context, the objective is to offer a comprehensive and in-depth review of academic research on Renewable Energy Communities (RECs), Citizen Energy Communities (CECs), and Collective Self-Consumption (CSC) in the European setting, identifying barriers and gaps to inform future research directions on the subject.

Table 2. 1. Systematic Literature Reviews on ECs [48]

Topic	Authors	Databases	Investigated years	Keywords	N° of reviewed papers	Source
Thermal Energy Community	[31]	Google Scholar; Scopus	2000-2022	Local energy community, Local production, Thermal energy	135	Energies
Emergence of ECs	[26]	Web of science	2012-2021	Drivers, Energy communities, Energy transition, Multy-level	75	Renewable and Sustainable Energy Reviews
Governments instrument	[38]	Scopus	2000-2020	Community energy; Energy transition; Government instruments	108	Energy Research & Social Science
Community based initiatives for heating and cooling	[49]	Web of knowledge; Scopus	Up to 2020	Energy community; Institutional analysis and development; Renewable energy technologies; Thermal energy community; Thermal energy system	134	Energy Research & Social Science
Smart Energy Community	[32]	Scopus; Science Direct; Web of Science	2018-2022	prosumer; REDII; renewable energy community; smart energy communities; smart energy system	78	Energies
Conceptualizing community in energy system	[27]	Scopus	Up to 2019	Community renewable energy;Decentralized energy resources; Local energy systems; Low-carbon transition; Peer-to-peer energy market; Prosumers	405	Renewable and Sustainable Energy Reviews
PV EC	[34]	Web of science; Scopus; Science Direct; IEEE Xplore	2015-2021	Consumer; local energy communities; Photovoltaic communities; PV; Renewable energy	64	Energies
Classify existing literature of EC	[28]	Google Scholar; Science Direct; Semantic Scholar	2000-2021	community energy; distributed generation; energy communities; renewable energy	67	Elektrotechnik&Informationstechnik
Business model for ECs	[46]	Web of Science ; Scopus ; Science Direct; Google Scholar; IEEE Xplore	Up to 2021	Business model canvas; Business models archetypes; Energy communities; Lean canvas;	99	Renewable and Sustainable Energy Reviews
Italy, ECs,	[50]	Scopus	Up to 2021	Business models; Energy communities; Prosumers; Self-consumption	100	Renewable and Sustainable

						Energy Reviews
Smart ECs	[29]	SciELO; Web of Science ; Science Direct; DOJA; IEEE Xplore; ACM	Up to 2021	Integrated community energy system; Prosumer community; Smart energy community; Smart grid community	103	Energy Strategy Reviews
Policy challenge in EU	[37]	Web of Science	2007-2019	Community energy; Directionality; Energy policy; Renewable energy; Transition challenges	99	Renewable and Sustainable Energy Reviews
Sub-Sahara Africa, ECs	[42]	Scopus	2010-2020	Energy communities; Energy democracy; Stakeholde r engagement;	77	Sustainabilit y
Community energy Research	[44]	Scopus	1997-2018		263	Current Opinion in Environmen tal Sustainabilit y
Integrated community energy system	[36]	Scopus	2004-2013	Distributed energy resources; Energy systems integration; Local energy systems; Self-organized energy communities; Smart grids	1258	Renewable and Sustainable Energy Reviews

This paragraph therefore addresses the following central research question: how is the academic community approaching the study of these new entities introduced by European directives? From this core inquiry, additional questions emerge. First, which disciplinary approaches and methodologies are utilized in studying the topic? Secondly, what are the current and future technologies, energy sources, and management strategies relevant to energy communities? This work introduces several innovations that contribute to a deeper understanding of the subject. One key innovation is the establishment of a clearly defined framework for analyzing the scientific literature concerning the three types of ECs introduced by the 2018 and 2019 European directives. To achieve this, approximately 200 documents published between 2018 and 2022 were gathered for analysis, specifically focusing on those related to Renewable Energy Communities (RECs), Citizen Energy Communities (CECs), and Collective Self-Consumption (CSC).

In order to address the key questions regarding energy communities, structural dimensions and analytical categories were identified to systematically organize the existing body of literature.

Structural dimensions refer to the primary elements that guide the categorization and examination of scientific works within a particular context. In this chapter, the focus is placed on dimensions such as energy resources, technologies, methodologies, and geographical scope. Analytical categories, on the other hand, represent specific subcategories that enable more detailed analysis within each structural dimension. For example, analytical categories under the energy resources dimension might include biogas, solar, hydrogen, wind, etc. These subcategories provide a finer level of detail for analyzing data and insights found in the scientific literature.

2.1.2 Methodological framework and resources

The methodology adopted for conducting the systematic literature review adheres to the guidelines provided by [51] and [52], aiming to combine both qualitative and quantitative analysis to explore a specific topic [53], thus minimizing the limitations commonly associated with narrative reviews [54]. According to [55], a systematic literature review is defined as a study designed to "'identify, evaluate, and interpret all available research related to a particular topic, research question, or phenomenon of interest." Unlike individual or primary studies, this is considered a secondary study that aggregates, organizes, and assesses research previously conducted by other scholars [56].

This methodology, which can be viewed as a form of content analysis, establishes a transparent and repeatable process for selecting and reporting research on a specific topic, following a set of clearly defined steps that begin with the formulation of research questions. This is followed by the collection of materials and a descriptive analysis, providing an initial categorization of the findings. The third step involves defining structural dimensions specific to the topic, along with their associated analytical categories. In the final stage, the gathered materials are evaluated using the established structural dimensions and analytical categories, with conclusions drawn in relation to the initial research questions [57]. The review process was broken down into five main phases, which are outlined in Figure 2. 1. This approach has been extensively applied in conducting reviews in fields such as supply chain management [58,59] and sustainability studies [60–62]. The methodologies and categories used for the evaluation, following the aforementioned phases, are presented in the subsequent sections.

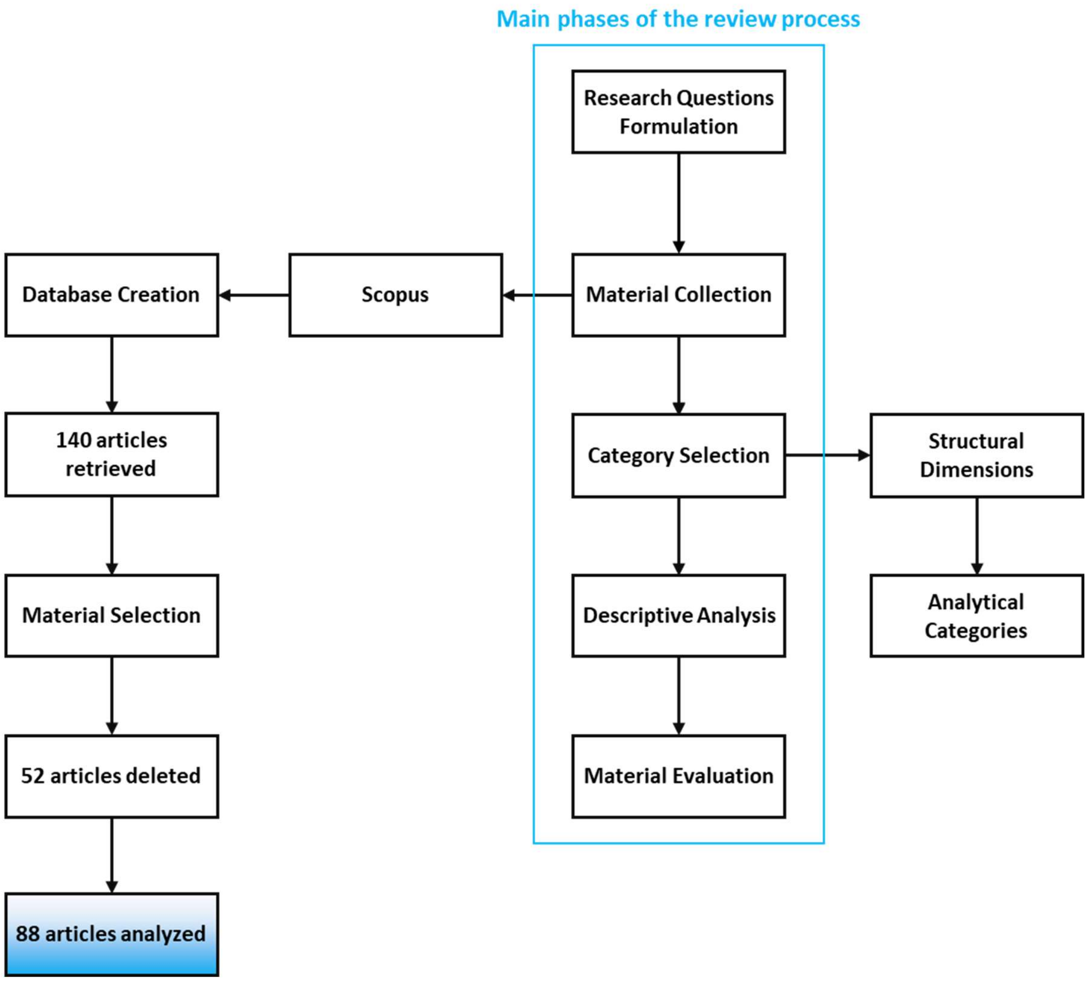


Figure 2. 1 Review process [48]

Material collection

The material for this review was gathered using Scopus as the primary scientific database. Since its introduction to the information market by Elsevier in 2004, Scopus has become one of the largest multidisciplinary scientific literature databases [63]. Furthermore, Scopus is recognized for its high level of uniqueness, a key attribute when selecting reliable sources for future research [64] As noted by [65,66], Scopus offers broader data coverage than the ISI database and applies more stringent methodological criteria for its content selection. In this review process, individual research articles were defined as the primary units of analysis. The focus was mainly on articles and reviews published in peer-reviewed academic journals, with specific search criteria applied to fields such as titles, abstracts, and keywords. Additionally, a chronological limitation was set, and only research from EU member countries was included. The query returned 140 results, which were subsequently evaluated to ensure they aligned with the scope and objectives of the review. Below is the query used for the Scopus search: (TITLE-ABS-KEY("Renewable Energy Community") OR TITLE-ABS-KEY("Citizen Energy Community")

OR TITLE-ABS-KEY(“Collective Self Consumption”) OR TITLE-ABS-KEY(“Collettive Self Consumption”) AND PUBYEAR > 2017 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (AFFILCOUNTRY, “Country xxx”) OR LIMIT-TO (AFFILCOUNTRY, “Country xxx”). To ensure the selected material was relevant to our research objectives, an initial screening was conducted by reviewing the abstracts. Subsequently, for articles requiring further evaluation, a comprehensive review of the full text was carried out. A total of 52 articles were excluded because their primary focus did not correspond to any of the three forms of ECs introduced by the EU directives. For instance, [67] included the term "renewable energy communities" in the keywords, but being published in early 2018, it did not address the specific European forms of ECs. Similarly, [68] presented a study in 2019 on local ECs, but the data analyzed were from a survey conducted between November and December 2017. Finally, [69] mentioned "collective self-consumption" in the keywords, though the description provided did not align with the definition established by the REDII.

Categories selection

In line with the research questions outlined in the introduction, the structural dimensions and analytical categories were selected [52,70]. This phase was characterized by a concept-centric approach to literature analysis [71], employing an iterative process with a deductive method to identify the analytical categories previously used in the literature. Referring to the research questions, Figure 2. 2 illustrates the process by which categories were chosen and materials evaluated. The feedback loop indicates the continuous refinement of structural dimensions and analytical categories as the literature review advanced.

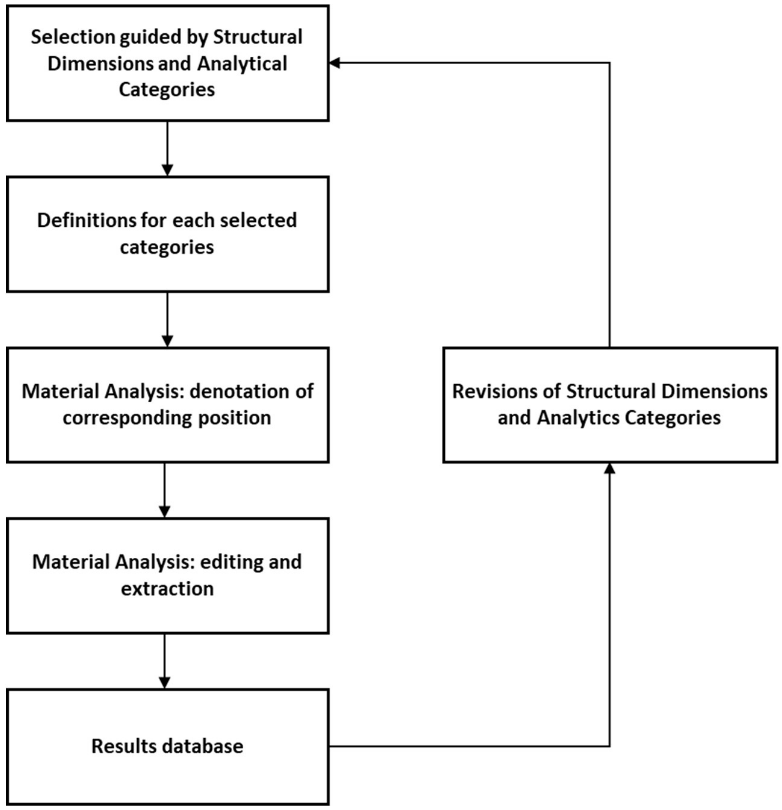


Figure 2. 2 Research process of review analysis [48]

This framework enabled an iterative process that began deductively, utilizing analytic categories identified in prior studies. After the initial identification, a preliminary scan of the collected material was conducted. Through an inductive process, categories that were not suitable for the review were discarded, and new ones were introduced as necessary [52,70]. The topic of ECs was analyzed using the selected structural dimensions and corresponding analytical categories, as outlined in Table 2. 2.

Table 2. 2 Structural dimensions and analytical categories [48]

Structural dimensions	**Analytical categories**
Energy resource	Biogas Biomass Fossil Fuel Geothermal Hydro Hydrogen* Solar Wind
Energy technologies	CHP CS DHN HP PV PtG SHW BESS EV WPP
Geographical focus	Comparative analysis Geographical area Single country
Legislative framework	CEC CSC REC Directive transposition National regulation
Management and control	Benefit sharing Control strategy Demand response
Research methodology	Case study Modelling and simulation Real data Review Survey Theoretical and conceptual
Subject area	Business and management Computer science Economic and finance Innovation Policy and legislation Social science Strategy management Technologies
Sustainability	Economic Environmental Social

* hydrogen is commonly recognized as an energy vector rather than a primary resource, for the convenience of categorization within the context of energy resources, it is included due to its substantial utilization as a viable energy source within communities.

2.1.3 Results: analytical description

To explore the correlation between the geographical location of the authors' affiliations and the research topics in the analyzed papers, CiteSpace [72], a free Java application for literature data analysis, was utilized. The first step involved creating network nodes based on the country of origin of each paper in the database. Following this, a clustering algorithm was applied to segment the network and identify clusters within the database. Specifically, the algorithm grouped together nodes with strong connections, while more loosely connected nodes were assigned to separate clusters [72]. After the clustering process, the cluster labels were generated using Automatic Cluster Labelling [72], which relies on noun phrases extracted from the paper titles. The labels were selected through a ranking algorithm based on the log-likelihood ratio (LLR) test [73]. The resulting network diagram, along with the cluster labels, is shown in Figure 2. 3.

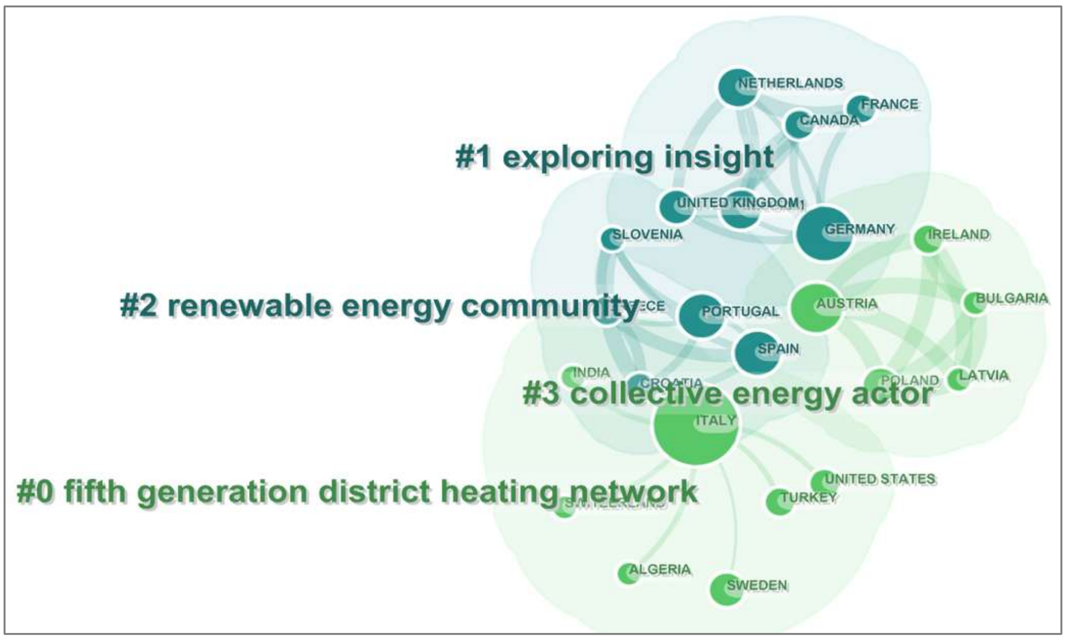


Figure 2. 3 Network diagram where countries represent the nodes, and paper titles are used to define the clusters [48]

As illustrated in Figure 2. 3, the clustering algorithm identified four distinct clusters:

- Fifth generation district heating network
- Exploring insight
- Renewable energy community
- Collective energy actor

It is noteworthy that the largest identified cluster is "Fifth generation district heating network," indicating a link between the concept of ECs and the exchange of thermal energy between buildings. This finding suggests that in the future, the concept of energy exchange might not only involve electricity but also thermal energy. Additionally, it is interesting to highlight that the most frequently cited country within this cluster is Italy, reflecting a strong research focus on ECs and DH. Moreover, examining the positioning of clusters in the network, there seems to be a strong connection between the "Fifth generation district heating network" and "Renewable energy community" clusters, indicating that the studies within these two groups are closely related. Regarding the geographical distribution of the authors' affiliations, Figure 2. 3 demonstrates that institutions across various countries are addressing the topic of ECs, each focusing on different aspects. Notably, countries within the "exploring insights" cluster appear to have minimal connections with those in the "Fifth generation district heating network" cluster. This observation suggests that research interests vary, with institutions concentrating their efforts on distinct aspects of the EC topic, even though all are related to the broader field of ECs.

2.1.4 Results: analysis of collected materials

Methodology

Initially, the structural dimension "Research Methodology" was applied for reviewing the documents, a dimension frequently covered in supply chain management studies focused on sustainability issues [58,74]. This dimension encompasses five primary methodological approaches (analytical categories): Case Study, Modelling and Simulation, Review, Survey, and Theoretical and Conceptual. To specifically identify studies examining the development of ECs using real consumption data, a new category titled "Real Data" was created. Real consumption data refers to operational energy loads, either directly monitored at end-users or gathered from datasets. These data reflect consumption variations over time due to high-frequency monitoring (e.g., every 15 minutes), allowing for an accurate depiction of user behaviour and enabling data-driven simulations. For instance, [75] utilized real consumption and generation data monitored via IoT devices with a 15-minute resolution; [32] employed real building energy load data from an energy distributor dataset; and [76] analyzed real data recorded from smart meters installed at users' premises. Figure 2. 4 illustrates the distribution of articles according to research methodologies. The most frequently used categories are "Modelling and Simulation" and "Case Study," with 51 and 53 papers, respectively. This indicates that researchers have largely adopted an experimental approach to investigate the potential and limitations of new EC models, simulating various scenarios under different national regulatory frameworks to better understand the key innovations introduced by EU directives. The methods and modelling approaches commonly utilized by scholars for the development of ECs are summarized in Table 2. 3 Modeling approach Table 2. 3. Many papers present case studies of a single country, while others offer comparative analyses, such as studies between the Netherlands and Denmark [77], or between France and Germany [78].

Other research adopted a "Theoretical and Conceptual" approach or employed surveys, likely driven by the complexity of EC models involving multiple actors, including producers, consumers, local authorities, and network operators. The "Survey" category also includes interviews, which serve as a valuable tool for collecting detailed information and insights about ECs. Like surveys, interviews allow the collection of perspectives on experiences, opinions, and approaches. For example, [79] used empirical data from the EU's REScoop Plus project, incorporating expert interviews and surveys among RECs to evaluate energy-saving efforts; [80] conducted a case study on planning a sustainable city district in Sweden, utilizing participatory interviews with relevant stakeholders; and [81] combined a literature review with expert interviews to provide scientific evidence supporting policy development for RECs in Eastern European Member States. Additionally, regulating and governing ECs requires a multidisciplinary and integrated approach that addresses technical, economic, social, and environmental aspects. For instance, [82] presented a framework analyzing the large-scale introduction of RECs; [83] focused on factors influencing business models for energy sharing; [84] examined data from 71 RECs to investigate their social role; and [85] compared the regulatory frameworks of nine European countries. [86] analyzed the role of RECs in the context of democratization and energy decentralization. The analytical category with the fewest contributions is "Review," with only five articles falling into this category. This is somewhat expected, given that academic research on the topic is still in progress, and the field is constantly evolving.

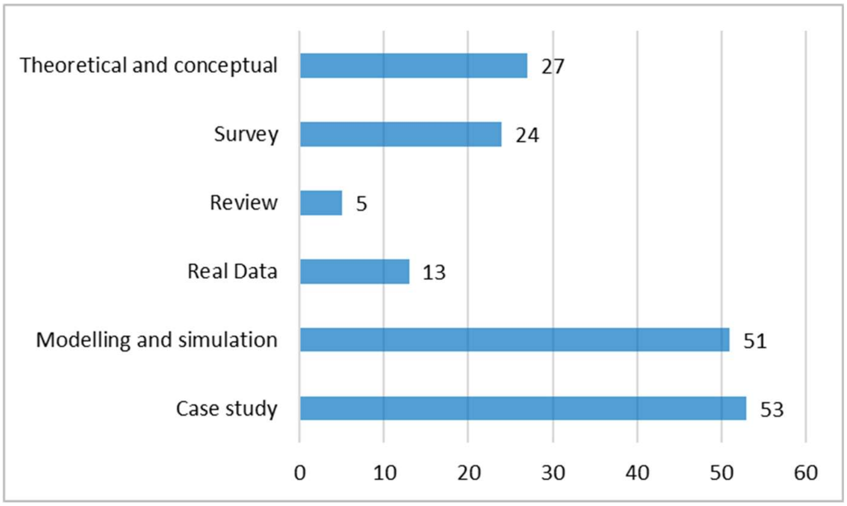


Figure 2. 4 Analytical categories related to research methodology [48]

Table 2. 3 Modeling approach [48]

Authors	Model Features	Software/Environment
[3] [87] [88] [89] [90]	MILP	Gurobi, Python
[91]	MPC	HomerPRO
[92] [93]	MOO	Borg MOEA, OpenDSS
[94] [95] [96]	LP	Pyomo, IBM (CPlex)

Subject area and sustainability

Figure 2. 5 and Figure 2. 6 illustrate the distribution of studies across the analytical categories related to the structural dimensions of Subject Area and Sustainability. Scholars have thoroughly explored various scenarios within different national regulatory contexts, with significant attention given to the "Economic and Finance" aspect, represented by 47 research papers. Additionally, the "Policy and Legislation" dimension of ECs has been the focus of 40 studies, highlighting its critical importance. This is particularly relevant because policy frameworks play

a key role in fostering the participation of diverse stakeholders in the generation and distribution of renewable energy at the community level. Several studies have concentrated on national regulations: [97] reviewed the policy framework in Spain; [50] focused on Italy; [81] analyzed regulations in Bulgaria and Germany, while [98] examined the benefits and challenges associated with the development of RECs during the transposition process by EU member states. Other studies took a social perspective on ECs: [84] applied the energy justice framework to explore how ECs contribute to promoting social equity by enabling the participation of marginalized groups; [99] introduced a tool designed to support decision-making regarding REC development in Crete (Greece); [100] used Foucault's governance theory to examine the compatibility between the ideals of energy communities and neoliberalism, which has shaped EU energy policy over the past four decades. Lastly, [101] conducted a study in Belgium investigating how attitudes, subjective norms, and perceived behavioral control influence individuals' intentions to participate in a REC.

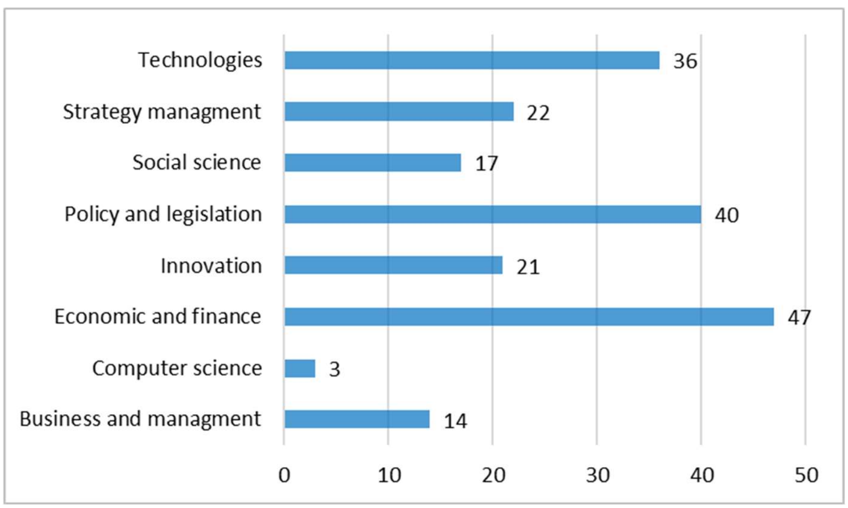


Figure 2. 5 Analytical categories related to subject area [48]

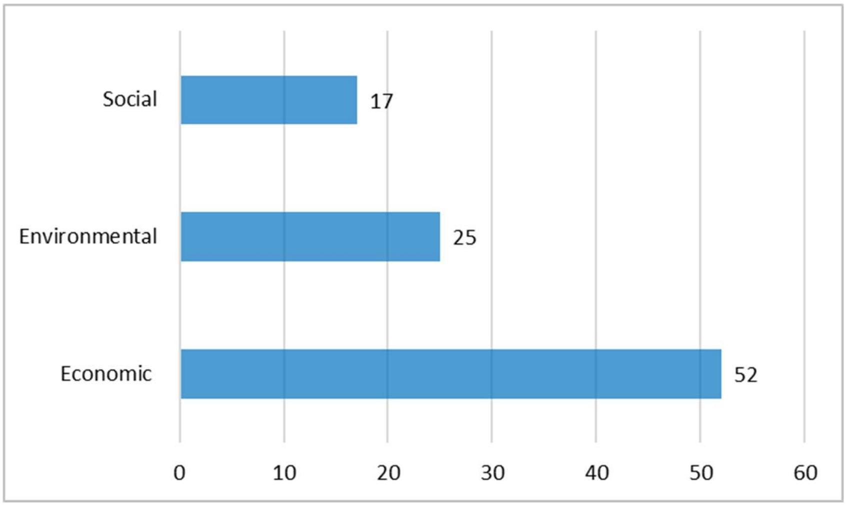


Figure 2. 6 Analytical categories related to sustainability [48]

Several studies have concentrated on evaluating the profitability of renewable energy projects and managing the associated investment risks. Stakeholders involved in these activities must consider various factors such as project costs, construction timelines, energy prices, financing availability, and potential regulatory obstacles. Table 2. 4 presents some of the most commonly used economic indicators employed by scholars to assess the development of ECs in the studies reviewed. The Net Present Value (NPV) is the most frequently used indicator for assessing the profitability of EC investments, as it accounts for the time value of money. Another widely used indicator is the payback period. Some studies utilize the Simple Payback Period (SPP), which does not factor in the time value of money or the discount rate, while others employ the Discounted Payback Period (DPP), which incorporates these considerations. In addition, some scholars have used less common economic indicators, such as the Break Even Point (BEP), which is applied in cost and revenue analyses to determine when a community generates sufficient revenue to cover all its costs. Other indicators include the Percentage Cost Reduction (PCR), used to assess the operational efficiency of a community, and the Equivalent Annual Cost (EAC), which calculates the annualized cost of an investment or project over its entire lifespan, enabling comparisons with alternative investment options.

Table 2. 4 Economic indicators for the impacts of ECs [48]

Authors	BEP	DPP	EAC	IRR	NPV	PCR	SPP
[102]					✓		
[103]					✓		
[104]		✓		✓	✓	✓	
[105]					✓		✓
[106]	✓		✓		✓		
[107]			✓		✓		
[93]		✓		✓	✓		
[89]					✓		
[108]							✓

Energy technologies and resource

Figure 2. 7 and Figure 2. 8 reveal that numerous studies investigate the energy technology dimension, often serving as the starting point for analysis. In many cases, the focus on energy technologies is primarily associated with photovoltaic (PV) systems (46 studies) and energy storage technologies (20 studies). The analysis also shows that relatively few articles address integrated systems or multi-energy systems (MES), where electricity, heat, cooling, fuels, and transportation optimally interact at various levels [109]. The literature mainly focuses on electrical ECs, with fewer studies addressing thermal ECs or the connection between RECs and DHNs or Power-to-Gas (PTG) systems. For example, the integration of photovoltaics, heat pumps, and absorption chillers to decarbonize a district heating network was explored by [102], while [105] studied an Energy Community that integrates a biomass-based organic Rankine cycle cogeneration plant, a mini-hydro plant, and a distributed PV plant. Regarding energy resources, solar energy is the most frequently mentioned (46 studies), while relatively few papers address hydrogen as an energy source. Notably, [110] increased physical self-consumption by introducing hydrogen into the local gas network, using it as a storage system. Additionally, recent European directives encourage the use of solid biomass, biofuels, and biogas for district heating in connection with RECs [111,112]. Although wind energy is the most prevalent renewable energy source in Europe [18], it is underrepresented in the EC literature. This could be due to the fact that wind technologies require more complex installations compared to PV systems, which can present both technical and economic challenges for homeowners and EC members. However, numerous initiatives across Europe are promoting the

use of wind energy at the residential level, such as the installation of small wind turbines in urban parks or on private land [113].

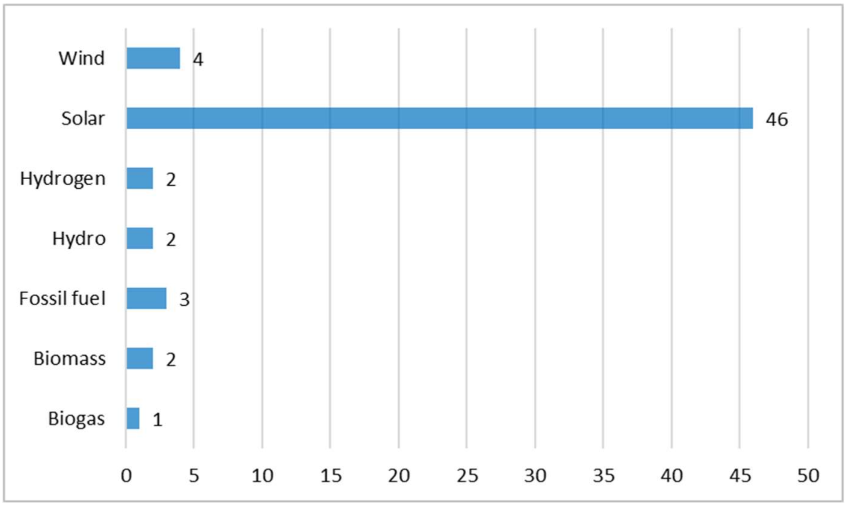


Figure 2. 7 Analytical categories related to energy resource [48]

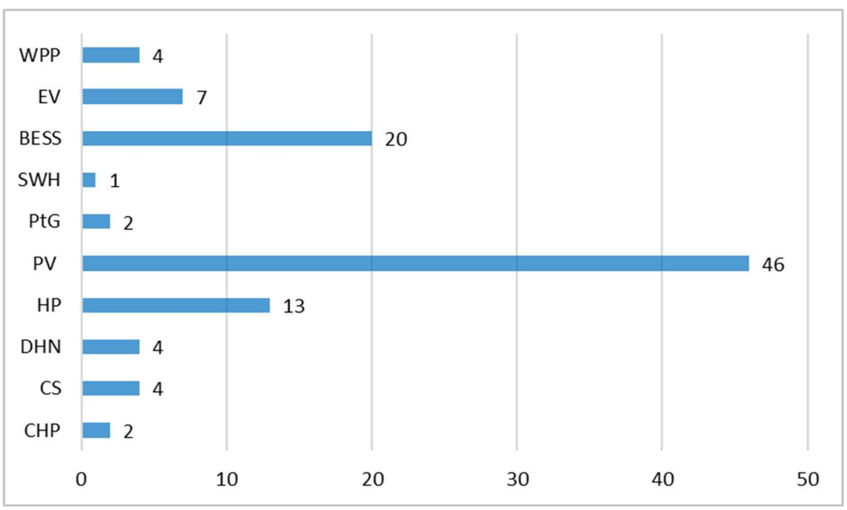


Figure 2. 8 Analytical categories related to energy technologies [48]

Focusing on PV technology, which is highly versatile and modular, making it suitable for various applications and integration with other technologies to optimize electricity production, Table 2. 5 highlights the most commonly integrated technologies (e.g., storage systems, heat pumps, electric vehicles) and their applications in studies on ECs. Additionally, PV systems can be easily incorporated into different settings, such as building facades, rooftops, or ground installations.

Table 2. 5 Integrated PV technologies for ECs [48]

Authors	MES	PV System	Sector
[104,114]	PV+ HP	RPV	Residential
[87,88]	PV+BESS	RPV PV	Commercial, Public service, residential
[115,116]	PV+BESS + HP	PV RPV	Residential
[117,118]	PV + BESS + HP + EV	RPV, BPV	Residential

Legislative framework

The next phase of the analysis involved categorizing the documents based on the legal entity of ECs and the status of the transposition of European directives concerning ECs. As shown in Figure 2. 9, the majority of the papers focus on Renewable Energy Communities (65), followed by Citizen Energy Communities (21), and finally, Collective Self-Consumption initiatives (14). By June 2021, EU Member States were required to transpose the RED II directive to create an enabling framework for promoting RECs. Several scholars have discussed the main developments in the transposition of these EU directives, highlighting the varying stages of progress across different national approaches [119,120]. Some studies have narrowed their focus to specific Member States, such as [81], who compared the regulatory frameworks in Bulgaria and Germany, and [121], who analyzed Germany and Italy. Other research has concentrated on different factors affecting the operational phase of RECs. For instance, [122] implemented a linear optimization model to address three key aspects of a REC: the optimal technology mix, the role of demand response, and the method for sharing benefits among participants—this last point was also examined by [94].

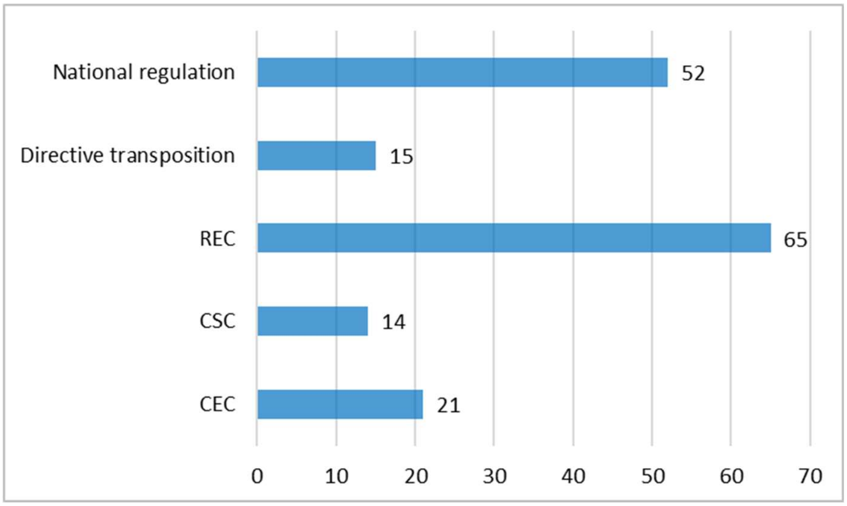


Figure 2. 9 Analytical categories related to legislative framework [48]

Geographic focus

This structural dimension examines the geographical focus of the studies analyzed. Figure 2. 10 shows that researchers adopt different approaches and perspectives regarding EC initiatives across Europe. The majority of studies focus on a single country (54): [104] explored various scenarios for the simulation of a CSC initiative within the Italian regulatory framework; [123] introduced a methodology for pairing consumers, tested in a specific region of Porto in accordance with Portuguese regulations; [124] proposed a case study involving 20 residential buildings on the island of Krk, Croatia; [80,125] analyzed case studies under Sweden's regulatory framework; [126] developed a virtual REC in Greece near Kimmeria; [127] presented data analytics tools designed to assist community members, tested in a case study in Belgium; [128] examined the factors influencing investment in a rural CER project in line with the Spanish government's strategic direction; while [85,86] focused on the UK prior to Brexit. Other scholars conducted comparative analyses between different countries (14 studies): [129] performed a comparative evaluation of case studies in Germany and the Netherlands, while [4] compared six countries, including Spain, the Czech Republic, France, the Netherlands, Italy, and the United Kingdom. According to Figure 2. 11, Italy is the most frequently mentioned country in the literature (36 studies), followed by Germany (11), Austria (10), and Spain (9). Notably, some European Union countries, including Cyprus, Estonia, Lithuania, Luxembourg, Malta, Romania, Slovakia, and Hungary, are not addressed in the scientific literature.

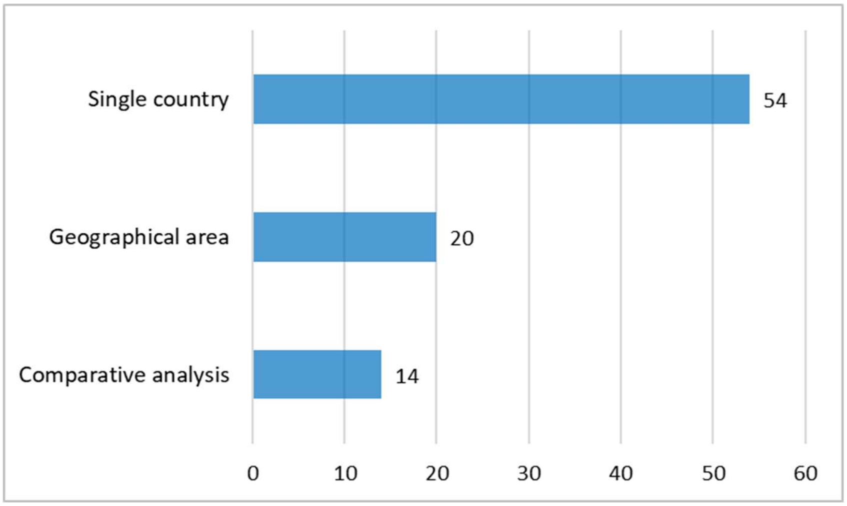


Figure 2. 10 Analytical categories related to geographical focus [48]

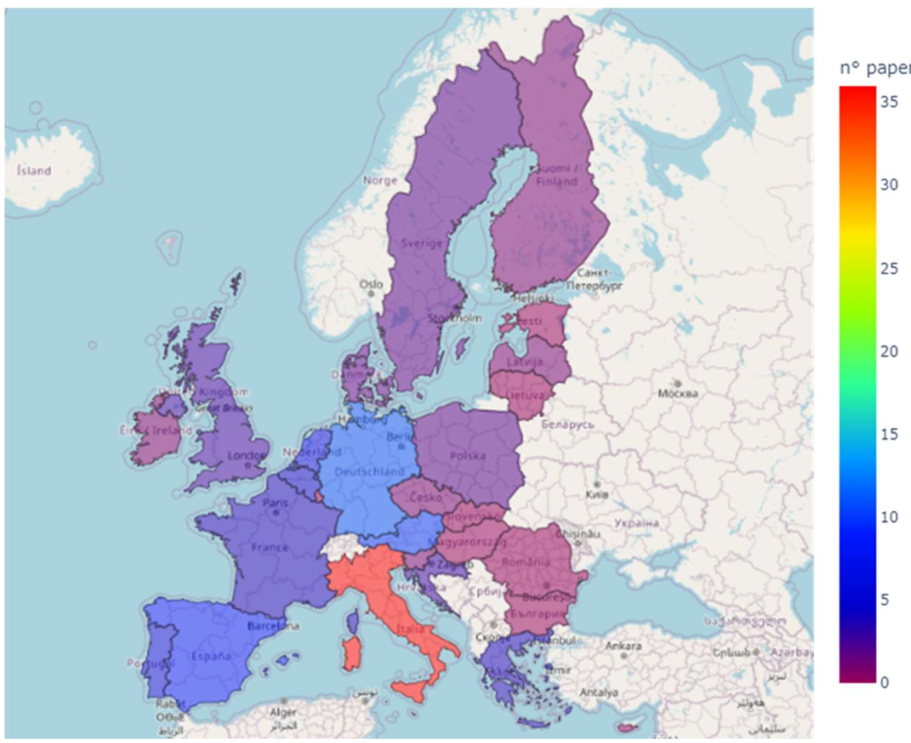


Figure 2. 11 Distribution of papers citing EU Member States (and the UK) [48]

Management and control

The final structural dimension explores the "Management and Control" of ECs through various analytical categories. A key challenge for ECs is to establish a fair and transparent method for allocating costs and revenues among their members, ensuring the equitable distribution of energy. This issue is reflected in the significant focus that many scholars have placed on "sharing mechanisms," as shown in Figure 2. 12. For example, [130] proposed three algorithms for distributing the profits generated from renewable energy production and consumption among community members; [131] introduced a modeling solution for distributing renewable electricity generation within a REC; [132] defined a fair method for allocating benefits among REC participants; and [3] applied a new cost allocation criterion along with price-based demand response programs to various community configurations. Additionally, the role of Demand Response (DR) programs has been a focus for several researchers, as these programs can be essential in maximizing the benefits of aggregation in ECs. DR enables intelligent and sustainable management of electricity demand, helping to avoid consumption peaks, reduce energy costs, and lower environmental impact within the community. For instance, [124] examined how increasing system flexibility through DR programs can benefit ECs, while [75] proposed a new approach to integrating DR participation within a CEC.

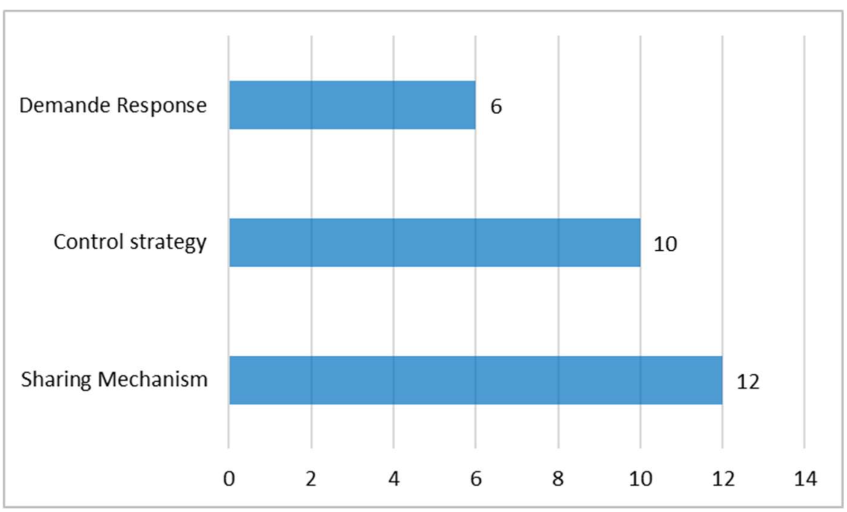


Figure 2. 12 Analytical categories related to management and control [48]

2.1.5 Discussion & main research findings

This section discusses the most significant findings of the work, emphasizing key trends in academic research on ECs. Following this, the primary limitations of the study are outlined, offering a foundation for potential future research and implications.

- Researchers predominantly adopt an experimental approach through case study simulations

Researchers frequently use an experimental approach, employing case study simulations to investigate the potential and limitations of EC models. This method enables them to analyze various scenarios within different national regulatory frameworks, providing a deeper understanding of the key innovations introduced by EU directives. By testing and simulating these scenarios, researchers aim to assess the practical effectiveness and applicability of these new models.

- Economic and financial aspects, influenced by policy regulations, are the most extensively studied areas in EC research

Economic and financial aspects are a primary focus in EC research, with a strong influence from policy regulations. Scholars have dedicated significant attention to these areas, recognizing their pivotal role in tackling global challenges such as inequality, energy poverty, climate change, and sustainable development. The development of new EC models underscores the importance of financial incentives as a crucial driver for their expansion, especially as these initiatives must compete in the energy market. Additionally, a substantial focus has been placed on the analysis of policies and regulations surrounding ECs. This is expected, given that policy frameworks are essential in fostering stakeholder participation in the production and distribution of renewable energy at the community level.

- Photovoltaic systems are the dominant technology in EC studies
- ECs are primarily studied from an electrical perspective, with less emphasis on thermal energy systems.

PV systems are the most commonly adopted technology in studies on ECs. This predominance can be attributed to two main factors: 1) the geographical focus of the studies, which often center on countries with high solar radiation levels, such as Italy and Spain [133]; and 2) the primary use of RES, where PV systems in residential settings drive the growth of the renewable energy sector [134]. This aligns with the ongoing decarbonization of energy systems, characterized by reduced final consumption and increasing electrification. Additionally, EC research primarily focuses on the electrical sector, as national legislative frameworks have historically favored electrical over thermal energy initiatives.

- The novelty of ECs is rooted more in political and social perspectives than in technological advancements

The innovative aspect of ECs is largely driven by political and social dimensions rather than technological breakthroughs. While advancements in energy technologies play a role, the core novelty lies in how ECs engage communities in decentralized energy production and distribution, foster social equity, and contribute to broader policy objectives related to sustainability and energy democratization.

- Renewable Energy Communities (RECs) are the most studied form of ECs

Renewable Energy Communities (RECs) are the most extensively researched type of EC in academic literature. This focus is likely due to the earlier introduction of the RED II directive in 2018, which predated the IEM directive by a year (2019), giving scholars a head start on REC-related research. Additionally, RECs are more frequently associated with incentive systems, as they are exclusively tied to the production of renewable energy, whereas Citizen Energy Communities (CECs) can incorporate other types of energy sources. The lower academic interest in Collective Self-Consumption (CSC) projects may stem from their limited scope, often being restricted to a single building, making them less appealing compared to the broader potential of ECs that involve multiple members and diverse scenarios.

- Most studies on ECs focus on the national regulations of the analyzed country

The 28 EU Member States had until June 2021 to integrate the RED II directive into their national legislations [4]. Since ECs represent a new concept, national regulations play a key role in providing the necessary guidelines and structures for their implementation. As a result, many researchers reference national legislation to better understand the context in which ECs operate, including the specific challenges and opportunities unique to each country. Some scholars have also examined the main developments in the transposition of EU directives, highlighting the differences in national approaches [119,120].

- Italy is the most frequently mentioned country in EC literature

Italy is the most cited country in EC-related literature, followed by Germany, Austria, and Spain. This is largely due to Italy's favourable legal framework, which allows scholars to explore various EC scenarios through clear regulations and incentives for shared renewable energy. On 28 February 2020, Italy introduced an experimental framework for the development of RECs and CSCs, ahead of the full transposition of the RED II directive. This framework, initiated by Article 42-bis of Decree-Law 162/19 and later implemented by Conversion Law No. 8/2020, enabled the sharing of renewable energy production among community members through existing networks. Additionally, financial incentives for shared energy make these regulatory frameworks economically attractive [104,135].

- The management of ECs requires the development of mechanisms for sharing benefits among members

Several countries have implemented virtual schemes for local energy sharing within ECs, often supported by national legislation that offers premium tariffs for shared energy. Key management aspects involve the distribution of shared energy and economic benefits, which vary based on the generation systems, users, and community goals. One of the major challenges ECs face is creating a fair and transparent method for dividing costs and revenues among members, ensuring equitable energy distribution. Many scholars have studied the development of sharing mechanisms, recognizing that a fair distribution of benefits fosters solidarity and cooperation, encouraging active citizen participation in the energy transition. This approach enables ECs to not only reduce energy costs but also enhance social cohesion and promote greater community engagement. Policymakers and researchers are particularly focused on two main aspects of energy sharing: internal guidelines for distributing costs and benefits within the EC [132], and external regulations that establish the broader legal framework [136].

2.1.6 Implications for PhD research strategy

The findings from the systematic literature review presented in the previous section have guided part of the PhD research activities towards the exploration of key themes. As illustrated in Figure 2. 13, which summarizes the main outcomes of the review, two critical aspects have shaped the research direction:

- The management of benefits arising from the establishment of an energy community
- The development of thermal energy communities

Both topics are closely tied to the concept of energy sharing and the role of the prosumer within energy communities, meaning users who not only consume but also produce renewable energy, making any surplus available to the community. In many national legislations, the economic benefits associated with shared energy are supported by incentive tariffs, encouraging users to invest in renewable energy not only to meet their own needs but also to contribute to the community's energy demand, thereby gaining multiple advantages. However, the effective management of these energy flows and the accurate accounting of exchanges between users can be complex, representing a challenge in ensuring an equitable distribution of the benefits derived from the community's establishment. A key aspect of this analysis is the need to extend the concept of energy sharing to thermal flows in order to enable the development of the first thermal energy communities. Although European directives, such as RED II, promote the use of renewable energy in all its forms, including thermal energy, the current literature remains limited on this topic. Historically, member states have tended to favour economic incentives for electricity over thermal energy, a factor that has hindered the development of energy communities focused on thermal flows. In this framework this thesis aims to address two main challenges:

- Developing methodologies for the optimal management of shared energy
- Developing technologies that enable thermal energy sharing among community members, leveraging infrastructures such as district heating and bidirectional substations.

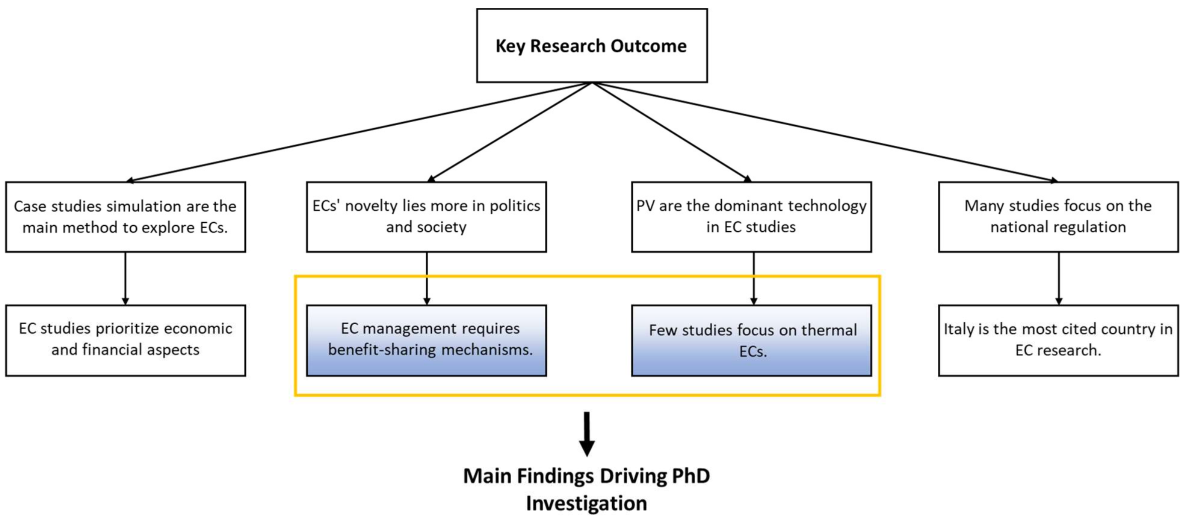


Figure 2. 13 Key research outcome scheme

Section 2.2 focuses on defining shared energy within virtual models and the challenges related to its calculation under specific conditions, while section 2.3 introduces the concept of thermal energy communities, linking them to district heating infrastructure for the sharing of thermal energy.

2.2 Regulatory approaches to sharing models in electricity communities

This section focuses on the concept of shared energy, a key factor in the success of energy communities. Section 2.2.1 provides a general overview of the concept of shared energy at the community level, culminating in its definition within the European regulatory framework introduced by the REDII directive. Section 2.2.2 examines the energy-sharing model adopted by Italian legislation, one of the first in Europe to regulate shared energy within energy communities through an incentive tariff, thanks to the experimental framework introduced in 2020. Section 2.2.3 offers a detailed definition of shared energy and, through practical examples, highlights the critical challenges that may arise when calculating this energy on an hourly basis. Finally, section 2.2.4 provides an overview of the current state of scientific literature on the calculation, management, and distribution of the benefits associated with shared energy in energy communities.

2.2.1 Contextualizing energy sharing in energy communities

As highlighted in section 2.15 of the systematic literature review, one of the key gaps identified is the need for methodologies to effectively allocate shared energy within ECs. The evolution of power systems, driven by the widespread adoption of distributed generation through renewable energy sources and the increasing role of prosumers, has brought about significant challenges [2]. In this evolving scenario, the concept of energy sharing has gained substantial attention, particularly concerning the distribution of energy among users via electrical networks or decentralized systems. This paradigm allows users to trade, sell, or acquire energy based on their production capacities and energy needs, thereby fostering a more dynamic and interactive energy ecosystem. The emergence of ECs has further emphasized the importance of local-level energy aggregation, with growing interest in promoting collaboration among energy users [3]. The potential of sharing energy from production plants is characterized as a new paradigm for the production and consumption of energy from renewable sources. Many countries have adopted a virtual scheme for local energy sharing without a physical basis for calculating intra-community energy exchanges, and national legislation often provides economic incentives for shared energy within the community. However, despite this interest, the literature review reveals a critical gap in the development of robust methodologies for fair and efficient energy distribution within these communities. Addressing this issue is essential to ensure that energy sharing in ECs is equitable, transparent, and capable of supporting the long-term sustainability of decentralized energy systems. When consumers gain ownership of renewable energy systems, they transform into prosumers, enabling them to share part of the energy they produce locally within an EC [4]. Prosumers in an EC can engage in multiple forms of energy transactions, such as selling energy to the public grid at real-time prices (RTP), conducting trades within their community, or participating in peer-to-peer (P2P) exchanges through bilateral agreements [5,6]. Recently, the sharing economy had also extended into the energy sector [137], driven by the rise of smart grids [7], with the goal of minimizing overall costs and reducing the peak-to-average ratio by leveraging energy-sharing algorithms [8] and optimization models [9]. This issue holds particular significance within the European Union, as regulatory frameworks for energy sharing are beginning to take shape. As discussed in *Energy Communities*, the European Commission first proposed formal recognition of collective self-consumption and energy sharing projects in 2016, through the "Clean Energy Package" (*European Commission. Clean energy for all European packages*), which laid the groundwork for the establishment of Energy Communities in European legislation. This package, finalized over the course of two years, resulted in the definition of two key directives: the EU Renewable Energy Directive 2018/2001 (*DIRECTIVE (EU) 2018/ 2001*) and the EU Internal Electricity Market Directive 2019/944 (*DIRECTIVE (EU) 2019/ 944*). RED II represents the key directive that formally introduces and regulates the concept of energy sharing in Europe for the first time, through two configurations outlined in Article 2: CSC in paragraph 15, and REC in paragraph 16. As previously defined in section 1.3, for clarity, a brief definition is provided here: a REC is a collective initiative involving various stakeholders—such as citizens, SMEs, and local authorities—focused on generating and consuming renewable energy within the community, with particular emphasis on self-consumption and sustainability. In contrast, CSC refers to users located within the same building or multi-apartment block, emphasizing the geographical proximity of participants. Both concepts differ from individual self-consumption, where a single user generates and consumes renewable energy solely for their own needs. By June 2021, all EU Member States were required to transpose the RED II directive into national law, creating a framework to encourage energy sharing within REC and CSC models. However, as emerged in section 2.15, many countries still face significant regulatory gaps when it comes to collective energy sharing and the formalization of ECs. For instance, while countries like Spain, France, Italy, and Portugal allow shared self-consumption among neighbouring homes using the existing distribution network, Germany has yet to fully establish regulations supporting this approach [140]. This discrepancy highlights the uneven progress among EU Member States in implementing comprehensive frameworks for ECs, an issue that continues to hinder the full potential of energy sharing across Europe.

2.2.2 Energy sharing according to Italian regulation

As highlighted in the section2.15, Italy is the most cited country in EC-related literature, followed by Germany, Austria, and Spain. This prominence is largely attributed to Italy's favourable legal framework, which offers clear regulations and incentives that allow scholars to explore various EC scenarios. On 28 February 2020, Italy introduced an experimental framework for the development of REC and CSC, in anticipation of the full transposition of the RED II directive. This framework, established through Article 42-bis of Decree-Law 162/19 (*Decreto Legge 162/19 (articolo 42bis)*) and subsequently implemented by Conversion Law No. 8/2020, has sparked significant academic interest, as it provides an opportunity to analyze the potential of ECs in real-world applications before the complete legal adoption of RED II. Within this framework, shared energy was formally defined for the first time in paragraph 4, letter b). This definition laid the groundwork for further exploration of energy distribution models within ECs, as scholars have been able to examine how shared energy impacts the economic and operational dynamics of energy communities. Additionally, the rights of end customers participating in the CSC and REC configurations are established in paragraph 5, letter c) of the same decree. In particular, the legislation mandates that relations between end customers must be regulated through a private law contract, which designates a responsible party for managing the distribution of shared energy. Subsequently, on April 1, 2020, the Authority released the consultation document ARERA 112/2020/R/eel, which sets out the guidelines for regulating the electricity market related to CSC or energy sharing within REC. The document outlines how the Authority intends to implement Article 42-bis of the Decree-Law, providing guidance on the definition and regulatory model of ECs, the role of GSE, and the rules for accessing the new regulatory framework. Additionally, the document identifies the electricity tariff components that may be subject to reimbursement, as well as considerations regarding potential incentives to be adopted. On August 4, 2020, the Authority published Resolution ARERA 318/2020/r/eel, which considers the feedback received in the consultation document and provides the provisions established for the regulation of economic transactions related to shared energy in CSC or within REC. On 15 September 2020, the Italian Ministry of Economic Development issued the implementing decree, which set the incentive tariffs (IT) for shared energy produced by renewable plants involved in CSC and REC configurations. These incentives, granted for 20 years, amount to:

- €100/MWh if the production plant is part of CSC
- €110/MWh if the production plant is part of REC.

Recent developments at the national level, following the approval of the decree by the European Commission, have led to the publication of the implementing decree introducing an updated IT for shared energy on January 23, 2020. This tariff is no longer fixed for the two configurations but varies based on the hourly zonal price (ZP) and geographic location. Below is the procedure for calculating the rate:

a) For power plants > 600 kW
   IT : 60 + max(0; 180 – ZP)
   IT cannot exceed the value of 100 €/MWh
b) For power plants > 200 kW and ≤ 600 kW
   IT : 70 + max(0; 180 – ZP)
   IT cannot exceed the value of 110 €/MWh
c) For power plants ≤ 200 kW
   IT : 80 + max(0; 180 – ZP)
   IT cannot exceed the value of 120 €/MWh

It is also necessary to consider the correction factor shown in the Table 2. 6.

Table 2. 6 Correction Factor for Incentive Tariff for energy communities

Geographic area	**Correction Factor**
Lazio, Marche, Toscana, Umbria, Abruzzo	+ 4 €/MWh
Emilia-Romagna, Friuli-Venezia Giulia, Liguria, Lombardia, Piemonte, Trentino-Alto Adige, Valle D'Aosta, Veneto	+ 10 €/MWh

The shared energy not only determines the economic savings for the EC members but also reduces the revenue for the electricity supplier. This financial model has further encouraged research into the economic feasibility and benefits of ECs within the Italian regulatory context. Given these considerations, the following paragraph will focus on the definition of shared energy within a virtual model, using the Italian framework as a reference for this analysis.

2.2.3 Definition of shared energy and allocation in virtual models

In this section, the definition of shared energy under virtual model is provided. Many countries have adopted a virtual scheme for local energy sharing, where intra-community energy exchanges are calculated without a physical basis, and national legislation often includes economic incentives for shared energy within the community. In order to clarify the concept of shared energy, Figure 2. 14 shows an example of a REC with a prosumer, who produces and consumes energy, and a producer who feed into the grid the entire produced energy. The community also includes consumers as remaining members. The figure highlights the main energy flows within the community, with the energy drawn from the grid shown in red, and the energy fed into the grid by the community's production plants displayed in blue.

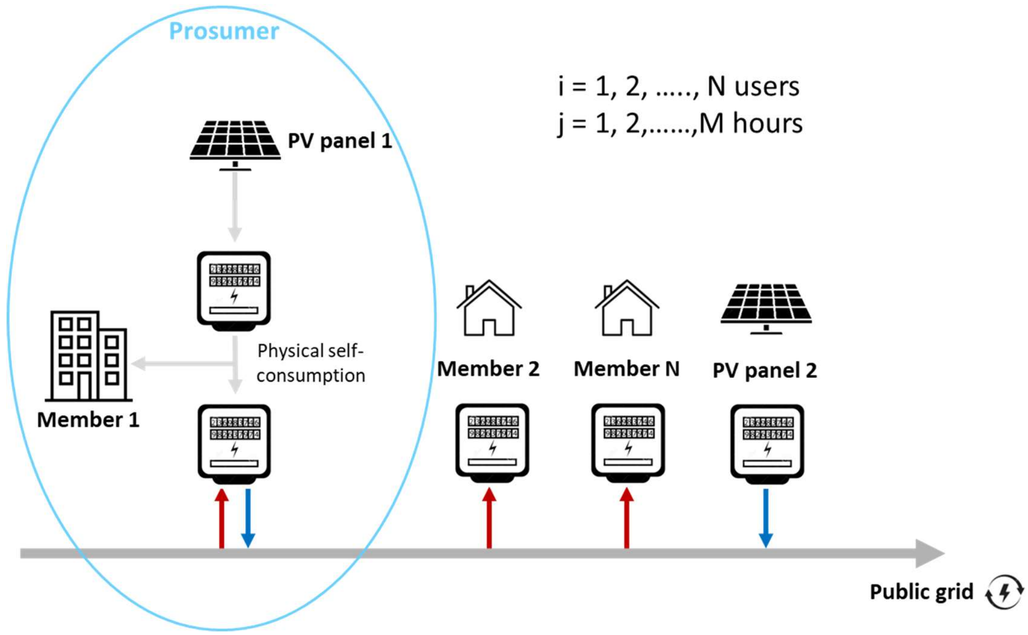


Figure 2. 14 REC configuration

According to the Italian regulatory framework, shared energy is defined as the minimum, in each hourly period, between the electricity produced and fed into the grid by renewable production plants and the electricity withdrawn by all associated end customers. This is represented mathematically by the following 2.1:

$$\sum_i^N SH_{i,j} = min\left(E_{inj,j}, \sum_i^N C_{i,j}\right) \quad 2.1$$

This definition highlights the balance between energy production and consumption within the community, forming the basis for calculating energy exchanges and the resulting economic benefits. At the hourly level, two different conditions can result in varying management approaches for CSC or REC:

- When the energy fed into the grid by production plants exceeds the total energy consumption, the shared energy allocated to each member can be assumed to match their actual hourly consumption.
- When the energy fed into the grid is less than the total consumption, it becomes difficult to precisely define the amount of shared energy attributable to each member.

Figure 2. 15 and Figure 2. 16 provide illustrative examples that highlight the two conditions mentioned above, illustrating the energy flows within a CER or CSC comprising three consumer members and a production plant that feeds a specific amount of energy into the grid.

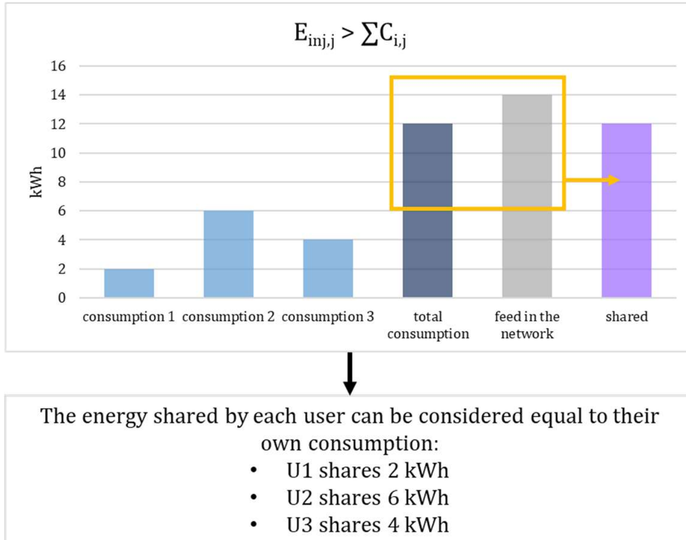


Figure 2. 15 Hourly shared energy calculation when energy fed into the grid is greater than consumption

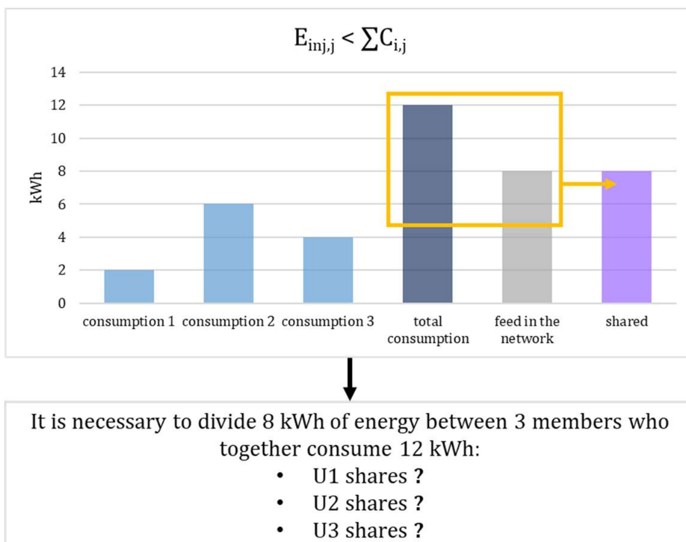


Figure 2. 16 Hourly shared energy calculation when energy fed into the grid is less than consumption

2.2.4 Overview of energy sharing solutions

In general, policymakers and researchers are particularly focused on two key aspects of energy sharing: internal guidelines for allocating costs and benefits within the community (Casalicchio et al., 2022), and external regulations that establish the broader regulatory framework [136]. Regarding energy distribution, in Spain and Portugal it is managed through distribution coefficients, while in France it is handled by a contract between the DSO (Distributed System

Operator) and the legal entity overseeing both consumers and prosumers. In Germany, distribution is based on an agreement between consumers [141], whereas in Austria, DSOs can require a predefined distribution key to allocate electricity among community members, using an ex-post algorithm [142]. Under Italian law, end customers regulate their relationships through a private law contract that designates a specific individual responsible for managing the distribution of shared energy, thus granting full autonomy in managing the benefits derived from shared energy. Several scholars have proposed new cost allocation criteria and methods to quantify shared energy in REC or CSC configurations [3]. Some of these methodologies are based on defining sharing coefficients, either static or dynamic, which distribute energy among consumers. For instance, [143] introduced sharing coefficients that account for various parameters such as energy demand or generation, applying weighting factors, while [141] classified static and dynamic distribution coefficients by evaluating their outcomes and practical application. Similarly, [144] proposed four different sharing coefficients to allocate the produced electricity among community members. Other studies focus on managing the benefits of shared energy under Italian law. For example, [130] developed an algorithm that allocates shared energy equally by assigning each user an amount equal to their minimum current consumption. [145] explored cooperative games to fairly distribute both the benefits and costs of the community, while [146] demonstrated that economic savings for REC participants increase with the amount of energy shared under the adopted virtual scheme. Achieving an equitable allocation of shared energy, and consequently economic savings, is a significant challenge for RECs and CSC configurations. To address this, several researchers have proposed innovative methods to optimize energy distribution, system scheduling, and community planning to maximize economic savings. For example, [147] applied genetic algorithms (GA) to optimize energy distribution within a REC through multi-objective optimization (MOO) of allocation coefficients, aiming to minimize discrepancies in payback periods and solar energy excess. [148] introduced a novel approach to optimize HVAC scheduling, aiming to maximize shared energy and economic efficiency while maintaining thermal comfort in REC buildings. Other researchers have focused on developing business models and optimization strategies for RECs. [149] proposed a business model for energy community aggregators, integrating a technical optimization framework to ensure fair reward distribution and proper compensation for aggregator services. [87] presented an optimal planning approach for RECs based on mixed-integer linear programming (MILP) to size technologies in a way that minimizes energy costs and environmental impact. [88] developed a multi-criteria optimization procedure to size REC facilities (PV + BESS) to improve self-consumption and self-sufficiency, identifying the most competitive form of community. [93] examined the impact of a bi-objective strategy to optimize the capacity of BESS systems coupled with PVs in RECs, maximizing self-sufficiency while minimizing storage capacity. Additionally, [90] highlighted how incentivizing tariff mechanisms that reward REC members for avoided CO_2 emissions can generate significant environmental benefits. Achieving a fair distribution of benefits not only fosters solidarity and collaboration but also promotes active citizen participation. By engaging in these initiatives, citizens become agents of change, contributing to reducing environmental impact, promoting renewable energy adoption, and enhancing the overall quality of life in their communities.

2.3 Implementation and empowering of thermal energy communities through DHN

This section introduces the concept of thermal energy communities. Specifically, section 2.3.1 highlights how thermal energy community initiatives in Europe remain quite limited, despite the REDII directive encouraging the use of all forms of renewable energy. It also emphasizes how district heating could provide a significant boost to the expansion of such communities. This can be achieved by converting thermal exchange substations into bidirectional systems, allowing users to act as prosumers—both consuming and producing energy, and sharing any surplus with the network, as discussed in section 2.3.2. Finally, section 2.3.3 illustrates how numerical modeling is an effective solution for simulating and optimizing bidirectional substations for district heating. This section also describes the modeling tool used, Dymola, and the key components employed in the process.

2.3.1 Exploring challenges in thermal energy community

As discussed in the introduction, in Europe, the heating and cooling sector accounts for a significant portion of the total energy demand, and globally, final energy consumption remains heavily reliant on fossil fuels, and despite recorded progress, in 2022 less than 25% of heat was produced from renewable sources. As emerged in *2.1.5 Discussion & main research findings*, most studies have focused primarily on the role of REC and CSC from the perspective of electricity production and sharing. While this focus is crucial, it has largely overshadowed the importance of other forms of renewable energy, such as thermal energy. Indeed, the REDII Directive does not limit energy sharing to only renewable electricity sources, but encompasses all forms of energy from renewable sources, including thermal energy, as highlighted in Figure 2. 17 and Table 2. 7.

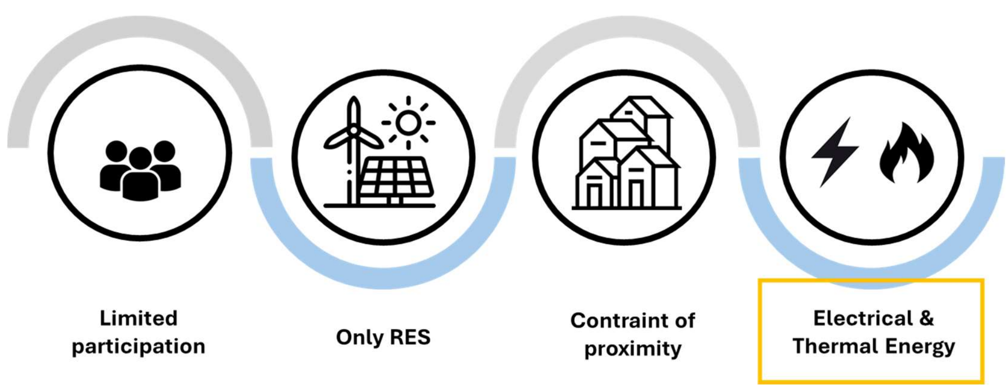


Figure 2. 17 REC technical points

Table 2. 7 REDII References

Reference	**Content**
Renewable Energy Community. Article 22, paragraph 2, point (b)	2. Member States shall ensure that renewable energy communities are entitled to: share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, subject to the other requirements laid down in this Article and to maintaining the rights and obligations of the renewable energy community members as customers;
Definitions. Article 2, paragraph (1)	(1) 'energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas;

In this context, the concept of thermal ECs becomes particularly relevant, offering a largely untapped potential to contribute to the decarbonization of the heating and cooling sector. Therefore, exploring the role of thermal ECs within the framework of the REDII can provide a significant contribution to the scientific community. Therefore, this work aims to answer the following question: what strategies can be employed to facilitate the sharing of renewable thermal energy within energy communities? District Heating System (DHS) represent a key strategy for facilitating the sharing of renewable thermal energy within ECs. These systems, seen as crucial infrastructures for decarbonisation, enable a more efficient integration of RES. The revised Energy Efficiency Directive (EED) introduces a more ambitious definition of 'efficient district heating,' improving both the efficiency and competitiveness of these systems. This paves the way for greater integration of waste heat and renewable energy, fostering a community-based energy-sharing model. Moreover, the inclusion of thermal prosumers in DHN allows them to become active contributors, sharing excess renewable heat and supporting the transition towards a more sustainable energy system. Another question that this work aims to answer is the following: what strategies can be employed to integrate thermal prosumers into DHN, and what challenges arise from their active participation in energy sharing? The creation of a thermal ECs and the interaction between multiple prosumers presents two main challenges: a regulatory challenge and a technical one. From a regulatory standpoint, as highlighted in the results of section 2.15, the success of REC is often linked to financial incentive schemes, a crucial factor for their growth, which is predominantly focused on electricity. Therefore, the regulatory challenge lies in developing pricing models and forecasting potential scenarios to characterize the future behaviour of thermal REC, particularly the interactions between users and between users and the production plant. From a technical standpoint, key questions arise: what criteria should be used to identify the most suitable users for installing renewable production systems? What are the optimal configurations for bidirectional thermal exchange? Which renewable generation systems are most appropriate? These are just a few of the technical questions that come into play when considering the potential implementation of thermal ECs. The focus of this analysis is primarily on the terminal point that enables the exchange of thermal power between the user and the DHN: the thermal substation. Figure 2. 18 presents a simplified diagram of a DHN, where the central plant generates thermal energy to meet the users' heating demands, which is then transported through the supply pipes (shown in red) to the end users. The same figure includes an enlarged detail of the substation, illustrating where the thermal power exchange takes place. In this case, it shows an indirect substation, where a heat exchanger is positioned between the user and the network to transfer heat from the primary circuit to the secondary circuit. Once the heat is transferred to the user, the cooled fluid returns to the central plant through the return pipe (shown in blue).

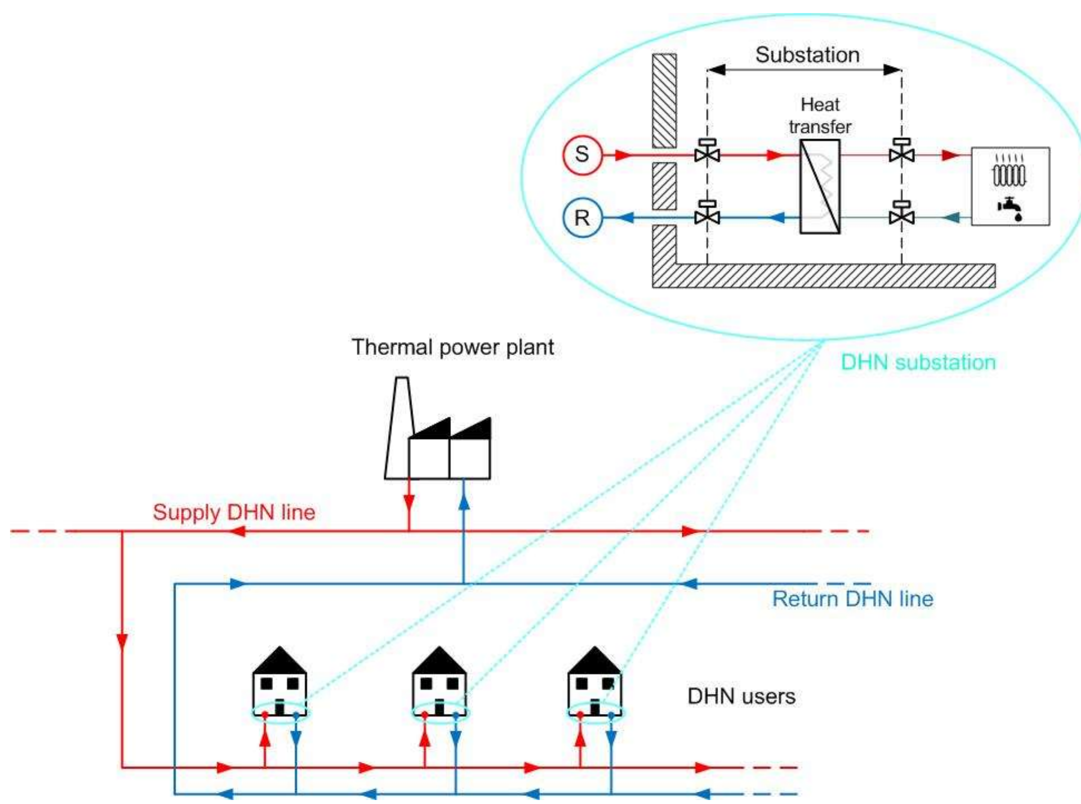


Figure 2. 18 DHN network scheme and focus on thermal substation

The goal of this work is to transform traditional substations from a passive configuration to an active one, capable of exchanging thermal power bidirectionally with the network. This would enable the integration of thermal prosumers, equipped with renewable energy systems (e.g., solar thermal collectors), who could not only consume energy for their own needs but also share any surplus with other users, thereby contributing to the decarbonization of the energy system.

2.3.2 Active District Heating and Bidirectional Substation

Although active district heating is already a reality, its widespread implementation as a decarbonization strategy remains limited. Energy Communities, as outlined in recent European directives, could provide the impetus needed to encourage large-scale adoption of advanced thermal networks. Active district heating emerges as one of the most promising solutions for optimizing energy resources and utilizing renewable sources in both civil and industrial sectors. These networks are designed to exchange thermal energy bidirectionally with connected users, thus integrating centralized production with distributed generation systems, such as renewable thermal production (e.g., solar thermal) or micro-cogeneration units installed on-site. In this model, the network acts as a storage system, facilitating thermal energy sharing among users, much like electricity sharing by prosumers within energy communities. This approach not only reduces the thermal power demand on central production but, in certain cases, allows for temporary shutdowns of central generation systems, for example, during summer months when heating demand is minimal. The benefits of this configuration include significant economic savings, improved conversion efficiencies, and a reduction in environmental impact, especially when distributed generation systems utilize renewable sources. In an active district heating system, each user is equipped with a distributed thermal energy generator, capable of fully or partially meeting their own energy needs and, in the case of surplus, feeding the excess into the district heating network. The network thus becomes a dynamic infrastructure, allowing each user to draw thermal energy from the system when self-production is insufficient or to inject excess energy only after covering their own consumption. To enable these functionalities, the DIN group at the University of Bologna has developed four main layouts for user substations, differentiated by the type of thermal generation system and the required temperature levels. The layouts presented below illustrate various configurations for active exchange:

1. "Supply to return" (Figure 2. 19): withdrawal of flow from the supply line and reinjection into the return line
2. "Supply to supply" (Figure 2. 20): withdrawal of flow from the supply line and reinjection into the same supply line
3. "Return to return" (Figure 2. 21): withdrawal of flow from the return line and reinjection into the same return line
4. "Return to supply" (Figure 2. 22): withdrawal of flow from the return line and reinjection into the supply line

In particular, in a "supply to return" configuration the water is drawn from the supply line of the district heating network and, after heat exchange with the user, is reinjected into the return line, as shown in Figure 2. 19. It is essential to maintain thermal balance among multiple active substations, particularly with regard to the temperature at which the water returns to the circuit and the central plant. If a cogenerator is in operation at the central plant, changes in return temperature could reduce thermal recovery efficiency, potentially resulting in the loss of CAR qualification and associated incentives. The main advantage of this configuration is the ability to connect to the user's supply lines without requiring modifications to the primary network pipes.

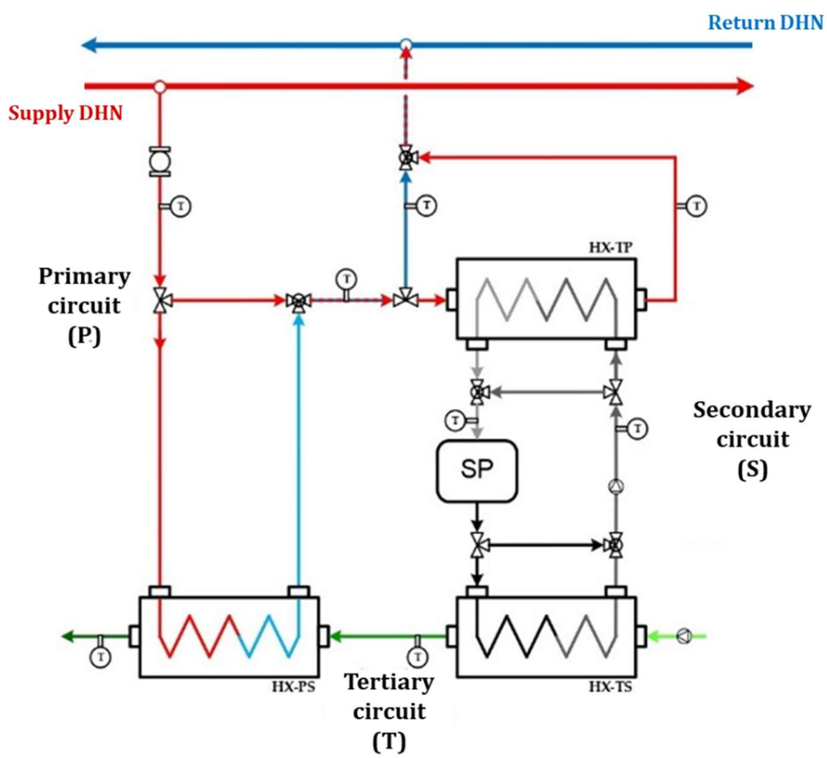


Figure 2. 19 "Supply to return" configuration [150]

Unlike the previous configuration, in a "supply to supply" configuration any surplus thermal power generated by the central system is transferred to the network by drawing water from the supply line and reinjecting it into the same line (Figure 2. 20). In this setup, the temperature of the production system's fluid must also be higher than that of the district heating network's supply water. The issues encountered are similar to those in configuration "supply to return", as the supply line temperature affects the return line temperature. This configuration also complicates interactions between users, especially those consecutively positioned along the network, since an increase in supply temperature by an upstream user can limit or prevent thermal power injection for a downstream user. Another limitation of this type of exchanger is that it cannot be implemented for terminal users.

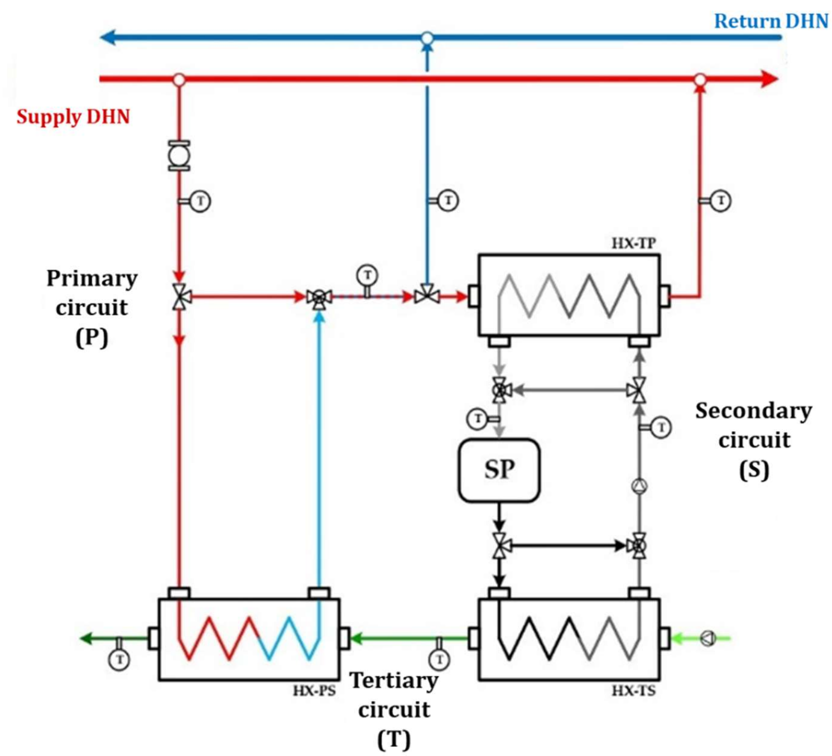


Figure 2. 20 "Supply to supply configuration" [150]

In the “return to return” configuration, to transfer surplus thermal power to the district heating network, water is drawn from the return line and reinjected into the same line after heat exchange with the production system (Figure 2. 21). The issues observed are similar to those in configuration “supply to supply”, concerning both the interaction between multiple active users and the inability to implement this configuration for terminal users.

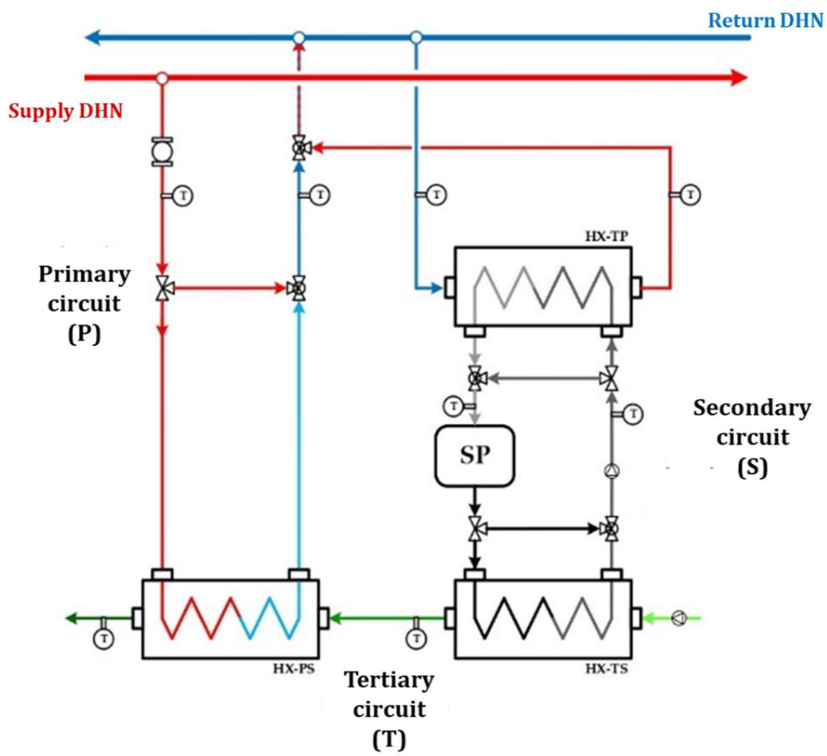


Figure 2. 21 "Return to return configuration" [150]

As in the previous configuration, in the “return to supply” configuration, the water to be heated for thermal power injection into the network is drawn from the return line; however, in this case, it is reinjected into the supply line (Figure 2. 22). This configuration requires a hydraulic adjustment of the network due to flow reversal in one or more branches, depending on the thermal power introduced by the decentralized production system. Consequently, network management becomes more complex, necessitating regulation of thermal power injection by active users to maintain constant hydraulic balance among them and with the rest of the network. On the other hand, this is the only configuration that allows prosumer-served users to be completely independent from the central plant, both thermally and in terms of pumping, as network pressure is maintained by the active users themselves. Converting the network from passive to active also allows for significant savings in the electrical energy needed for pumping. Active users function as production units, creating sub-networks that can (partially or fully) supply other users. As a result, the central production plant can operate at a lower thermal power, reducing thermal dispersion and load losses. This configuration is thus the most suitable for the development of the network from an active perspective.

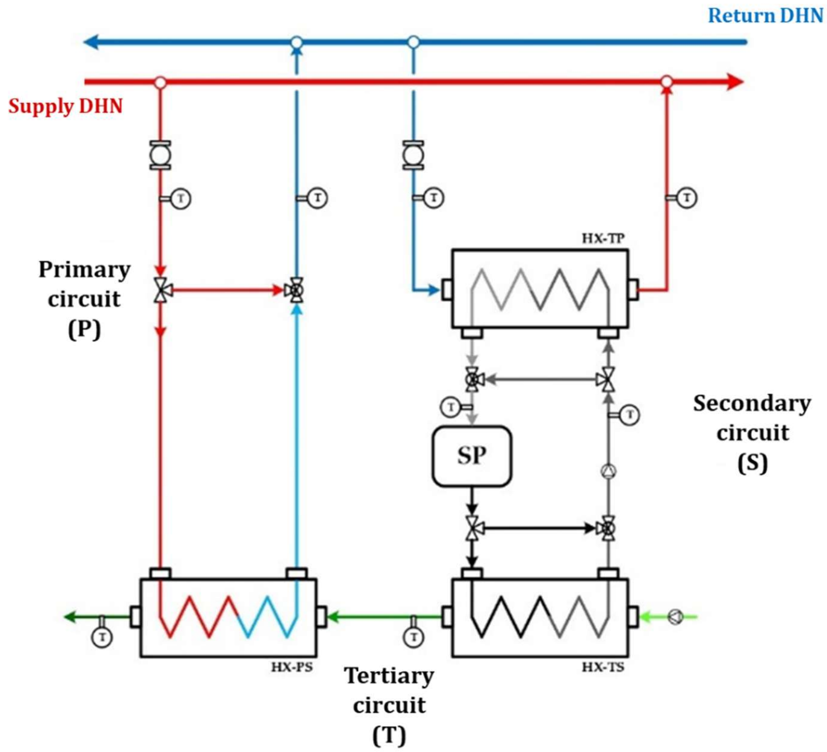


Figure 2. 22 "Return to supply" configuration [150]

While numerous studies have explored the functionality and potential of power-only thermal substations, research on bidirectional substations remains limited. [151] focused on developing a numerical model for a bidirectional substation in district heating networks (DHN) with thermal prosumers, particularly creating and validating a dynamic model using Dymola. This model is based on experimental results obtained from a prototype substation, as detailed by [152], who conducted dynamic experimental tests demonstrating that the prototype performed reliably and was able to manage pressure variations in both the building's heating system and the DHN. Similarly, [153] used the same prototype to develop a dynamic model of the bidirectional substation with TRNSYS. To demonstrate its potential, they applied the model to a prosumer in two locations with different irradiance levels (Palermo and Berlin), analyzing the results. The same prototype was further explored by [154] in an experimental campaign aimed at evaluating the annual performance of a bidirectional substation in optimizing the use of thermal energy from renewable sources and heat recovery in densely populated areas. The substation was fully integrated in real-time with TRNSYS models of a residential building and a distributed generation (DG) system via hardware-in-the-loop (HIL) configuration. [155] developed a thermal network model incorporating multiple prosumers and dynamically monitored the key thermohydraulic parameters of the network. [156] presented results from a control system they developed for a bidirectional substation, tested using the HIL technique, while [157] proposed a control approach that combines temperature target assignment for actuators with weighted error functions. [158] examined the specifications and architecture of bidirectional solar-powered substations, presenting results from two days of simulations. Their study highlighted the potential for solar energy reinjection into a DHN, contributing 6.3% of the total user load and 5.1% of the collected solar energy, despite total energy production exceeding consumption. In a subsequent study, [159] described tests on a prototype bidirectional substation connected to a real DHN using HIL configuration. Conducted over 12 days, these tests showed poor control performance on colder days but good performance in summer, with a solar fraction of 52%. This represents one of the most extensive studies on bidirectional substation experimentation.

2.3.3 Numerical modelling

The practical implementation of a thermal ECs presents significant technical challenges, particularly in converting existing substations into bidirectional ones and adapting the infrastructure of DHN. These operations not only entail high costs but also require complex interventions that can be technically demanding and logistically challenging. In this context, numerical modeling represents the ideal mean for designing, simulating, and optimizing thermal ECs before any field intervention. Through numerical modeling, it is possible to numerically reproduce the behavior of a thermal ECs, simulating different configurations and operational scenarios without needing physical alterations to the existing network. This approach allows for an advance evaluation of the energy balance and thermal flow of the network, accurately predicting the effectiveness of various substation configurations and identifying potential issues before implementation. Furthermore, numerical modeling makes it possible to optimize the community's performance by simulating operating conditions that would be challenging to replicate in real-world settings, such as variations in temperature, flow, and energy demand.

In this work, numerical results presented are obtained by means of Dymola. Dymola is a modeling and simulation tool used for model-based design of complex systems. It employs the open-source modeling language Modelica, ensuring high performance and efficiency, with code generally compiled in C language. Dymola’ s main features include multi-domain simulation, enabling the use of model libraries across various engineering fields, such as mechanical, electrical, control, thermal, pneumatic, hydraulic, transmission, thermodynamics, vehicle dynamics, and HVAC. This multi-domain capacity makes the models comprehensive and true to real-life behaviors. Modelica allows users to create and adapt model libraries, accelerating development timelines and facilitating the creation of new components or adaptation of existing ones. Modeling in Dymola is intuitive, with libraries that include elements corresponding to physical devices, and interactions represented by graphical connections that reflect the physical coupling of components. A further advantage of Dymola is its ability to reuse acausal and equation-oriented models, enabling components to be utilized in various contexts. Symbolic equation processing makes simulations more efficient and reliable, eliminating the need for users to convert equations into assignment statements or block diagrams. Dymola also supports real-time simulation via Hardware-in-the-Loop Simulation (HILS) and provides interoperability options, including full support for the FMI standard for model import/export, Python scripting, and Simulink interfacing. Modelica is a language for modeling lumped-parameter systems used to simulate time-based phenomena described by ordinary differential equations (ODEs), though it does not support partial differential equations (PDEs). As a declarative programming language, it describes the desired end result without detailing each operational step, making programming more concise than imperative languages. This acausal approach allows users to write the constitutive equations directly, which, combined with conservation laws for mass, energy, and momentum, describe the processes and components involved. Modelica can numerically solve large systems of differential and algebraic equations (DAEs) by assembling the system model from elementary components, enabling easy modification and reuse of models across various applications. In object-oriented programming, code is organized into classes, with the Modelica package representing a collection of classes, including other packages, constants, functions, blocks, and models. Object-oriented programming is particularly beneficial for graphical interfaces, providing an intuitive, understandable representation of graphical systems where icons represent system components and lines indicate physical connections. The 'replaceable' keyword designates components whose type can be modified in the future, allowing the creation of new models without the need to reconnect. Inheritance allows for defining components within a hierarchical structure, where complex parts derive from base models. The 'Partial' keyword identifies incomplete classes that cannot be directly instantiated but are used in 'extends' or 'constrainedby' clauses.

Components for modeling a heat exchange substation

The two primary libraries used for modeling the bidirectional substation are the Modelica Standard Library and the IBPSA Library. The Modelica Standard Library is a free resource offering essential components for modeling various systems, including mechanical, electrical, thermal, and control systems, as well as functions for numerical, string, and file handling. The IBPSA Library, also free, contains over 300 classes for developing Modelica libraries for energy and control systems and is compatible with standard Modelica Library models, particularly with Modelica.Fluid and Modelica.Media. To facilitate the connections between the main devices and components within the substation, *StaticPipe* models were used. These models represent straight pipes with a constant cross-section and operate with constant balances of mass, momentum, and energy, without accumulating mass or energy. Each fluid port is associated with two thermodynamic states. The momentum balance is formulated for both states, considering momentum flows, friction, and gravity. To model the boundary conditions, *MassFlowSource_T* and *Boundary_pT* were primarily used. *MassFlowSource_T* represents a mass flow source model, simulating an ideal source with specified values for mass flow rate, temperature, composition, and any trace substances in the fluid. This model allows setting a predefined flow rate, thus establishing a constant amount of mass entering or exiting the system. This configuration can also be managed via an input connector, enabling interaction with external signals. Similarly, the flow temperature can be fixed to the desired value, contributing to defining the system's thermal characteristics, or it can be regulated through input signals. *Boundary_pT* allows setting key parameters such as pressure, temperature, and fluid composition for boundary conditions within a model. These values can be set as constants or provided through external inputs, offering flexibility in adapting the model to specific requirements. It is important to note that the defined boundary conditions affect fluid flow only when the flow moves from the component toward the system's exterior. If the flow is directed in the opposite direction, the boundary condition definitions have no impact on the simulation, acting merely as a sink. For sensors, *TemperatureTwoPort* and *MassFlowRate* were primarily used. *TemperatureTwoPort* was employed to monitor the fluid's temperature in motion, proving essential for implementing the substation's control logic. Notably, as an ideal sensor, its use does not affect fluid behavior. *MassFlowRate* provides the mass flow rate across fluid ports a and b, and, being ideal, does not alter fluid behavior.

Heat Exchanger

One of the critical elements in developing the bidirectional thermal exchange substation is the heat exchanger, as it is responsible for the transfer of thermal power between different flows. To represent this component, the *ConstantEffectiveness* model was used. This type of heat exchanger has two inlet ports and two outlet ports, operating with constant efficiency and transferring thermal power according to Equation 2.2. This model originates from the IBSA Fluid library, within the HeatExchanger sub-package, and its simplified layout is shown in Figure 2. 23.

$$Q = \varepsilon \cdot Q_{\max} \qquad 2.2$$

Where ε represents the heat exchange efficiency, and Qmax represents the maximum amount of power that can be transferred when the fluid with lower thermal capacity is brought to the same temperature as the fluid with higher thermal capacity, simulating an infinite exchange area in the heat exchanger. Specifically, this thermal power is shown in Equation 2.3.

$$Q_{max} = C_{min} \cdot (T_{hot_i} - T_{cold_i}) \qquad 2.3$$

Where C_{min} (Equation 2.6) represents the minimum between the hourly thermal capacity of the hot fluid and the cold fluid (kW/K), defined in Equations 2.4 and 2.5, respectively.

$$C_{hot} = m_{hot} \cdot C_{ph} \qquad 2.4$$

$$C_{cold} = m_{cold} \cdot C_{pc} \qquad 2.5$$

$$C_{min} = min(C_{hot}, C_{cold}) \qquad 2.6$$

Where m_{hot} and mcold are the mass flow rates of the hot and cold fluids, respectively (kg/s), and c_{ph} and c_{pc} are the specific heats at constant pressure of the hot and cold fluids, respectively (J/kgK).

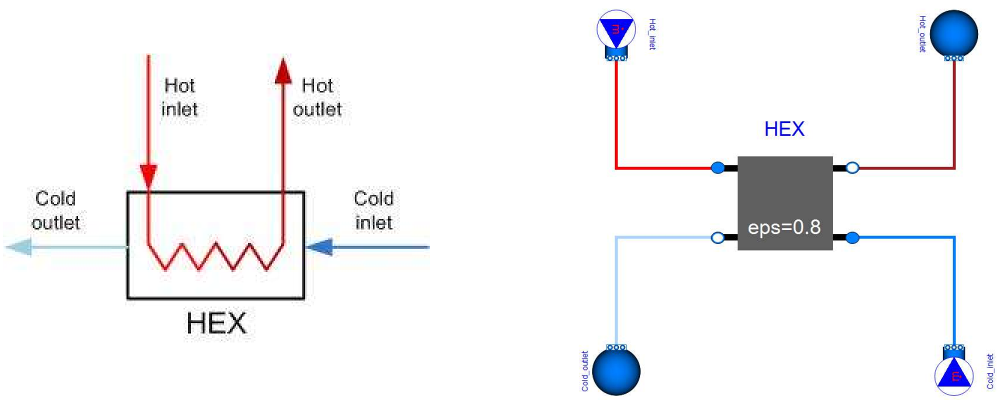


Figure 2. 23 Heat exchanger scheme and Modelica model

To understand the operating logic of this model, it is necessary to refer to the inherited classes from which it extends. Specifically, *PartialFourPort* defines an interface for components with four ports and the types of fluid medium passing through them. *PartialFourPortInterface* represents the interface for models that handle two types of fluids flowing through four ports. It is used by other models to incorporate equations for heat transfer, mass transfer, and pressure loss. *FourPortFlowResistanceParameters* is a class that includes flow resistance parameters for four-port models and also defines the nominal pressure drop for both flows. *StaticFourPortHeatMassExchanger* is a component that manages the transport of two fluid flows between four ports, without mass or energy accumulation. *PartialEffectiveness* is a partial model used to implement heat exchangers. Classes that extend this model must incorporate specific forms of mass and heat balance equations, assuming no mass exchange or heat loss to the environment. For heat transfer, Equation 2.2, as previously noted, is applied. Consequently, efficiency is the key parameter governing thermal transfer in the *ConstantEffectiveness* component, maintaining a constant value throughout the entire simulation once configured.

Three-way valve

The three-way valves in the substation model are designed to divert the fluid flow of the primary and tertiary circuits. Specifically, these valves were represented using the *ThreeWayValveLinear* component from the IBPSA library, as the Modelica Standard Library does not include three-way valves. To understand the operating logic of this model, it is necessary to refer to inherited classes, as was done for the heat exchanger and the dual-internal-exchanger tank. The classes involved are: *PartialThreeWayValve*, which extends *ActuatorSignal*, *ValveParameters*, and *PartialThreeWayResistance,* which in turn extends *LumpedVolumeDeclarations*. *PartialThreeWayValve* is a partial model for a three-way valve, used as a base for valves with different opening characteristics. In these models, two-way valves are employed to construct the three-way valve. Specifically, the two main components are represented by two-way valves on the primary branches (called res1 and res3), while the bypass branch consists of a pipe with no pressure loss or transport delay. ActuatorSignal is a model that uses a filter to simulate the actuator response time, while *PartialThreeWayResistance* is a partial model for a three-port flow resistance, like that of a three-way valve. *ValveParameters* is the model defining the valve parameters, such as the flow coefficient. Users can select among various types of coefficients (Av, Kv, Cv) or set a nominal pressure drop using *CvTypes.opPoint*. Referring to Figure 2. 24, which represents the ThreeWayValveLinear model, flow typically enters through port 1, exits through port 2, and can either enter or exit through port 3. To characterize the three-way valve in diverting mode, modifications were made by reversing flows through the three fluid ports compared to the standard model. Specifically, flow was adjusted to enter through port 2, pass through res2 (a pipe with no pressure loss, independent of the control signal), and exit through either port 1 or port 3. These adjustments were implemented on the three-way valve based on control signals 0 and 1 from the integrated control logic, leveraging the linear opening characteristics of valves res1 and res3. When the input signal is 1, the flow is diverted from port 2 to port 1, while when the input signal is 0, the flow is diverted from port 2 to port 3.

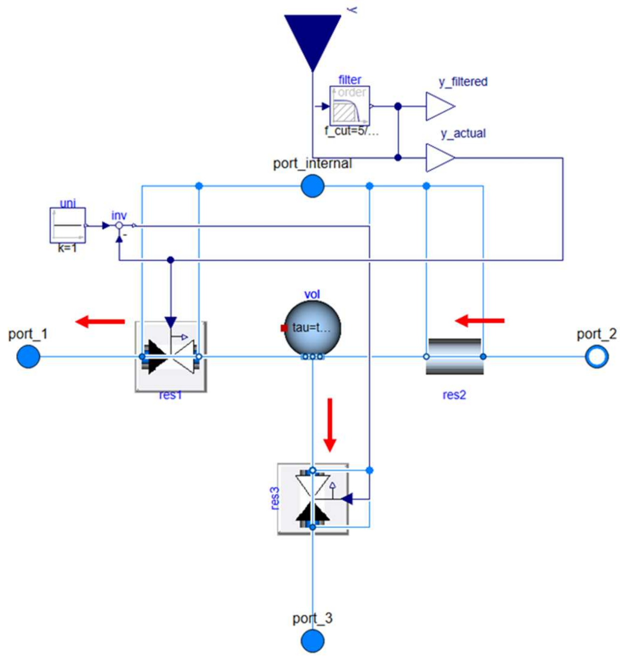


Figure 2. 24 Three-way valve Modelica model

Tank with double internal exchanger

The tank model with a dual internal exchanger was custom developed specifically for the substation, as no such model previously existed. Starting from various tank models available in the IBSA library, a new tank model was created, with a detailed explanation provided in Chapter 5.

2.3.4 Outline of the following chapters

This section provides an overview of the main topics covered in the following chapters, helping guide the reader's understanding of the content.

Chapter 3 explores the concept of shared energy within a REC, analyzing the role of electricity sharing in a DHN to support decarbonization. Different scenarios are examined, employing various strategies for energy sharing, with a comparative analysis of these approaches. Special attention is given to the analysis of an integrated system, consisting of photovoltaics, chillers, and heat pumps, which represents the innovative aspect of the current case study. This chapter offers an overall view of the REC, focusing on its operation and the broad benefits derived from promoting energy sharing. However, to fully understand the community's impact, it is also essential to investigate the benefits for each individual member.

In Chapter 4, the focus shifts to the role of individual members within the REC, a key aspect for understanding the full impact of energy sharing. Since no univocal method exists for allocating the benefits of energy sharing, four ad-hoc algorithms were developed, each applying different criteria and strategies to distribute the shared energy fairly among members, promoting justice and transparency. These algorithms were tested on a case study, with the results thoroughly analyzed. Furthermore, these algorithms can be applied not only to electricity but also to thermal energy, paving the way for the adoption of thermal energy communities.

Finally, Chapter 5 examines how thermal energy can be shared among users of a DHN located in northern Italy. Specifically, the retrofit of an existing thermal substation is proposed, transforming it into a bidirectional substation capable of sharing the surplus energy from renewable sources with other users in the network. The numerical model of the new substation was developed in Dymola and validated energetically based on experimental results obtained from the prototype, tested in the EURAC labs in Bolzano.

REC DESIGNS FOR DHN: ITALIAN CASE STUDY

In this section, it is examined how the Renewable Energy Community concept can be applied to district heating networks to improve overall energy-economic performance. This concept was highlighted through the analysis of a specific Renewable Energy Community, under Italian legislation. This objective can be achieved by optimizing internal energy sharing, especially the surplus electricity produced by the photovoltaic system. Various strategies, including heat pumps, are adopted to maximize energy self-consumption and self-sufficiency, as well as evaluating the most economically efficient investments, taking advantage of incentive tariffs on shared energy. The results show that system performance can be improved with the proposed layout, achieving a significant reduction in system energy demand, emissions, and costs.

3.1. Case study and methodological approach

3.1.1. Intelligent Virtual Network tool

To optimize the distribution of thermal, electrical, refrigeration, and fuel energy flows, and to assess the benefits of a Renewable Energy Community, the intelligent Virtual Network (iVN) software [160] has been utilized. iVN serves as a tool for mapping and analysing networks, operating on the principle of energy balance at nodes. The aggregation model follows a hierarchical scale, where connections are made from "parent" nodes to "child" nodes. An example of iVN network configuration is depicted in Figure 3. 1. Within iVN, units are modelled using load-dependent efficiencies, defined through a lookup table approach. Building energy demands can be provided by users as temporal series or automatically estimated by iVN based on site information. Energy produced by photovoltaic panels is modelled based on inclination, orientation, nominal efficiency, and incorporates load and temperature-dependent conversion efficiency.

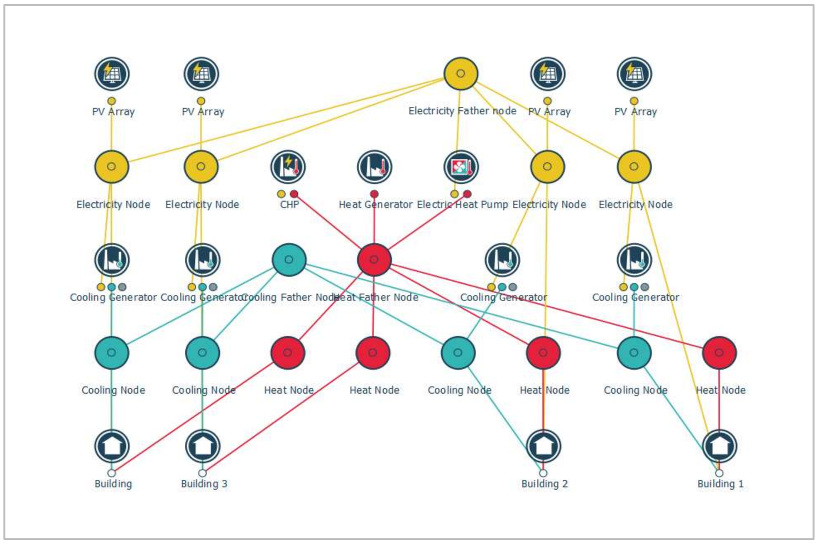


Figure 3. 1. Intelligent Virtual Network layout 2-D view [102]

3.1.2. Case study

The assessment of a Renewable Energy Community (REC) combined with a District Heating Network (DHN) was conducted using an existing network as a case study. The chosen location for this case study is a residential area situated in the suburb of Corticella on the outskirts of Bologna, Italy. Bologna is positioned at a latitude of 45°37' and a longitude of 11°21'. A polar solar diagram in Figure 3. 2, illustrating the sun's trajectories in terms of solar altitude and azimuth throughout the day, provides contextual information. In this diagram, points of equal azimuth are connected by rays, while points of equal height are joined by concentric circles.

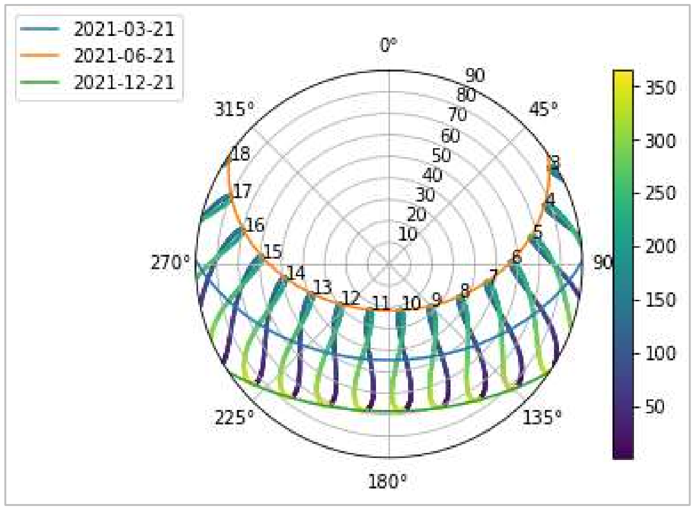


Figure 3. 2. Solar diagram for Bologna [102]

The selected residential area relies on a thermal plant and a DHN for the generation and distribution of hot water to fulfil both space heating (SH) and domestic hot water (DHW) requirements. Currently, the thermal plant is situated at the heart of the DHN and serves as the sole heat source for the network. The thermal plant comprises four boilers, each designed to produce 2900 kWth of heat output, along with an internal combustion cogeneration engine with a design power and heat output of 1400 kWe and 1500 kWth, respectively. The combined thermal output of the plant is approximately 13100 kWth, supplying hot water to the DHN at pressures of 10 bar and temperatures ranging from 80°C to 90°C. The pressure drop across the entire network (both delivery and return lines) is approximately 6 bar. Figure 3. 3 illustrates the layout of the thermal power station in Corticella.

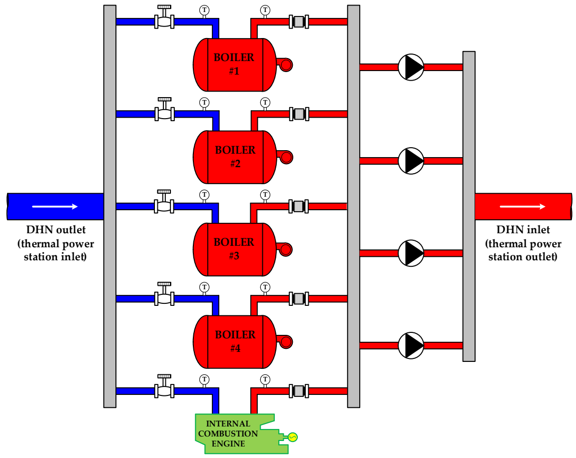


Figure 3. 3. The configuration of the considered thermal power station [102]

The DHN serves 17 users, comprising 13 residential buildings totalling 960 apartments, two schools, a medium-sized supermarket, and a hospital. These users receive energy for both SH during winter and DHW production throughout the year. This study utilized energy demand profiles for a typical summer, winter, and mid-season day for each user served by the plant. These profiles were derived from earlier investigations into the Corticella district heating network* and are depicted from Figure 3. 4 to Figure 3. 6. The heat demand encompasses both DHW and SH needs, while the electricity requirement includes daytime and nighttime lighting for utilities and common areas, as well as the use of household appliances in residential buildings and various appliances in the hospital. Additionally, the cooling demand relates to summer air conditioning within the premises.

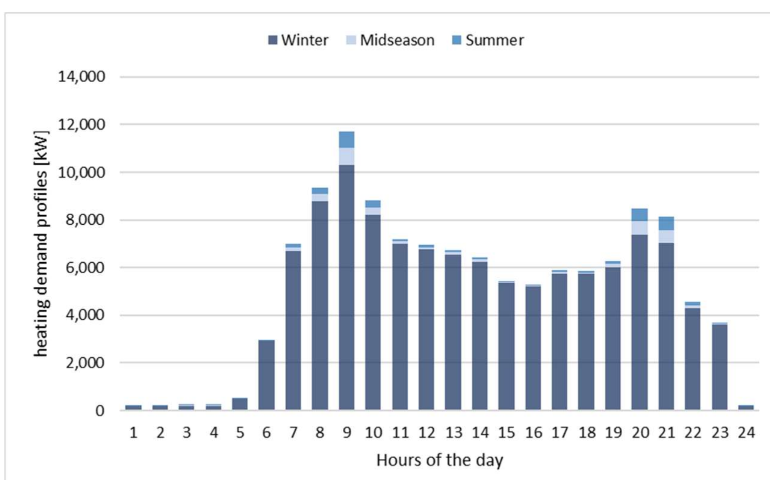


Figure 3. 4. Heating demand profiles [102]

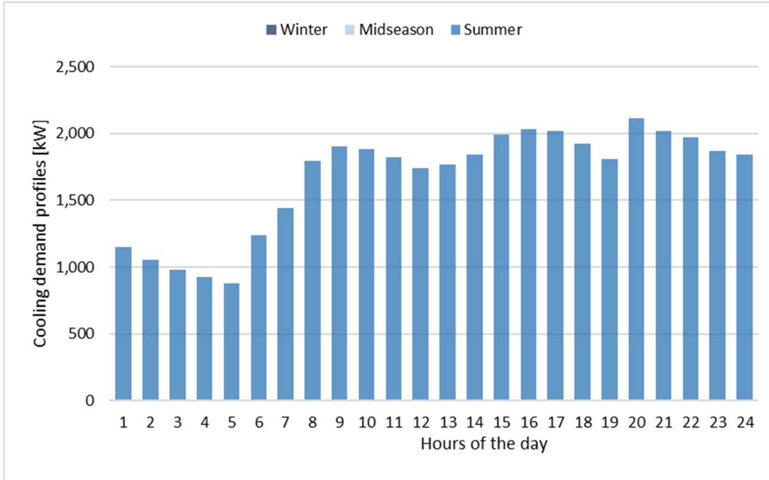


Figure 3. 5. Cooling demand profiles [102]

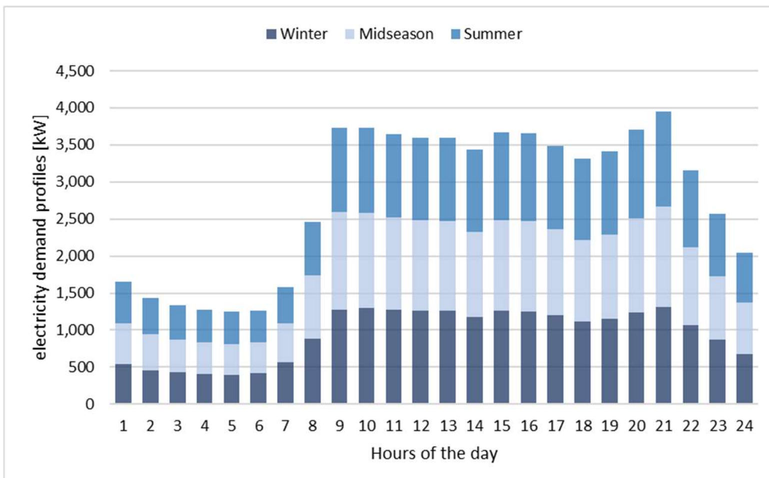


Figure 3. 6. Electricity demand profiles [102]

3.1.3 Simulation scenarios

This study involves simulating various scenarios aimed at exploring the feasibility of integrating different electrical and/or thermal generation systems:

- Scenario 0 (S0): the baseline scenario where the energy demand for DHW and SH is satisfied by the Combined Heat and Power (CHP) unit during winter and by the four boilers throughout the year. Electricity and cooling demands are met by the grid, with compression refrigeration units installed at each user. Additionally, it's assumed that the electricity produced by the CHP unit powers the plant's auxiliary services and the pumping group of the DHN.

- Scenario 1 (S1): the scenario considers the replacement of compression refrigeration units with absorption refrigeration units at each user, with the absorption chillers utilizing heat from the DHN. Here, the CHP unit operates during both heating and cooling seasons.
- Scenario 2 (S2): building upon Scenario 0, this configuration involves installing PV systems on the roofs of the 17 user buildings depending on the available useful surface area.
- Scenario 3a (S3a): in addition to PV systems, all configurations of Scenario 3 incorporate the deployment of a centralized heat pump to supply heat to users. The heat pump's size is determined through parametric analysis to maximize shared energy, self-sufficiency, and cost-effectiveness. In S3a, the heat pump operates only when the CHP is inactive.
- Scenario 3b (S3b): similar to S3a in unit composition, this scenario schedules the heat pump to operate when the CHP is inactive, with operating hours set from 9 a.m. to 5 p.m., aiming to enhance self-sufficiency.
- Scenario 3c (S3c): this scenario, sharing the unit composition of S3a, aims to further boost the heat pump's self-sufficiency. Here, the heat pump is controlled to activate only when a sufficient portion of its energy demand is covered by surplus electricity generated by local PV installations.

The main features of the different scenarios are summarized in Table 3. 1.

Table 3. 1. Summary of the analysed configurations [102]

	ICE	Boilers	CC	AC	PV	HP
Scenario 0	●	●	●			
Scenario 1	●	●		●		
Scenario 2	●	●	●		●	
Scenario 3a	●	●	●		●	●
Scenario 3b	●	●	●		●	●
Scenario 3c	●	●	●		●	●

The proposed scenarios were simulated using the iVN software to assess the optimal annual operational configuration of the entire network. Network simulation is conducted on an hourly basis for the year 2021, as outlined in Table 3. 2.

Table 3. 2. Network simulation characterization [102]

Network simulation	
Start date	01/01/2021 00:30
End date	31/12/2021 23:30
Time step (min)	60

The key attributes of the introduced systems, detailed in Table 3. 3, are outlined as follows:

- PV Panels - Scenarios 2 and 3(a-c): The sizing of the installed photovoltaic systems is determined by the available roof surface area across the 17 user buildings. This parameter is computed within iVN after importing building data via Open Street Maps. Subsequently, the usable surface area is multiplied by a corrective factor of 0.6 to provide a conservative estimate for the space available for PV modules. The tilt and azimuth angles are selected based on optimal conditions for the specified location (latitude 44°30'27"00 N, longitude 11°21'5" 04 E).
- Centralized Heat Pumps - Scenarios 3(a-c): The Coefficient of Performance (COP) is chosen with reference to existing literature [161]. All three scenarios incorporate the installation of a centralized heat pump, which generates hot water at 80 °C. This centralized heat pump is utilized to produce hot water for integration into the district heating network during both summer and winter seasons. However, it is not utilized in chiller mode for cooling during summer. In summer, the District Heating Network (DHN) is also utilized to provide heat for domestic hot water supply, necessitating the use of the heat pump.
- Absorption Chiller - Scenario 1: The Energy Efficiency Ratio (EER) is selected based on relevant literature, similar to the approach for heat pumps [161].

Table 3. 3. Main parameters of the systems considered in the implemented scenarios [102]

Compression Chiller	
COP	4
Absorption Chiller	
EER	0.7
Centralized Heat Pumps	
COP	2.2
PV panels	
Total Surface	18200 m^2
Total peak power	2.7 MW_p
Tilt angle	30°
Azimuth	180° (south)
Module nominal efficiency	15%

3.1.4 Key performance indicators

The various scenarios are simulated, and assessment based on energy, economic, and environmental criteria. From an energy standpoint, the analysis focuses on two key indicators: self-consumption (SC) rate and self-sufficiency (SS) rate. SC rate represents the ratio between locally produced energy used on-site and total locally produced energy, while SS rate signifies the ratio between locally used energy and total local energy consumption. In terms of economic analysis, parameters related to operating and investment costs are presented in Table 3. 4 and Table 3. 5, respectively. For electricity and natural gas procurement costs, statistical data from the Italian authority for electricity and gas markets (ARERA) were referenced. Specifically, 2019 energy costs for household end-users were utilized for electricity, while values for industrial applications were applied for natural gas (*ARERA: prezzi finali del gas naturale per consumatori industriali*). Assumptions regarding investment costs for PV panels [164], absorption units[165], and heat pumps[166] were drawn from available literature sources. In Italy, energy shared within a Renewable Energy Community (REC) is incentivized. According to the Italian regulation[167], the shared energy within an energy community is calculated hourly as the minimum between the feed-in energy and the total electric energy demand. This "shared energy" is incentivized with a dedicated tariff of approximately €11/MWhe, in addition to the price paid for electricity feed-in. To assess the viability of the proposed investments, the Net Present Value (NPV) parameter was employed and showed in 3.1 equation. NPV is a highly effective tool for determining the most economically advantageous investment option.

$$NPV = \sum_{i=1}^{n} \frac{Ct}{(1+r)^t} - Co \qquad 3.1$$

where Ct represents the cash flow, Co is the investment cost, r the interest rate, assumed equal to 6% (which considers the riskiness of the project itself, and n is the useful life, assumed equal to 20 years.

Table 3. 4. Operating expenses for the economic analysis [102]

Parameter	**Unit**	**Value**
Cost of electricity	[€/kWh$_e$]	0.232
Selling price electricity	[€/kWh$_e$]	0.06
Cost of fuel	[€/m^3]	0.732
Shared Energy (REC)	[€/kWh$_e$]	0.11
Maintenance ICE	[€/kWh$_{th}$]	0.02
Maintenance Boilers	[€/kWh$_{th}$]	0.006
Maintenance HP	[€/kWh$_e$]	0.01
Maintenance AC	[€/kWh$_c$]	0.0025

Table 3. 5. Capital expenditure for the economic analysis [102]

Parameter	Unit	Value
PV panels	[€/kW$_P$]	1891
Heat Pump	[€/kW]	358.9
Absorption Chiller	[€/kW]	250

To conduct a thorough environmental analysis, CO2 emission factors for electricity supply and natural gas usage were determined. Following the data reported in [168], an emission factor of 234 gCO2/kWh was utilized to estimate CO2 emissions associated with electricity consumption[169]. Additionally, for natural gas, an emission factor of 202 gCO2/kWh was applied [170].

3.3. Results & Discussion

This section presents the outcomes concerning the self-consumption and self-sufficiency rates of buildings with PV plants installed, the results of the parametric analysis conducted for sizing the heat pumps in scenarios 3a-c, and finally, the findings of the energy, economic, and environmental analyses for all implemented scenarios. Figure 3. 7 illustrates the trends of the self-consumption rate and self-sufficiency rate for the 17 users served by the district heating plant, each equipped with a photovoltaic system on the roof. While the self-consumption rate exhibits a relatively high value, indicating substantial utilization of locally generated energy, there is a notable surplus production across almost all users. This suggests promising potential for energy sharing within a renewable energy community. Conversely, the self-sufficiency rate stabilizes at approximately 25-30%, implying that the installed PV capacity falls short of meeting the entire electricity demand in the area.

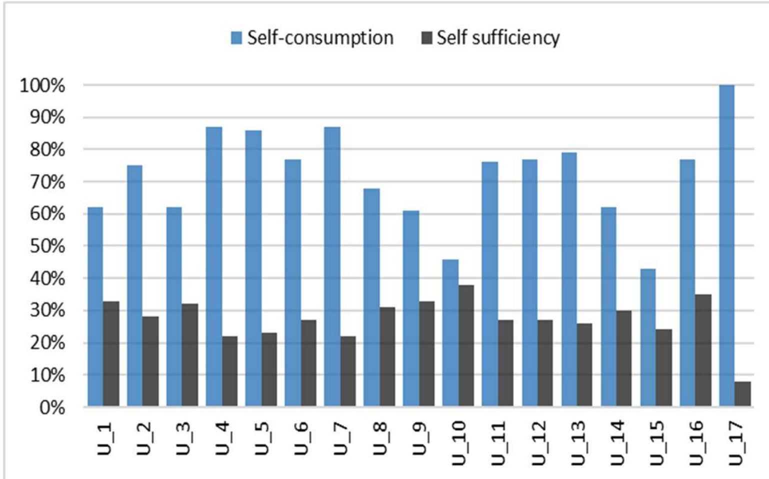


Figure 3. 7. Calculated in the rate of self-consumption and self-sufficiency of the 17 users with photovoltaic system [102]

To establish the design to be compared across scenarios 3a-c, a parametric analysis was conducted to determine the optimal size of the heat pump. The decision was based on the aim of maximizing shared energy, self-sufficiency, and net present value (NPV) of the investment. Shared energy pertains to the surplus electricity produced by the photovoltaic systems, which is utilized by the heat pump. Figure 3. 8 illustrates the outcomes for Scenario 3a, where the heat pump operates throughout the entire day during the summer season. Among the options considered, the 100 kW and 150 kW heat pumps emerge as the only economically viable ones. Consequently, for Scenario 3a, the 150 kW heat pump was selected, despite having a slightly lower NPV compared to the 100 kW pump. However, it boasts a higher self-consumption and self-sufficiency rate of 9.5% and 35.8%, respectively. Figure 3.9 showcases the results for Scenario 3b, where the heat pump can only be utilized during the summer season, from 9:00 a.m. to 5:00 p.m. In this instance, the 100 kW heat pump is identified as the optimal size, with an NPV of 17700 € and self-consumption and self-sufficiency rates of 7% and 73.1%, respectively. The surplus electricity from photovoltaics remains constant. With increasing heat pump size, the growth rate of self-consumed energy lags behind that of absorbed electricity. Consequently, the self-sufficiency rate, determined by the ratio between self-consumed energy and absorbed electricity, tends to stabilize beyond 600 kW.

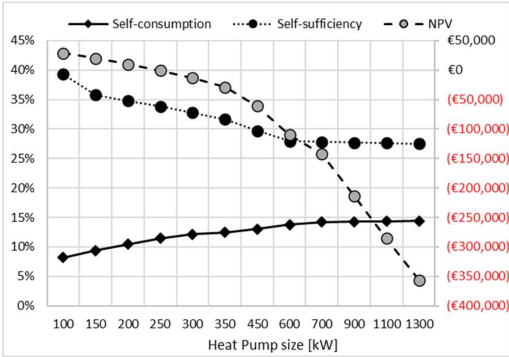


Figure 3. 8. Self-consumption, self-sufficiency and NPV in Scenario 3a [102]

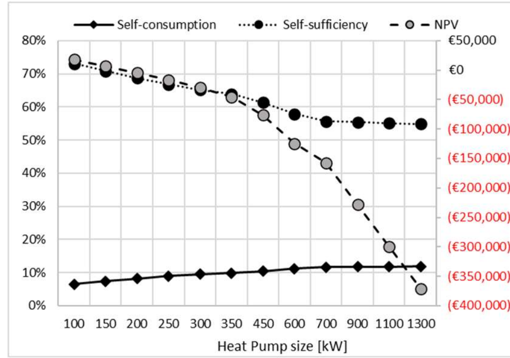


Figure 3.9. Self-consumption, self-sufficiency and NPV in Scenario 3b [102]

Based on the obtained results, a third analysis was conducted, where the heat pump operates only when the surplus production from the PV panels exceeds certain thresholds (25%, 50%, 75%) of the hourly heat delivered by the heat pump in a hypothetical continuous operation (Scenario 3c). Three heat pump sizes of 100 kW, 200 kW, and 300 kW were examined. Table 3. 6 presents the results, indicating significant improvements compared to the previous scenarios. Consequently, the 200 kW heat pump was selected for this scenario, which operates when the photovoltaic surplus exceeds 25% of the heat load supplied by the heat pump. This choice resulted in self-consumption and self-sufficiency rates of 12.6% and 97.3%, respectively, along with an NPV of 32387 €. Figure 3. 10 illustrates how the NPV, used to assess the heat pump investments in scenarios 3a, 3b, and 3c, varies with and without incentives for Renewable Energy Communities (RECs). It becomes apparent that establishing an Energy Community can yield significant economic advantages, rendering the investment financially viable thanks to incentives on shared energy.

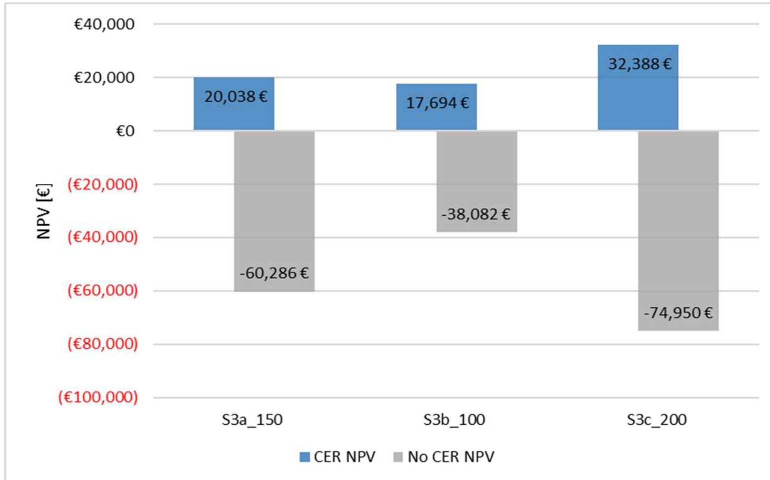


Figure 3. 10. Comparison between NPV for heat pumps in the case with and without REC [102]

Figure 3. 11 and Figure 3. 12 show a summary of the primary energy demand, and a comparative analysis of the scenarios analyzed with respect to the reference Scenario 0. In Scenario 2, the installation of PV panels significantly affects the energy supplied by the electricity grid with a reduction of 20.3%. Furthermore, in scenario 3c there is a reduction of 20.2% of the electricity supplied by the grid, despite the addition of a centralized 200 kW heat pump. This is because the surplus production of the PV systems is shared with the heat pump, minimizing the withdrawal from the grid. Furthermore, in scenarios 3a-3c there is a reduction (albeit minimal) of fuel consumed, thanks to the installation of heat pumps with different operating profiles. In Scenario 1 there is a 13.21% reduction in electricity consumption, because the compression refrigeration units (which absorb electricity) have been replaced with absorption refrigeration units (which absorb thermal energy) and a consequent increase of 23.9% of fuel used. Figure 3. 13 and Figure 3. 14 provide a summary of the CO2 emissions of the entire network across the various analysed scenarios, alongside a comparative analysis with the reference scenario. Notably, promising outcomes are observed in all scenarios, except for Scenario 1. In Scenario 1, where renewable energy production plants are not incorporated, but compression refrigeration units are replaced with absorption units powered by the thermal plant, there is a resultant increase in fuel consumption.

Table 3. 6. Summary of the self-consumption, self-sufficiency and NPV values for the parametric analysis of Scenario 3c [102]

% heat energy	HP size [kW]	SC [%]	SS [%]	NPV [€]
25%	100	9.2	98	40,427
50%	100	8.2	100	32,423
75%	100	7.5	100	25,847
25%	200	12.6	97.3	32,387
50%	200	11	100	19,427
75%	200	9.6	100	7,717
25%	300	15.1	97	17,361
50%	300	12.8	100	-1,648
75%	300	10.9	100	-17,178

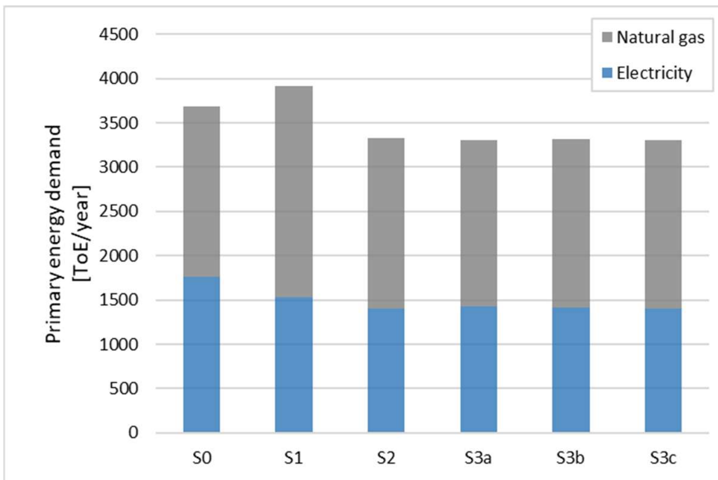


Figure 3. 11. Scenario comparison: primary energy demand [102]

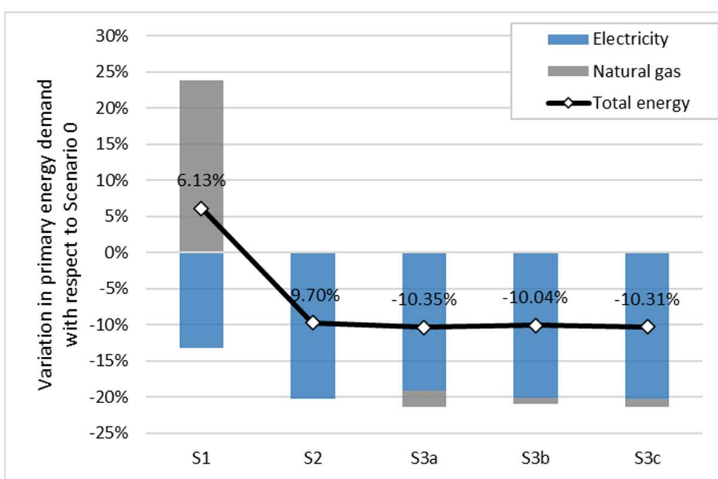


Figure 3. 12. Scenario comparison: primary energy demand, variations with respect to S0 [102]

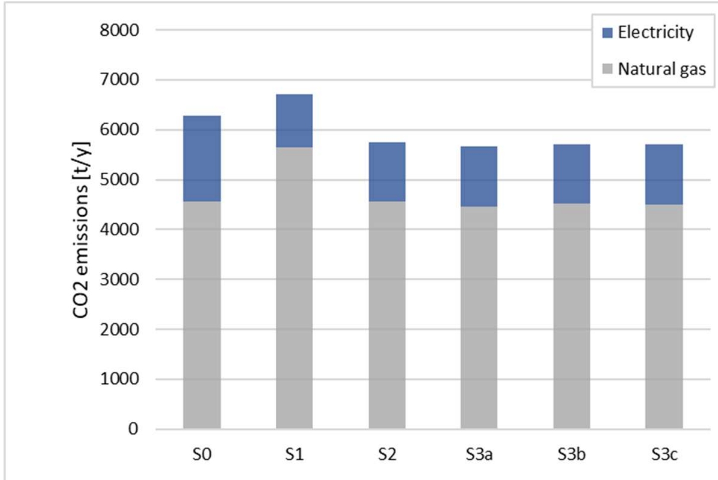


Figure 3. 13. Tons of CO2 emitted in the various scenarios implemented [102]

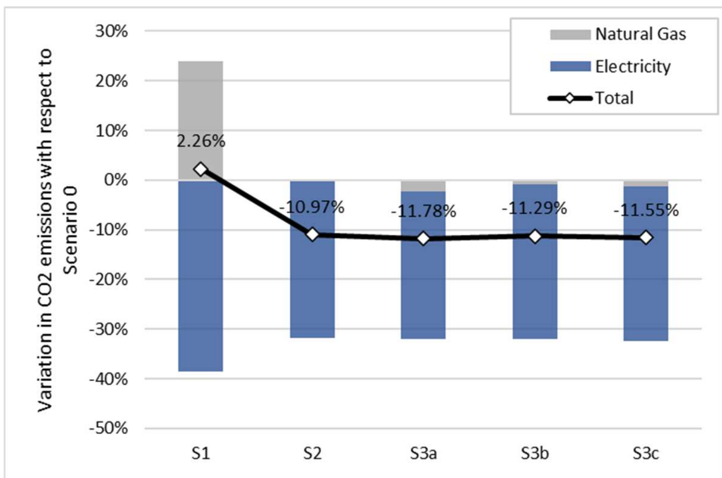


Figure 3. 14. Scenario comparison: CO_2 emissions, variations with respect to Scenario 0 [102]

Figure 3. 15 and Figure 3. 16 focus on system costs. The results indicate a positive improvement in scenarios 2, 3a-c compared to the reference scenario, albeit limited. Notably, there is a noteworthy enhancement in the NPV in scenarios 3a-3c when compared to Scenario 2. This disparity is particularly pronounced in Scenario 3c, where the NPV nearly doubles that achieved in Scenario 2. This underscores the significant potential of utilizing surplus heat from PV systems to supply the local DHN, especially when incentives are available for energy communities. Additionally, Figure 3. 15 underscores the importance of incentives for energy communities, as they constitute a major contributor to the difference in the net economic outcome between Scenario 2 and Scenarios 3a-c.

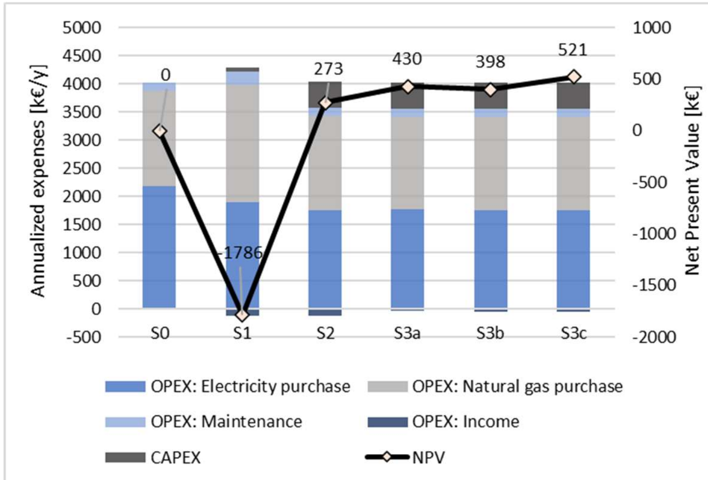


Figure 3. 15. Results of the economic evaluation of investments [102]

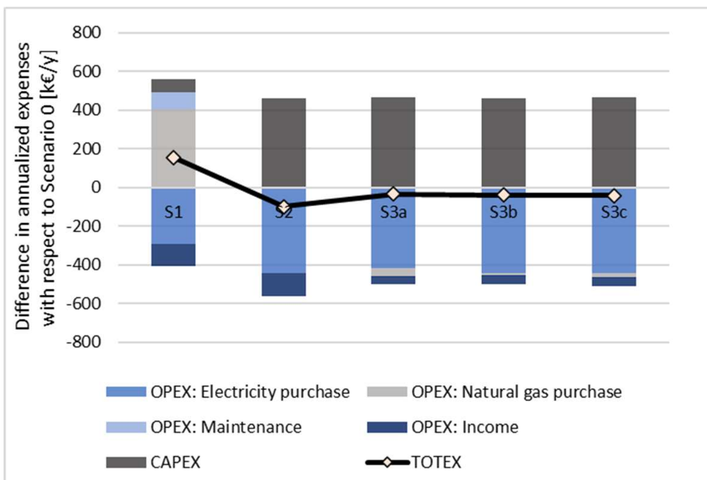


Figure 3. 16. Results of the economic evaluation of investments, presented as the difference in comparison to the Scenario 0 [102]

The analysis of how the configuration of the REC impacts economic performance can be conducted by examining the breakdown of Scenarios 3a-c. In Scenario 2, profits solely benefit PV panel owners, who receive approximately 40,000 € per year for the energy they sell to the grid. This value remains consistent in Scenarios 3a-c, with additional income from shared energy incentives for energy communities, totalling €7,000, €4,900, and €9,400 per year in Scenarios 3a, 3b, and 3c, respectively. While these contributions to the system's OPEX are relatively minor (approximately €3,500,000 per year for Scenarios 3a-3c), results indicate they, along with the installation of a centralized heat pump, lead to an overall improvement in the system's NPV.

3.4. Conclusion

The recent focus on renewable energy and citizen energy communities, particularly within the European Union, is anticipated to drive the necessary expansion of renewable energy generation, particularly at a decentralized level. This section examines the potential of utilizing surplus solar energy from local rooftop PV installations to power heat pumps, which can then supply useful heat to the local district heating network, especially during winter months. The study compares these scenarios with the existing network and two alternative approaches: one involving the use of absorption chillers for summer cooling to maximize cogeneration unit utilization, and the other considering the installation of PV panels without heat pumps. These scenarios are simulated and applied to an existing district heating network in Bologna, Italy. Results indicate that the most significant improvement arises from installing PV panels on community rooftops, which alone generates the greatest economic benefit (with a calculated 20-year NPV of €273,000) and environmental impact (reducing emissions by 11% compared to the reference scenario). Additionally, in this specific case study, locally produced and self-consumed energy is relatively high (averaging approximately 70%), mainly due to the neighbourhood's high density. However, despite not being the optimal scenario for an energy community, utilizing heat pumps to supply part of the heat to the district heating network increases the NPV from €273,000 to €398,000-€521,000 depending on the scenario. This increase is attributed partially to enhanced conversion efficiency and to the additional net income (€4,900-€9,400 per year) generated by energy community incentives. The study demonstrates how establishing an Energy Community incentivizes investment in heat pumps to decarbonize district heating networks, leveraging the tariff incentives for shared energy within the community. In this research, the application of Renewable Energy Communities (RECs) to district heating networks is analysed through a relatively straightforward simulation-based approach. Future developments will aim to optimize both the design and operation of the system, incorporating additional technologies such as storage. This chapter raises several further questions requiring exploration. It suggests investigating the utilization of energy storage, both electric and thermal, alongside optimizing heat pump control to enhance self-consumption and shared energy incentives. Additionally, exploring the potential of decentralized heat generation with heat pumps, combined with bidirectional energy exchange systems, warrants comparison with the proposed analysis. Finally, this study highlights the importance of optimizing the economic benefits associated with establishing an energy community. Rather than focusing on individual members, the approach considers the community as a collective entity that invests and benefits as a whole.

ALGORITHMS FOR DYNAMIC ENERGY SHARING

Identifying and quantifying the benefit for each member of the community is essential to promote active participation and support the diffusion of shared energy models. This section introduces four algorithms designed to facilitate energy sharing based on participants' contributions to the energy community under virtual model. These algorithms use different repartition dynamic keys: a consumption-proportional key, a key utilizing the Pearson correlation coefficient to assess correlation between electricity consumption and surplus production, a trend-based key considering disparities in energy acquisition and injection, and a hybrid key combining elements of the former two. Utilizing real hourly energy consumption and production data from an Italian Renewable Energy Community comprising eight representative users, the research aims to conduct an annual comparative assessment of these methods. The objective is to determine the varying levels of shared energy allocated to each user based on their contribution, thereby elucidating the strengths and weaknesses of each approach.

4.1 Outline of the implemented methods

This paragraph elaborates on the methodologies devised for distributing shared energy, as depicted by Equation 4.1. These methodologies only work when the energy supplied to the grid from production plants is less of the community's total energy consumption.

$$\sum_{i}^{N} SH_{i,j} = min\left(E_{inj,j}\,, \sum_{i}^{N} C_{i,j}\right) \qquad 4.1$$

4.1.1 Method M1

This method proposes assigning each member an amount of shared energy (SH_i) in proportion to their consumption. As a result, it's ensured that no member receives more shared energy than their consumption. Thus, the shared energy allocated to the i-th member of the REC at any given time ($SH_{i,j}$) can be calculated using Equation 4.2.

$$SH_{i,j} = r_{i,j} \,.\, E_{inj,j} \qquad 4.2$$

In the case of M1 methodology, $r_{i,j}$ can be expressed by Equation 4.3:

$$r_{i,j} = \frac{C_{i,j}}{\sum_i C_{i,j}} \qquad 4.3$$

The sum of r_i values allocated to each member is equals 1, ensuring that no member receives an amount of shared energy exceeding the community's total. With the M1 methodology, a larger portion of shared energy is assigned to members with higher consumption, while those with lower consumption receive comparatively smaller shares. Consequently, this approach may not incentivize members to decrease their energy usage; instead, it could inadvertently encourage them to increase consumption rather than promoting energy efficiency and savings. This distribution method is easily calculable and has been proposed and utilized in other energy community studies. For example, one study [141] incorporates both static and dynamic distribution coefficients, including a coefficient proportional to consumption, and proposes a hierarchical distribution criterion based on collected savings. Another study [144] introduces new sharing coefficients, such as hybrid and uniform ones, comparing them to static and dynamic coefficients proportional to consumption. In yet another study [171], each community member is allocated a portion of shared energy using a sharing key that adjusts based on whether the user exports or imports energy, proportional to the energy purchased from the grid.

4.1.2 Method M2

The application of this method is based in the research delineated in [130]. Choosing this algorithm, which is already documented in scientific literature, was driven by the need for a comparative analysis among various methods. M2, as designed, guarantees that each user receives at least an amount of shared energy equivalent to the hourly consumption of the user with the lowest energy demand and aims to distribute shared energy evenly among all members. As per this approach, if members are arranged in descending order based on their energy demands, the shared energy corresponds to the green area depicted in Figure 4. 1, while the grey columns represent the portion of energy needed that isn't supplied by renewable sources and is drawn from the grid. More intricate details about the implemented algorithm are available in Appendix B of the same scholarly article [130]. Consequently, the M2 methodology favors members with the lowest hourly electricity consumption, who contribute minimally to the total shared energy. However, M2 could disadvantage users with high consumption and high sharing potential, while benefiting users with lower consumption who contribute less to energy sharing.

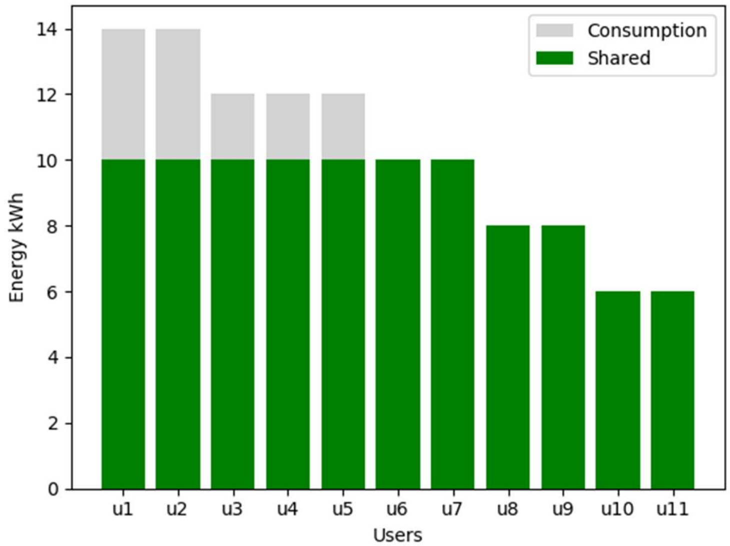


Figure 4. 1 M2 shared energy allocation calculated for hour for all the EC members [172]

4.1.3 Method M3

This method examines the relationship between the energy consumed by each user and the energy supplied to the grid by production plants. M3 employs the Pearson correlation coefficient to discern the daily correlation between individual energy consumption and feed into the grid energy from production plants. The Pearson correlation coefficient is a statistical measure used to evaluate the strength and direction of the linear relationship between two continuous variables ("Pearson Product-Moment Correlation," n.d.). To compute this coefficient, data on daily energy consumption and renewable energy production load profiles were gathered to account for energy self-consumption by users linked to the plant. The correlation between these load profiles was computed using the scipy.stats Python library for statistical analysis [174]. In instances of high input from renewable plants, a positive correlation (close to 1) between the two curves suggests an uptick in consumption, while a negative correlation (near -1) indicates a decline in consumption. A value near 0 implies no correlation between the consumption and injection curves. This coefficient reflects favourable user behaviour, where a positive correlation indicates increased consumption when renewable energy production is high, thereby augmenting shared energy within the community. Similar to M1, Equation 4.1 can express the shared energy attributed to each community member, while Equation 4.4 defines the dynamic sharing key, ri,j, distinguishing M3 from M1 in methodology.

$$r_{i,j} = \frac{p_{i,j}}{\sum_i p_{i,j}} \qquad 4.4$$

As previously discussed, even in this context, the sum of distribution coefficients assigned to each member remains at 1. To ensure that the shared energy allocated to each user aligns with their consumption, a more complex algorithm was devised. Should the shared energy exceed a user's consumption, their Pearson correlation coefficient is set to zero, and the shared energy allocation equals their consumption. For further insights into the implemented algorithm, refer to Figure 4. 2's flow diagram. After confirming that grid-fed energy doesn't surpass the cumulative consumption of all members, during each iterative cycle (j), the residual energy (RESj) and partial (shared) energy (PRji) attributed to each member are computed to distribute the shared energy, SHi,j. This process iterates until the sum of shared energies for each member no longer matches the energy fed into the network.

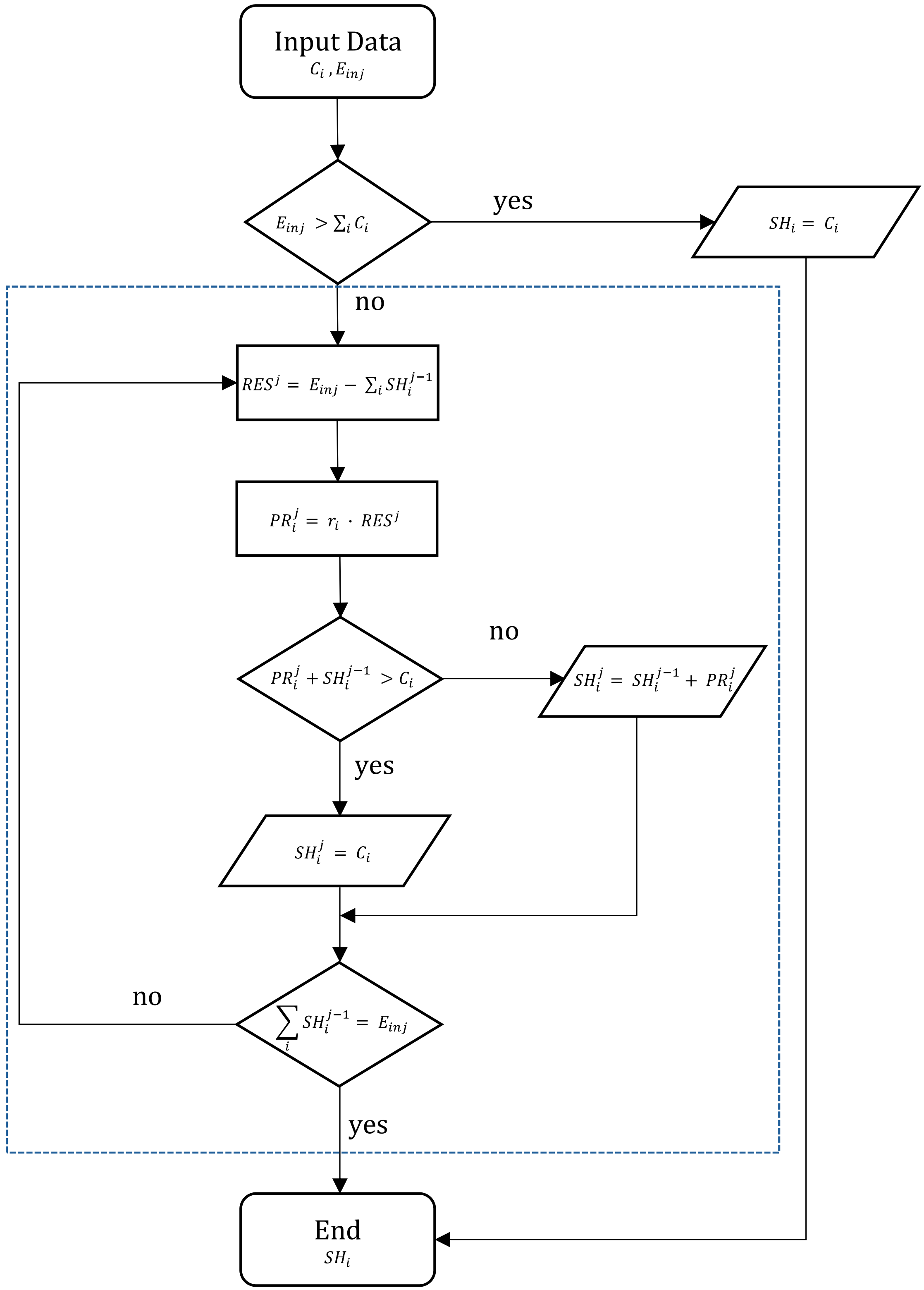


Figure 4. 2 Flowchart of the implementation algorithm based on the dynamic sharing key r_i [172]

4.1.4 Method M4

The functioning of M4 aligns with the principles outlined in M3, but with a notable difference: the dynamic sharing key relies on an alternative parameter termed the "sharing rate" (SR). This parameter was devised to monitor and potentially penalize individuals who exceed the energy consumption limits set by community production plants. Particularly during production hours, managing energy usage is critical; however, it's imperative to discourage excessive consumption. A scientifically robust approach necessitates maintaining equilibrium between energy supply and demand, curbing waste, and fostering overall energy efficiency. As depicted in Figure 4. 3, the assumed sharing rate SRi follows a linear increase if the ratio of a user's consumption to the energy supplied by the production plant to the grid is less than 1. Conversely, it exhibits an exponential decrease if the ratio exceeds 1. Consequently, users consuming more energy per hour than what is available to the community will be assigned a coefficient that decreases as the gap between consumption and grid-fed energy widens. The diminishing exponential function is illustrated in Figure 4. 3, with the y-axis denoting the sharing rate and the x-axis representing the consumption ratio of the i-th user to the total grid-fed energy.

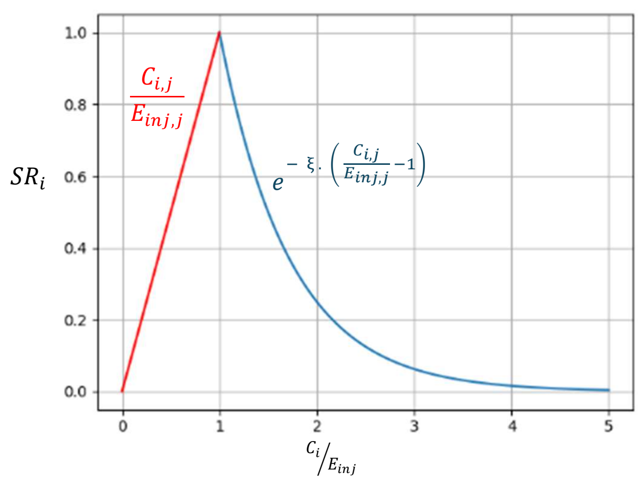


Figure 4. 3 Trend of the defined sharing rate ($SR_{i,j}$) at hourly level [172]

The function is mathematically represented below in Equation 4.5.

$$SR_{i,j} = \begin{cases} e^{-\xi \cdot \left(\frac{C_{i,j}}{E_{inj,j}}-1\right)}, & \frac{C_{i,j}}{E_{inj,j}} < 1 \\ \frac{C_{i,j}}{E_{inj,j}}, & \frac{C_{i,j}}{E_{inj,j}} \geq 1 \end{cases} \tag{4.5}$$

To define the decay constant, the initial analysis arbitrarily assumed a sharing rate of 0.5 when the ratio between the consumption of the i-th member and the energy supplied into the network equalled 1.5 (i.e., consumption exceeded input by 50%). Building on this assumption, the resulting decay coefficient was computed to be 1.386. The calculation of the dynamic sharing key ri, in this scenario, is demonstrated below using Equation 4.6:

$$r_{i,j} = \frac{SR_{i,j}}{\sum_i SR_{i,j}} \qquad 4.6$$

As described above, also in this scenario the sum of the distribution coefficients assigned to the i-th member is equal to 1.

4.1.5 Method M5

The operation of M5 follow to the principles delineated in M3 and M4, albeit with a notable difference: the dynamic sharing key (ri,j) is no longer solely based on either the Pearson correlation coefficient (pi) or the sharing rate (SRi), but rather on a combination of both. Merging the methodologies of M3 and M4 involves introducing two distinct weights, denoted as α and β, whose sum equals 1. These weights dictate the relative significance of each method in relation to the other. For instance, if α is assigned a higher value than β, greater emphasis is placed on the degree of synchronization between consumption and injection; conversely, if β holds greater weight, more importance is attributed to the amount of energy consumed by the user compared to the energy injected into the grid and potentially shareable. Similar to M1, M3, and M4, the shared energy allocated to the i-th member of the community at any given time can be expressed using Equation 4.1. In this instance, the calculation of the dynamic sharing key ri was performed utilizing Equation 4.7, as illustrated below:

$$r_{i,j} = \frac{\alpha \cdot p_{i,j} + \beta \cdot SR_{i,j}}{\sum_i \alpha \cdot p_{i,j} + \beta \cdot SR_{i,j}} \qquad 4.7$$

Initially, α and β were assumed arbitrarily equal to 0.5. As described above, also in this scenario the sum of the dynamic sharing key assigned to the i-th member is equal to 1.

4.2 Methods assessed on an hourly basis

To gain a deeper understanding of the methodologies M1, M2, M3, M4, and M5, they were applied to the consumption data of three typical residential users at an hourly level. The hourly consumption of users u1, u2, and u3 was extracted from a dataset, which is analysed in greater detail in the following paragraph. In this section, these data are used solely for demonstration purposes to illustrate the hourly behaviour associated with each proposed method. Figure 4. 4 illustrates the consumption patterns of the users alongside the energy supplied to the grid within the same hourly interval, which is less than the total energy purchased by all users combined. Additionally, Figure 4. 5 presents the distribution of shared energy among users for that hour using M1. As anticipated, the total shared energy matches the energy fed into the grid, and it is allocated proportionally based on the users' consumption, with u3 receiving the highest share and u2 the lowest. Similarly, M2 was executed in Python using the hourly consumption data of u1, u2, and u3 from Figure 4. 4. Figure 4. 6 depicts that this algorithm tends to distribute shared energy equally among the most consuming members. After assigning an amount of shared energy equal to the minimum consumption to u2, the remaining energy is split evenly between u1 and u3, regardless of u3's higher consumption compared to u1. Consequently, u1 receives a larger share of shared energy compared to M1, nearly doubling from 0.38 to 0.54 kWh. Thus, u1 benefits more from M2 as it obtains shared energy equivalent to its entire actual consumption, almost double what M1 allocates. Regarding M3, the Pearson coefficients (rescaled from 0 to 1) were assumed to be p1 = 0.64, p2 = 0.23, and p3 = 0.51 for u1, u2, and u3, respectively. As depicted in Figure 4. 7, u1 receives the highest share of shared energy due to its strong correlation with input, whereas u2 receives the smallest share owing to its weaker correlation. It's noteworthy that M3 consistently penalizes u3, despite its higher consumption, because u3's Pearson coefficient is slightly lower than u1's, which is highly correlated throughout the day and thus rewarded by M3.

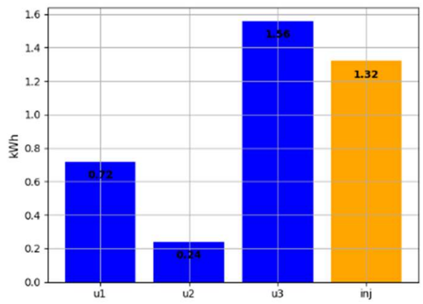


Figure 4. 4 Hourly consumption and Injected energy [172]

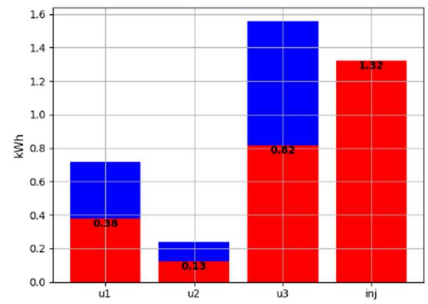


Figure 4. 5 M1 repartition of shared energy [172]

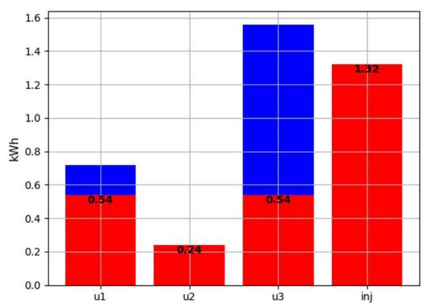


Figure 4. 6 M2 repartition of shared energy [172]

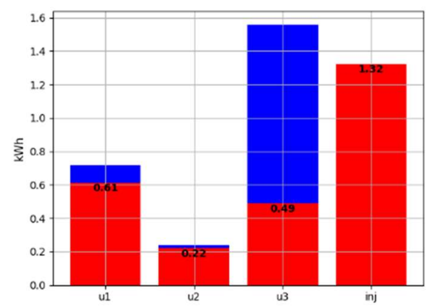


Figure 4. 7 M3 repartition of shared energy [172]

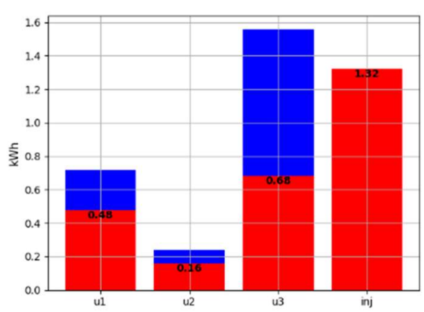


Figure 4. 8 M4 repartition of shared energy [172]

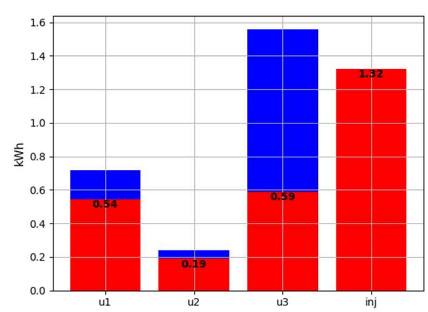


Figure 4. 9 M5 repartition of shared energy [172]

4.3 Case study

In the preceding section, the core principles of each method were outlined, with a focus on their hourly operations. The next phase of this work involves evaluating five algorithms using data-driven hourly consumption patterns and comparing these methods through an annual simulation of a Renewable Energy Community (REC). The chosen case study examines the potential establishment of a REC in a northern Italian city, utilizing consumption and production data from a PV system feeding all generated energy into the grid. Table 4. 1 details the primary characteristics of the energy community members, including: a manufacturing company (Small Medium Enterprise, u1) that provided its consumption data anonymously, downloaded from the local distributor's portal; two types of residences (apartments and single-family homes), with consumption data from two family units (u2 and u5; u3 and u4). Additional average consumption profiles for residential customers, varying by power classes (u6, u7, and u8), were sourced from ARERA, the Italian Energy Networks and Environment Regulatory Authority. The solar production profiles were provided along with the consumption data, the latter corresponding to actual hourly production. Hourly consumption data were retrieved from the ARERA portal [175] and selected based on geographic location to integrate with other community members. ARERA processed measurement data to develop these average data-driven profiles, made available by distribution companies through the Integrated Information System [176], which manages information flows such as measured energy data. To obtain more significant and generalizable results, each hourly residential consumption was accounted for 20 times, creating a composite profile representing 20 identical residential users. This proportion aimed to achieve global energy sharing exceeding 90%, ensuring correct community sizing and clearly illustrating the differences between the methods in the comparative analysis. The simulation covers a one-year period, summarized in Table 4. 2.

Table 4. 1 Main features of energy community members [172]

REC members	Users grouping	N° of members	Prosumer	N° of users	Power contract [kW]	Area [m²]	Demand [kWh/y]
u1✦	SME	-	Yes	1	-	-	419,894
u2	res	3	No	20	3	80	31,491
u3	res	5	No	20	3	190	70,950
u4	res	2	No	20	4.5	180	61,743
u5	res	4	No	20	3	145	44,917
u6♦	res	-	No	20	6	-	190,897
u7♦	res	-	No	20	4.5-6	-	86,077
u8♦	res	-	No	20	3-4.5	-	65,760

✦ the SME did not provide any information regarding contract power, number of occupants and available surface area ♦ the processing of the data obtained through the ARERA portal does not report the number of occupants for domestic users and the available area

Table 4. 2 Time of simulation [172]

Simulation time	
Start date	01/04/2022 00:00:00
End date	31/03/2023 23:00:00
Timestep	60 minutes

From Figure 4. 10 to Figure 4. 12 illustrates the weekly profiles for energy purchase and feed into the grid of the SME, and from Figure 4. 13 to Figure 4. 15 of all residential users in the community. To effectively represent seasonal energy patterns, three weeks were chosen from each of the three periods (winter, summer, and mid-season). These representative weeks were selected to highlight the distinct energy consumption behaviors typical of the varying climatic conditions throughout the seasons. Although the overall amount of shared energy at the community level is notably high, nearly 90% of the energy fed into the grid, amounting to 79,855 kWh/year. For implementing the M3 and M5 methods, the correlation between each member's consumption curve and the renewable plants' injection curve was calculated using the daily Pearson correlation. The coefficient was scaled from 0 to 1, and each user was then assigned a normalized coefficient based on the sum of all coefficients for each hour.

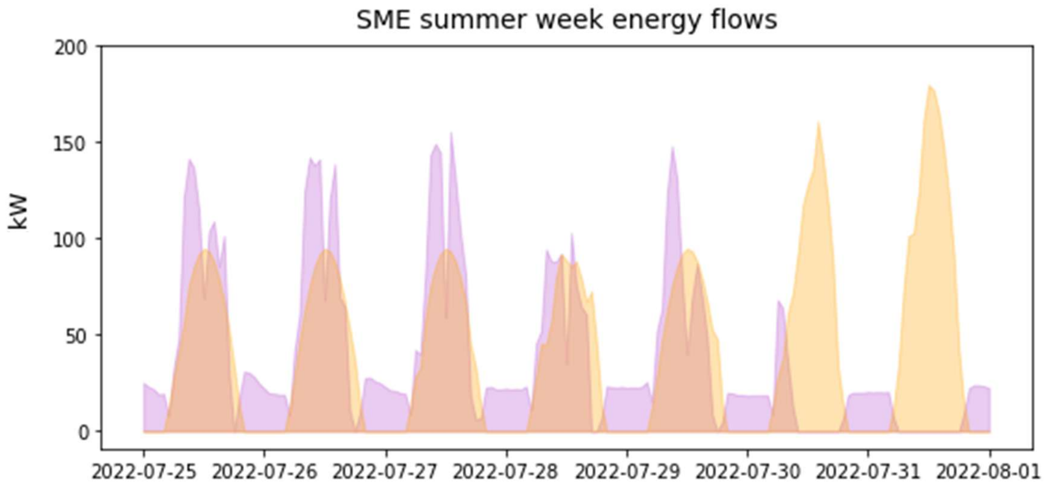


Figure 4. 10 Summer weekly profiles of energy purchased and fed into the grid for SMEs [172]

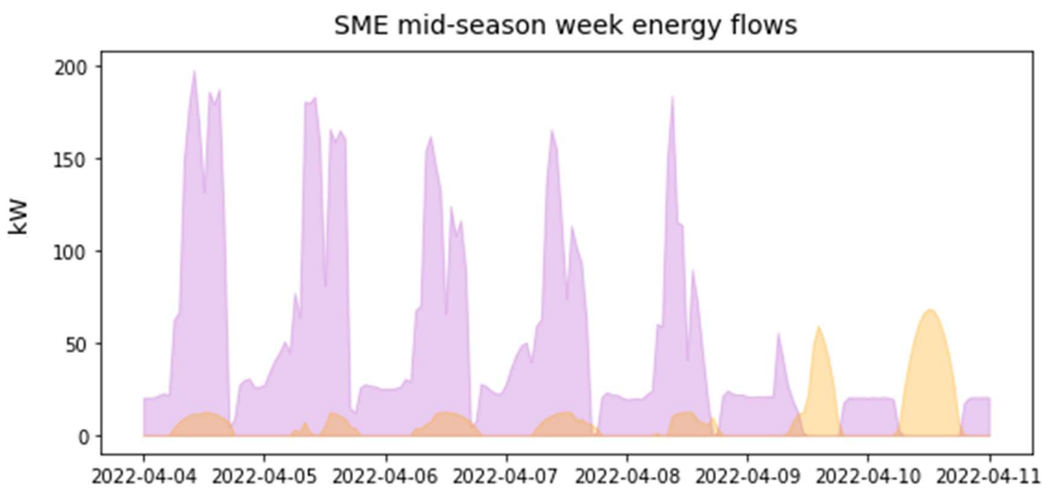


Figure 4. 11 Mid-season weekly profiles of energy purchased and fed into the grid for SMEs [172]

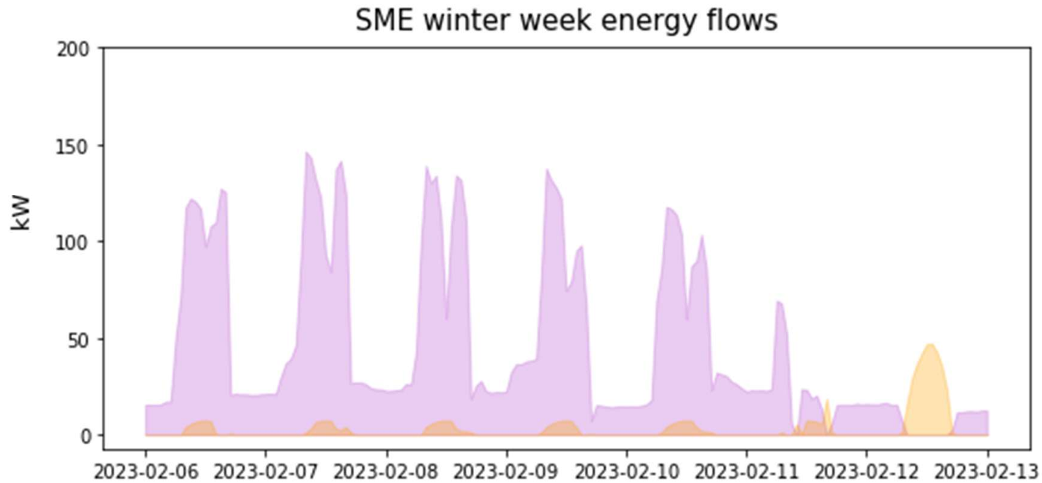


Figure 4. 12 Winter weekly profiles of energy purchased and fed into the grid for SMEs [172]

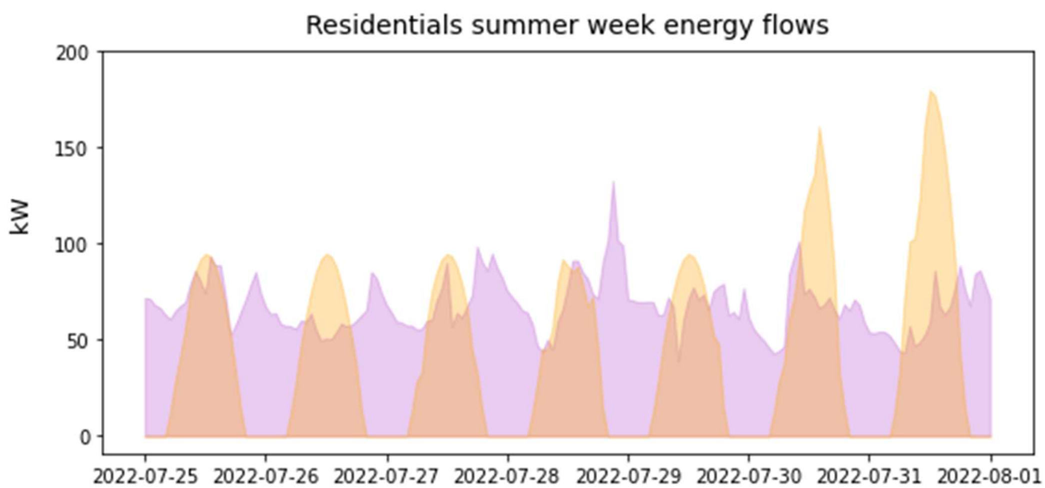


Figure 4. 13 Summer weekly profiles of energy purchased and fed into the grid for residentials [172]

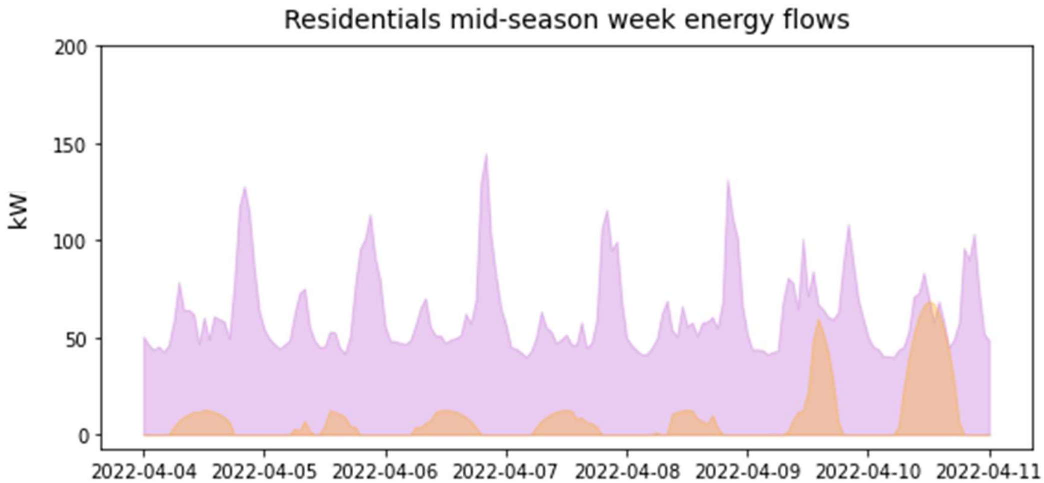


Figure 4. 14 Mid-season weekly profiles of energy purchased and fed into the grid for residentials [172]

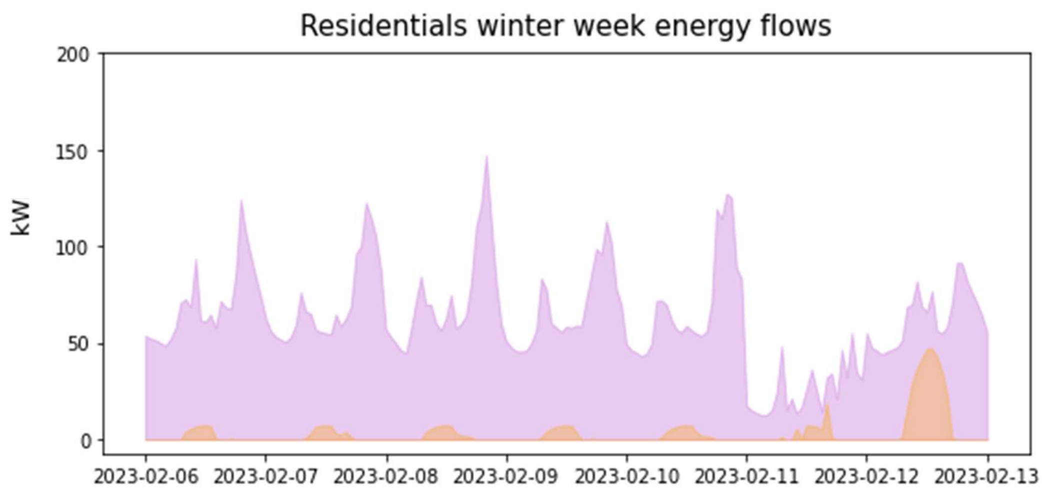


Figure 4. 15 Winter weekly profiles of energy purchased and fed into the grid for residentials [172]

Figure 4. 16 displays a box plot of the distribution of normalized Pearson values for each user. The first quartile for u1 shows significant variations in the correlation coefficient, with 50% of its values ranging approximately from 0.05 to 0.021 throughout the year, indicating that its consumption is not always positively correlated with the energy fed into the grid; however, it remains higher compared to all other members. For member u6, the first and third quartiles have a narrow range of values, between 0.07 and 0.09, and are often negatively correlated with the energy injected into the grid on many days of the year, compared to the other members. Observing Figure 4. 17, which shows the box plot excluding weekend days, reveals that the variations in the first quartile for u1 are significantly reduced, making this user the most positively correlated, while the distribution of values for other users remains similar to that in Figure 4. 16. This trend is due to the SME's consumption substantially decreasing, nearly to zero, during weekends when it is closed.

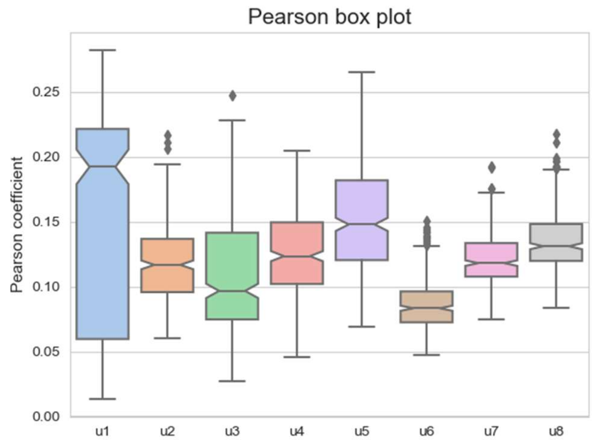


Figure 4. 16 Notched box plot of daily normalized Pearson correlation coefficient [172]

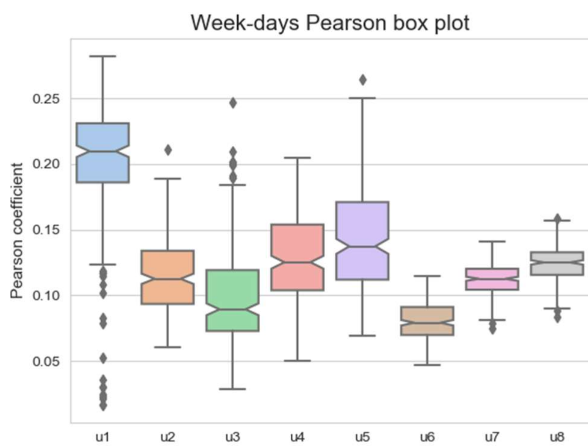


Figure 4. 17 Notched box plot of normalized Pearson correlation coefficient excluding weekends [172]

4.4 Results & Discussion

Figure 4. 18 shows the amount of shared energy allocated to each user by different methods in relation to their actual consumption. This figure demonstrates that, irrespective of the distribution method employed, the shared energy assigned to each member is substantially lower than their total consumption. In Figure 4. 19, the shared energy allocated by each method is again presented, but this time it is compared with a parameter called Shared_limit, as defined by Equation 4.8.

$$SH\_lim_{i,j} = min(E_{inj,j}, C_{i,j}) \quad 4.8$$

This quantity represents the maximum energy each member could share with the community if there were no other members. In particular, methods M2, M3, M4, and M5 tend to distribute energy almost uniformly among most members, except for u1, u6, and u5, which exhibit a more varied distribution across the methods. Despite u6 having the highest annual consumption among residential users due to its contracted power of 6 kW, it is penalized by M3. This may be to its hourly consumption which does not align well with the shareable energy profile. As shown in Figure 4. 16, 50% of the normalized Pearson values for u6 range between 0.07 and 0.09, indicating a significant lack of correlation between consumption and grid injection. It is also noteworthy how M1 allocates the most shared energy to u1, the member with the highest consumption, but its actual contribution, i.e., defined as the maximum energy it could share (the shared limit)—is lower than that of u6, which receives less energy from M1. Conversely, u2 and u5 are the most disadvantaged by the M1 method, as they have the lowest consumption among all participants and provide the least effective contribution to the community. For u2, aside from M1, all methods allocate similar amounts of shared energy, with M4 showing slight differences, likely due to u2's low consumption often being much lower than the energy input at any given time.

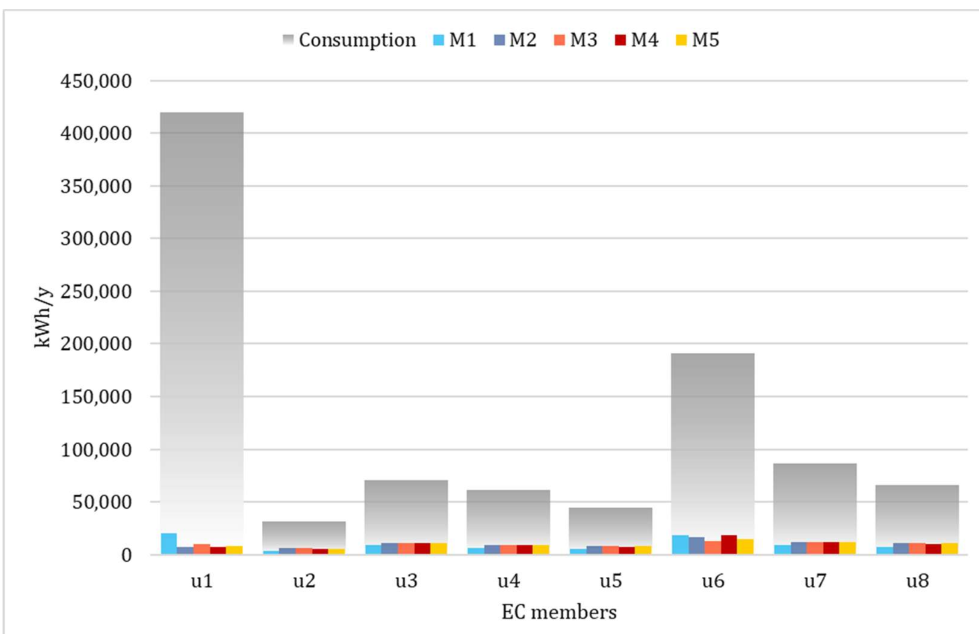


Figure 4. 18 Comparative analysis of the methods used for the allocation of shared energy with respect to total consumption [172]

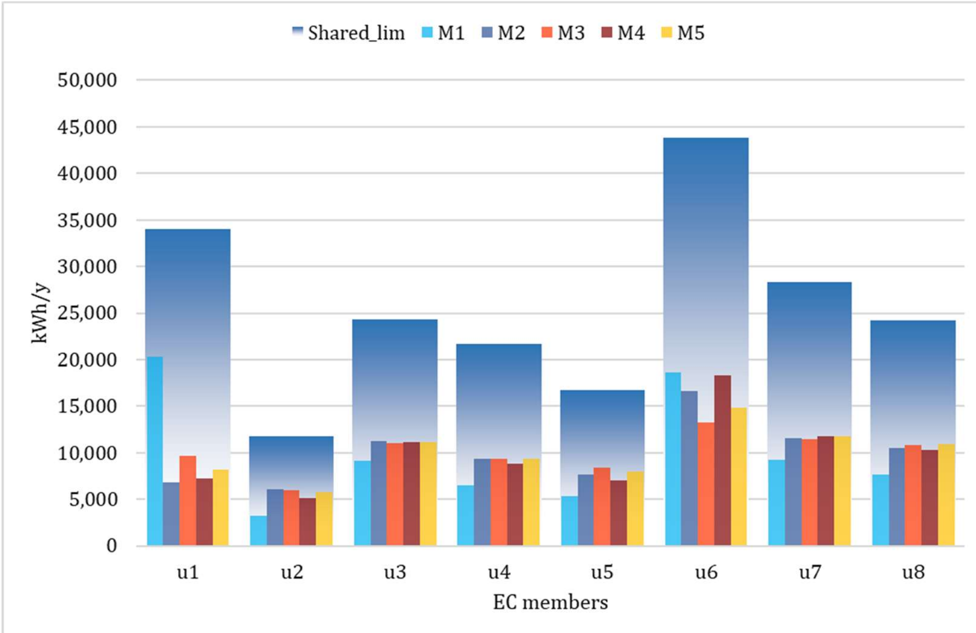


Figure 4. 19 Comparative analysis of the methods used for the allocation of shared energy with respect to the shared energy limit [172]

This trend occurs because M1 only considers energy consumption without accounting for its distribution over time. Since u1 does not consume energy on weekends, it contributes "fewer hours" than u6, which has a higher annual shared_lim. However, during the hours u1 does contribute, its consumption is significantly higher. Figure 4. 20 and Figure 4. 21 illustrates how the hours of consumption for u1 and u6 are distributed in relation to the hours of energy fed into the grid throughout the year. For u1, it is evident that weekend consumption is zero, especially when feed-in energy values are high (100-175 kWh), whereas during weekdays, u1's consumption is high when feed-in energy values are low. For u6, weekend consumption aligns with high feed-in energy values, but u6 also shows high consumption values even when feed-in energy is low.

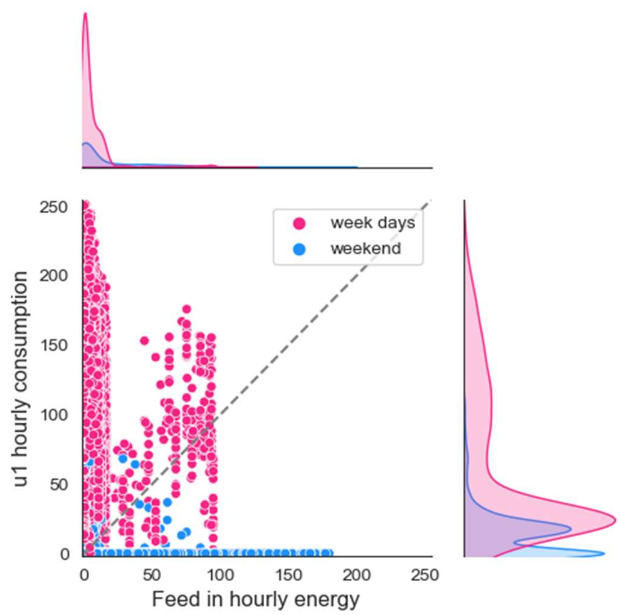


Figure 4. 20 Distribution of consumption hours compared to feed in hours for users u1 [172]

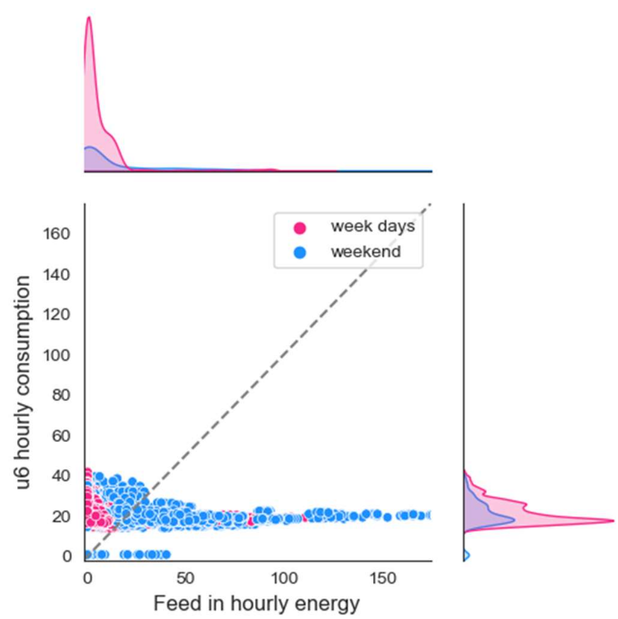


Figure 4. 21 Distribution of consumption hours compared to feed in hours for users u6 [172]

To conduct a comparative analysis of the methods, they were systematically compared with M1 using scatter plots, as depicted from Figure 4. 22 to Figure 4. 25. The x-axis represents the shared energy according to M1, while the y-axis represents the shared energy according to the other methods. If a point lies above the reference line, it indicates that the particular method assigns a higher shared energy to the i-th member than M1; if the point is below the reference line, it indicates that M1 assigns a higher share to the i-th member. Figure 4. 22 illustrates the comparison between M1 and M2: the majority of members receive a greater amount of shared energy from the M2 methodology, except for u1 and u6, which are favored by M1. Specifically, u6 is quite close to the reference line, while u1 is significantly distant, as M1 assigns it a much higher energy share than M2. Figure 4. 23 presents the comparison between M1 and M3: the results are similar to the previous one, with u1 and u6 being favored by M1; u6 is further from the reference line compared to the previous figure, while u1 gets closer, though still distant from it. Figure 4. 24 shows the comparison between M1 and M4: u6 is almost on the reference line, indicating that M1 and M4 essentially allocate the same amount of shared energy. For the other members, the scenario remains similar to what was previously observed. Lastly, Figure 4. 25 shows the comparison between M1 and M5: once again, u1 and u6 are favored by M1 over M5, following a pattern similar to the previous comparisons.

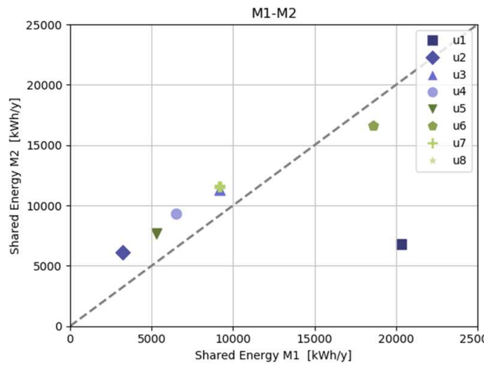


Figure 4. 22 Comparison between the shared energy assigned by M1 and M2 [172]

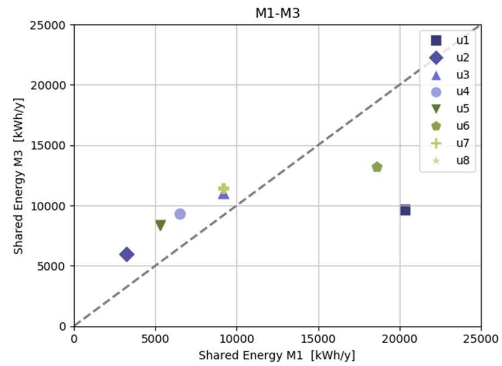


Figure 4. 23 Comparison between the shared energy assigned by M1 and M3 [172]

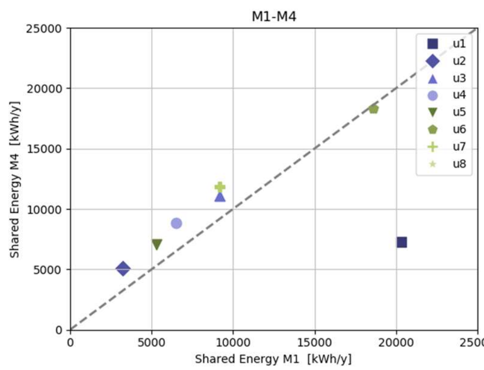


Figure 4. 24 Comparison between the shared energy assigned by M1 and M4 [172]

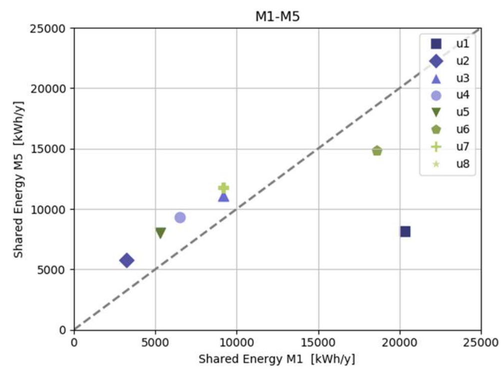


Figure 4. 25 Comparison between the shared energy assigned by M1 and M5 [172]

Due to the significant differences observed for users u1 and u6 when compared with M1, a detailed analysis was conducted to examine how the shared energy assigned by M2, M3, M4, and M5 varies for these two users as a percentage relative to that assigned by M1. This comparison for u1 is presented in Figure 4. 26, showing both the trend of the annual shared energy as the distribution method varies and the percentage variation of this energy with respect to M1. For u1, M2 and M4 result in the greatest reductions in shared energy, with decreases of 66.5% and 64.1%, respectively. M2 tends to distribute the shared energy equally among all members, disadvantaging users with high consumption, while the M1 method favors high-consumption users and penalizes those with lower consumption. Conversely, M4 penalizes u1 because it is the major consumer in the community, exceeding the energy fed into the grid at certain times of the day. Consequently, it results in a SRi,j that negatively influences the sharing key determining the amount of energy assigned. The method that penalizes u1 the least is M3; as shown in Figure 4. 16, 52.4% of the normalized Pearson coefficients can vary widely, correlating positively with the energy fed into the grid on some days of the year. Figure 4. 27 presents similar measures for u6. The implemented methods do not penalize u6 as severely as they do u1. However, M3 is the method that penalizes u6 the most, since ri,j is influenced by $p_{i,j}$. As seen in Figure 4. 16, 50% of the coefficients fall within a narrow range between 0.07 and 0.09, correlating negatively with the energy fed into the grid on certain days of the year. As previously observed, M4 assigns an amount of shared energy similar to M1 because, although u6 has the second-highest consumption after u1, it does not exceed the energy fed into the grid by the production plants, thus SRi,j is not excessively penalized.

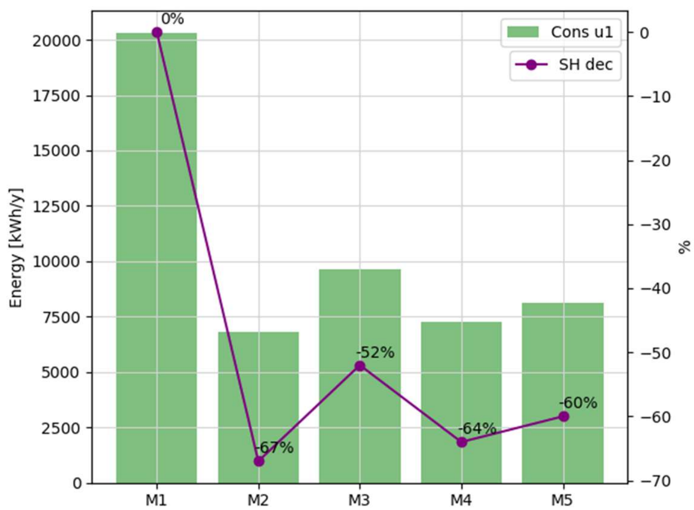


Figure 4. 26 Trend of the shared energy assigned to u1 with respect to M1 [172]

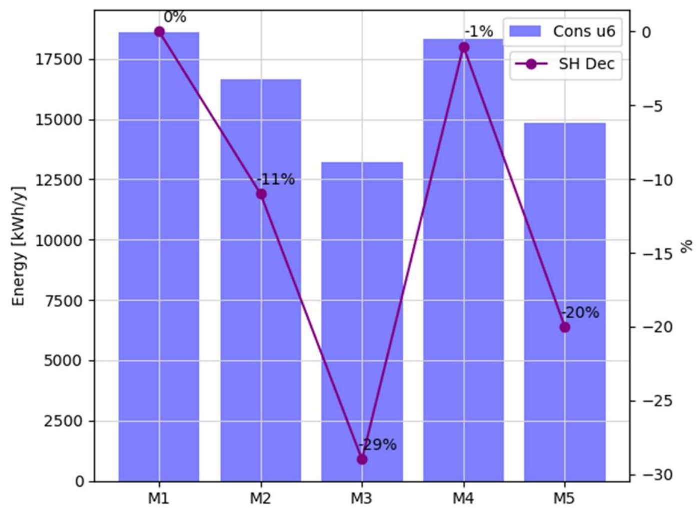


Figure 4. 27 Trend of the shared energy assigned to u6 with respect to M1 [172]

Table 4. 3 outlines the shared energy contributions allocated to each member by various methods in relation to the energy fed into the grid by the production plants. Key observations include:

- Except for users u1 and u6, methods M2, M3, M4, and M5 generally assign a larger share of energy to community members.
- Methods M2, M3, M4, and M5 tend to distribute energy relatively evenly among most members.
- Users u1 and u6, who have the highest annual consumption, are consistently favored by the M1 methodology, which allocates them a greater share of energy than the other methods.
- User u1 is significantly penalized by the other methodologies compared to u6, illustrating how M1 tends to overestimate the shared energy proportionally to consumption.
- User u6 is particularly penalized by M3 due to a negative correlation throughout the year; however, M4 rarely penalizes u6, often maximizing the share rate compared to other members.

Table 4. 3 Contribution of shared energy of each member compared to the energy shared by the entire energy community [172]

Users	Demand [kWh/year]	M1	M2	M3	M4	M5
u1	419,894	22.6%	7.6%	10.8%	8.1%	9.1%
u2	31,491	3.6%	6.8%	6.7%	5.7%	6.4%
u3	70,950	10.2%	12.5%	12.2%	12.4%	12.4%
u4	61,743	7.2%	10.3%	10.4%	9.8%	10.4%
u5	44,917	5.9%	8.5%	9.3%	7.8%	8.9%
u6	190,897	20.7%	18.5%	14.7%	20.4%	16.5%
u7	86,077	10.2%	12.9%	12.7%	13.1%	13.1%
u8	65,760	8.5%	11.7%	12.1%	11.4%	12.1%

To enhance the robustness and validity of the developed algorithms, it is recognized that applying them across a broader range of case studies would provide greater support and reliability for their operational effectiveness. At the same time, the use of real-world data from actual users is prioritized to ensure meaningful testing and evaluation. In this context, the algorithms were tested on a second case study involving a Renewable Energy Community (REC) composed of eight hotel activities located in northern Italy, as detailed in **Appendix A**. This additional case study features user profiles distinct from those of the first, further broadening the scope of the analysis. The analyses described earlier were replicated to verify the consistency and reliability of the main findings observed in the initial case study. Specifically, Table A. 1 summarize the principal characteristics of the community members and the simulation period, respectively. Figure A. 1 shows the main energy flows of community's members, Figure A. 2 to Figure A. 6 depict the weekly energy profiles and a representative box plot of the distribution of normalized Pearson coefficients for each user. The outcomes of the algorithm applications are presented in Figure A. 7 to Figure A. 9. As observed in the first case study, the user with the highest annual consumption (u3) was allocated the largest share of energy by M1. M4 assigned an amount nearly identical to M1, as u3's consumption remained below the energy fed into the grid for the majority of the year, as shown in Figure A. 6. Conversely, the user with the lowest annual consumption (u6) received the smallest share of energy from both M1 and M4. In line with Figure A. 5, users u2 and u7 obtained the greatest benefits from M3, as their energy consumption patterns were more synchronized with the grid's energy feed. In conclusion, the results highlight the algorithms' operational consistency when applied to varying annual periods and distinct user profiles. These findings emphasize the importance of employing diverse case studies and real-world data to validate and refine the algorithms, thereby strengthening confidence in their applicability across different contexts.

The algorithms, tested on hourly consumption data over a year, demonstrate computational feasibility for typical energy community sizes, such as those analyzed in this study. However, more complex algorithms, such as M3, M4, and M5, which rely on correlation coefficients or nonlinear functions, show a higher computational load than M1, which uses simple proportional calculations. In terms of scalability, understanding as the ability to handle larger or more complex community configurations, all methods generally maintain applicability. However, M5, being a hybrid method, presents the greatest challenges in this area. Its effectiveness in large-scale scenarios may require optimizations, such as parallel processing or dimensionality reduction techniques, to sustain operational efficiency. Successful implementation critically depends on the accuracy of hourly consumption and production data. Furthermore, managing heterogeneous configurations, i.e. ensuring fairness among users with different profiles, such as companies and households, remains a key challenge, especially to prevent disproportionate disadvantages for specific user categories. Overall, the algorithms appear well-suited to current energy community configurations. However, further research focusing on computational optimizations and implementation strategies could improve their applicability on a larger scale. While an exact quantification of computational costs and the true scalability of the algorithms are beyond the current scope, these remain critical areas for future investigations. The methods were developed within a research context, with the awareness that, in a real-world setting, specific skills would be required. Nonetheless, it is believed that in the future, new professional roles specialized in the field of energy communities will emerge, capable of utilizing and applying these methods.

4.5 Conclusion

This study aims to support the internal management of Renewable Energy Communities (RECs) and Collective Self-Consumption (CSC) configurations by developing algorithms to allocate shared energy among their members. The focus is on modeling and simulating a Renewable Energy Community, employing a remuneration model based on energy sharing as outlined in Italian regulations which adopted virtual model. Specifically, four algorithms were created based on dynamic sharing keys to distribute hourly shared energy, addressing the critical challenge that arises when the energy fed into the grid is less than the energy purchased by users. In such scenarios, determining each user's actual contribution without a physical basis for energy exchanges becomes difficult. The developed algorithms include M1, which is based on a consumption-proportional key; M2, developed by the University of Turin; M3, which utilizes a Pearson correlation key to assess synchronism between injected and purchased energy; and M4, which employs a sharing trend key that considers the difference between purchased and injected energy. Additionally, M5 combines aspects of the previous two methods. These methods were tested through an annual simulation of dynamic energy exchanges with hourly resolution in an energy community comprising "typical" users. The testing utilized real energy consumption profiles from eight users, including seven residential profiles and one Small to Medium Enterprise (SME) with a PV system available to the community. Some residential consumption data were aggregated at an hourly level and multiplied to create a representative profile of 20 residential users. The main objective was to evaluate the allocation of shared energy through the five developed methods.

The results indicate that, aside from users u1 (the SME) and u6, methods M2, M3, M4, and M5 generally assign a larger share of energy to community members compared to M1. These methods tend to distribute energy relatively evenly among most members. Users u1 and u6, who have the highest annual consumption, are consistently favored by the M1 methodology, which allocates them a greater share of energy than the other methods. User u1 is significantly penalized by the other methodologies compared to u6, illustrating how M1 tends to overestimate the shared energy proportionally to consumption. User u6 is particularly penalized by M3 due to a negative correlation throughout the year; however, M4 rarely penalizes u6, often maximizing the share rate compared to other members. The study also highlights the importance of rewarding users who consume energy when the community provides surplus energy from renewable sources, as seen in method M3, which could stimulate greater sensitivity to energy efficiency and sustainability. At the same time, users should be encouraged to maintain or reduce their consumption compared to pre- and post-community configurations, as emphasized by method M4.

The study contributes to the growing body of research on RECs and CSCs in Europe, which are gaining importance as several authors delve into these topics, garnering considerable attention in recent times. By addressing emerging challenges in energy sharing and analyzing new national regulations adopting a virtual sharing model, the implemented algorithms offer practical solutions and represent a conceptual innovation in energy sharing at the community level. Utilizing data-driven energy profiles enhances the accuracy of the results, allowing for a more precise evaluation of the algorithm simulations. Furthermore, the findings can provide tangible support for decision-making and policymaking in the energy sector, contributing both to academic knowledge and to the practical implementation of tools and approaches aimed at improving efficiency and fairness in energy distribution within community members.

These algorithms, designed to adapt to different types of energy communities, can be applied not only to electrical communities but also to thermal ones. In this regard, the scientific work [177] demonstrates the effectiveness of such algorithms in quantifying shared energy within district heating networks, where energy surplus is redistributed among community users. This approach highlights the flexibility of the proposed algorithms and their potential contribution to creating sustainable and scalable energy-sharing models across various community contexts.

NUMERICAL MODELLING OF BIDIRECTIONAL SUBSTATION FOR EXISTING DHN

Extending the concept of energy sharing to thermal flows is essential to promote the spread of thermal energy communities. Active district heating, with its established infrastructure and effective integration with renewable sources, can represent a successful strategy to drive the development of thermal energy communities. This section presents a novel approach to adapt traditional district heating substations into bidirectional heat exchange devices, enabling prosumers not only to use thermal energy for their needs but also to inject surplus energy back into the grid. An optimized layout in a 'supply-to-return' configuration is proposed, using an existing network in northern Italy as a case study. An experimental campaign conducted by EURAC Research on a substation prototype, designed to replicate the bidirectional configuration, provided the necessary input data for developing a detailed numerical model. Using the multi-domain software Dymola, the model was built to analyze the performance and benefits of the proposed configuration, focusing on summer and mid-season operations. The experimental data collected not only enabled precise modeling of the substation but also allowed for an energy validation of the model, thereby ensuring its robustness and reliability in simulation. The model integrates customized systems and control logics based on standard library models to accurately represent the substation's behavior under specific conditions.

5.1 Overview of the DHN & current substation

The DHN being examined supplies thermal power to 34 residential buildings situated in Turin, northern Italy. Each building is fitted with its own substation, which includes heat exchangers that deliver thermal power for space heating (SH) and domestic hot water (DHW). The network's supply temperature is set at 80°C during the winter and 70°C in the summer, while the return temperature to the generation plant is 60°C in winter and 50°C in summer, maintaining a temperature difference (ΔT) of 20°C. The network utilizes a two-pipe configuration (typical configuration for networks serving residential and tertiary needs): a supply pipe that delivers thermal power for SH and DHW to the substations, and a return pipe that transports the cold fluid back from users to the heat production facility. Figure 5. 1 illustrates the schematic representation of the DHN extending just over one km north of Turin. This network is powered by a thermal power plant that consists of a cogeneration internal combustion engine and two boilers, utilizing hot water as the heat transfer fluid for distribution. The network features a branched structure with several branching points, where the main pipeline has a diameter of DN250, while most of the connection pipes have a diameter of DN60.

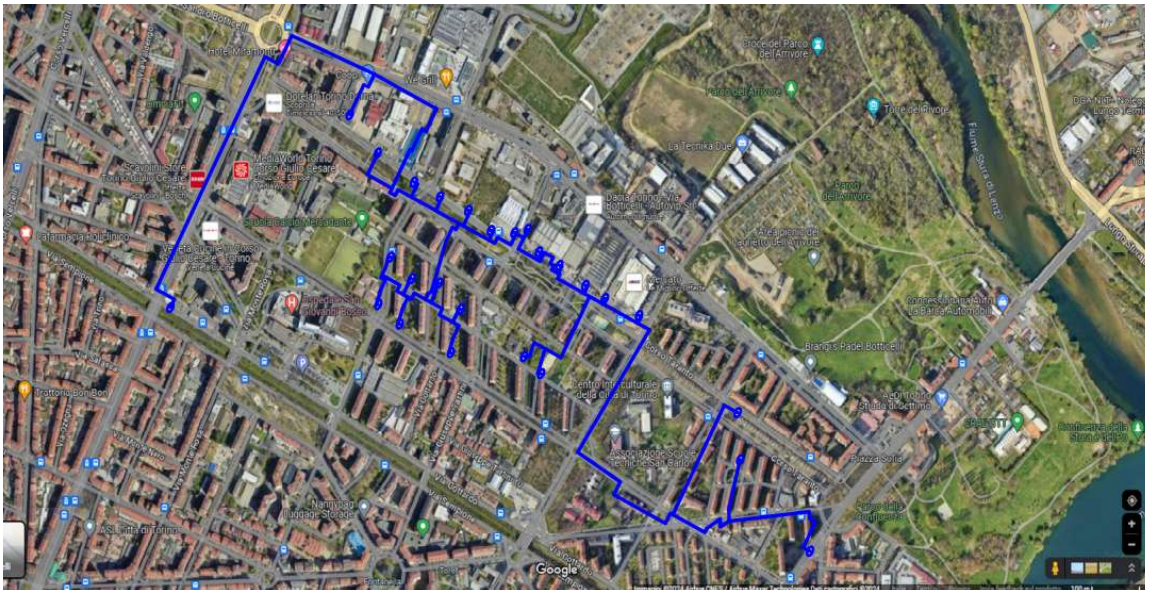


Figure 5. 1 Turin District Heating Network [177]

To partially meet the thermal demand for domestic hot water (DHW), several buildings are equipped with flat plate solar collectors that were installed in 2012. In total, there are sixteen similar buildings housing 652 residential units, all fitted with these solar collectors. Ten of these buildings have 30 solar collectors oriented southeast, inclined at 30° to the horizontal plane, which together cover an area of approximately 77 m². In contrast, six buildings are equipped with 36 solar collectors oriented east, also inclined at 30°, providing a total installed area of about 92 m². The present work analyzes one of these substations, which incorporates a heat exchanger between the network and the end-user. The current setup features a heat exchanger that serves both SH and DHW, along with a storage system comprising five thermal tanks dedicated solely to DHW as shown in Figure 5. 2, which presents a photograph of the substation facility observed in Turin.

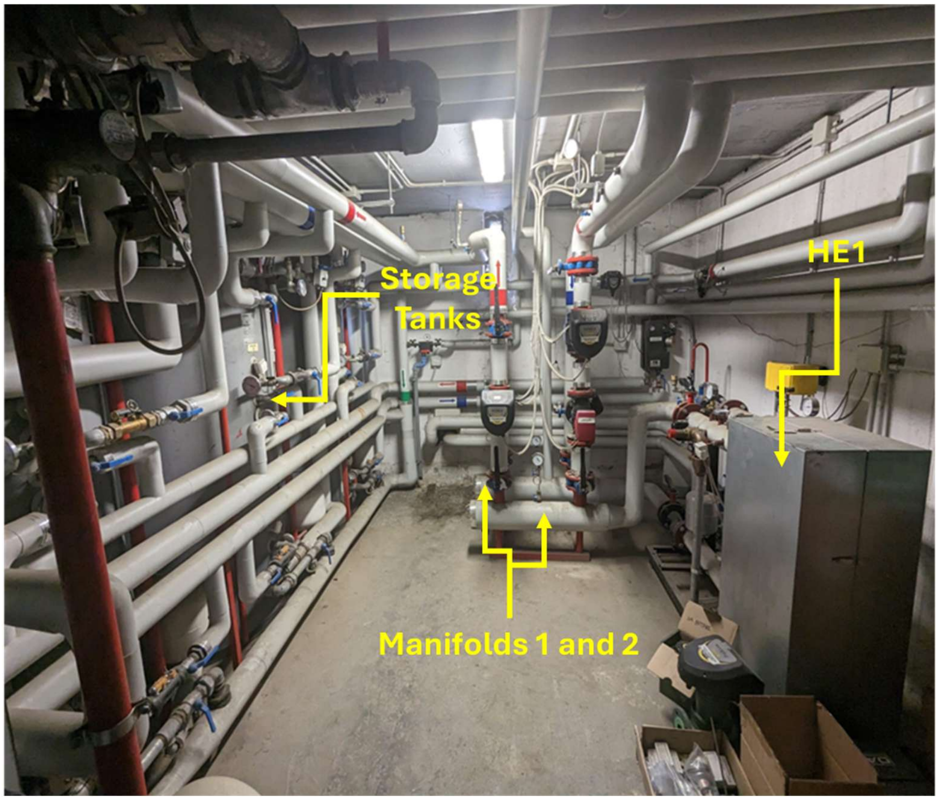


Figure 5. 2 Substation room photography

A portion of the thermal load for DHW is met by the thermal power generated from solar collectors installed on the building's roof. This solar circuit feeds the heat exchanger located at the bottom of the thermal storage tanks. When solar radiation is insufficient for heating the water, the DHN supplies the necessary thermal energy to achieve the desired temperature within the storage tank. Figure 5. 3 presents a simplified diagram of the substation currently part of the DHN in Turin. The diagram highlights only the essential components to the interaction between the DHN and the end-user, outlining three main circuits:

- The primary circuit connected to the supply pipeline (in red) and the return pipeline (in blue) of the main DHN, allows heat to be transferred from the main DHN to the secondary circuit through the HE1, satisfying the user load.
- The secondary circuit allows heat to be transferred from HE1 to the user’s SH circuit and the upper heat exchanger of the DHW tank.
- The tertiary circuit allows heat to be transferred from the local production (solar collectors) to the lower heat exchange of the DHW tank.

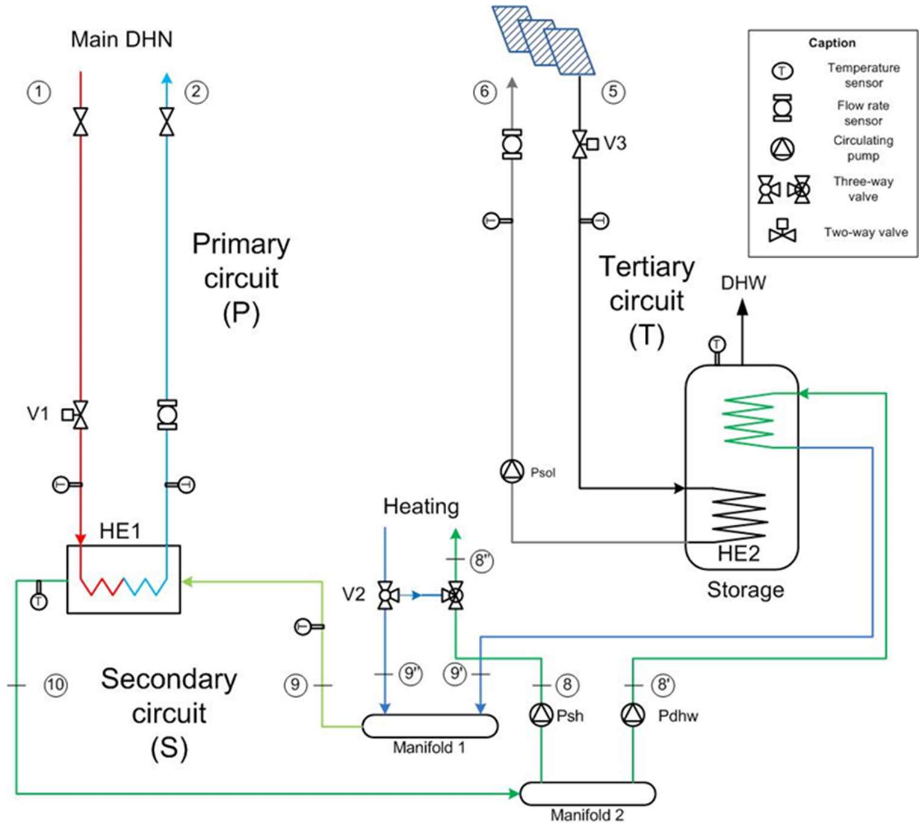


Figure 5. 3 Current substation layout

The substation control is achieved through a thermo-electric system based on flow and is managed by valves and circulators in the various circuits. In particular,

The V1 valve fully opens (on/off) if:

- Heating season (October 15th-April 15th): 6-22
- Storage temperature (= T_{tank}) < 70°C

The V2 mixing valve which regulates the flow temperature to the user based on the external temperature through the climate control.

The V3 valve fully opens (on/off) if:

- T_{tank} < 70 °C and Solar temperature (=T_5)> T_{tank} + ΔT (5°C)

5.2 Retrofit design for bidirectional substation

This paragraph describes the retrofit performed on the existing substation in order to obtain the bidirectional set up and share the unused solar thermal power with the network. For the retrofit of the current configuration, some limits have been considered. In particular:

- The inability to act on the main DHN branch outside the substation room requires operating in a limited space.
- The control logics of the existing valves (described in the previous paragraph) have not been modified.

Figure 5. 4 shows the new layout of the substation with the retrofit components highlighted in orange. The layout includes an additional heat exchanger (HE3) in a "supply to return" configuration. The fluid is taken from the supply line of the primary circuit and reintroduced into the return line at a higher temperature after exchanging thermal power with solar collectors. When the solar collectors produce more thermal power than required by the DHW demand, the substation allows – if temperature levels permit – to transfer this surplus to the grid through heat exchanger HE3.

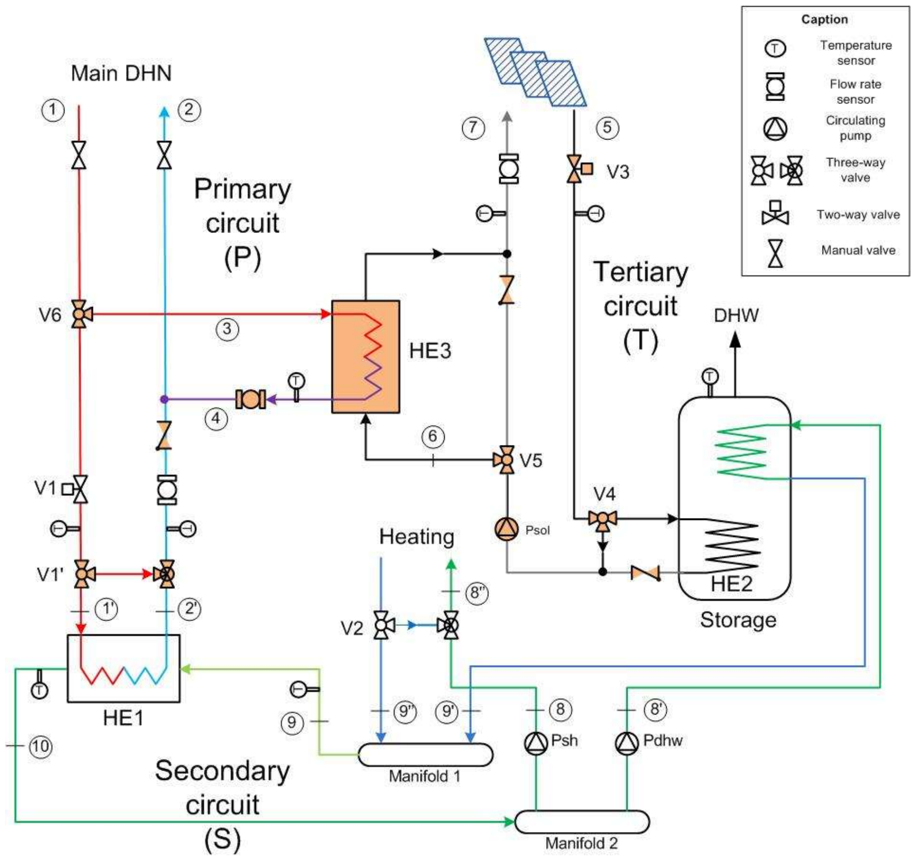


Figure 5. 4 Bidirectional substation layout

Compared to the unidirectional configuration, the installation of new valves and the implementation of new control strategies have been proposed. In particular:

Valve V1' regulates the flow from the supply branch of primary circuit to HE1, based on the temperature in section 10. This is done in order to maintain a constant value of the supply temperature ($T_{10} = T_{10,obj}$) through PID control. In detail:

- if $T_{10} > T_{10,obj}$, it diverts the fluid, bypassing HE1;
- if $T_{10} < T_{10,obj}$, valve V1' increases the flow sent to HE1;
- if $T_{10} = T_{10,obj}$, valve V1' maintains its current opening position;
- if valve V1 is closed, then V1' does not work.

The V3 valve fully opens (on/off) if:

- $T_{tank} < 70$ °C and Solar temperature ($=T_5$)> $T_{tank} + \Delta T$ (5°C)

or

- T_5 > supply temperature + ΔT (5°C)

Valve V6 deviate the flow from the supply (primary) branch to heat exchanger HE3:

- if T_6 > supply temperature + ΔT (5°C), valve V6 diverts the flow sent to HE3;
- if T_6 < supply temperature + ΔT (5°C), the valve closes.

The V4 and V5 valves instead follow the same control logic as V6, working simultaneously. To avoid intermittent on/off cycles of heat exchangers HE1, HE2, and HE3, and hysteresis of 2 °C is added to the nominal control value used for activation.

In the next sections, the workflow of the analysis, as illustrated in Figure 5. 5, will be further detailed, focusing primarily on the numerical modeling approach. The goal was to develop a dynamic simulation model of the bidirectional substation to evaluate its performance under different operating conditions. Experimental tests conducted by EURAC Research at their laboratories provided essential input data for this process, and the collaborative approach facilitated the energy validation of the model, thereby testing and enhancing its robustness. While the experimental phase played a supportive role, the core of the analysis remained focused on the development of the numerical model and the simulations carried out in Dymola. The following sections will provide a comprehensive description of the tested prototype, as well as a detailed analysis of the numerical model and the associated results.

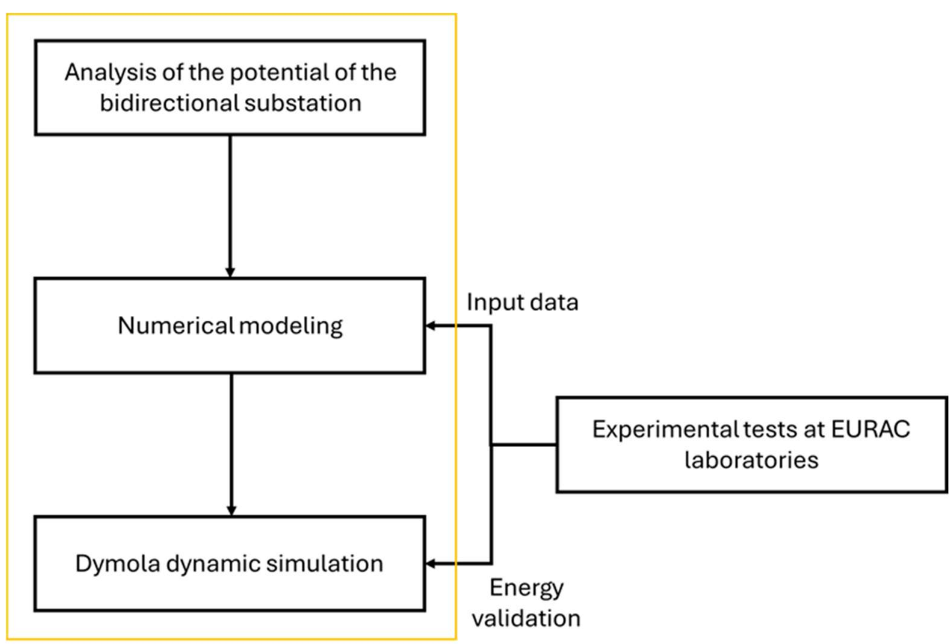


Figure 5. 5 Workflow of the bidirectional substation potential analysis

5.3 Experimental campaign: insights into the bidirectional substation prototype

In recent years, ENEA, in collaboration with the University of Bologna, has developed a prototype of a bidirectional substation that was tested in various configurations at the EURAC laboratory in Bolzano. However, this substation was originally designed for new installations in emerging networks, featuring a different layout compared to the one presented in the previous paragraph. Consequently, the existing prototype has been modified to replicate the layout of the Turin network, allowing for the analysis of the substation's performance in a retrofit setup. Figure 5. 6 provides an illustration of the 3D CAD drawing, while Figure 5. 7 display photographs of the substation interior and its connection to the Energy Exchange Lab through flexible pipes. The substation is designed and constructed for outdoor use, with external dimensions of 3.15 m in length, 1.90 m in height, and 1.10 m in width

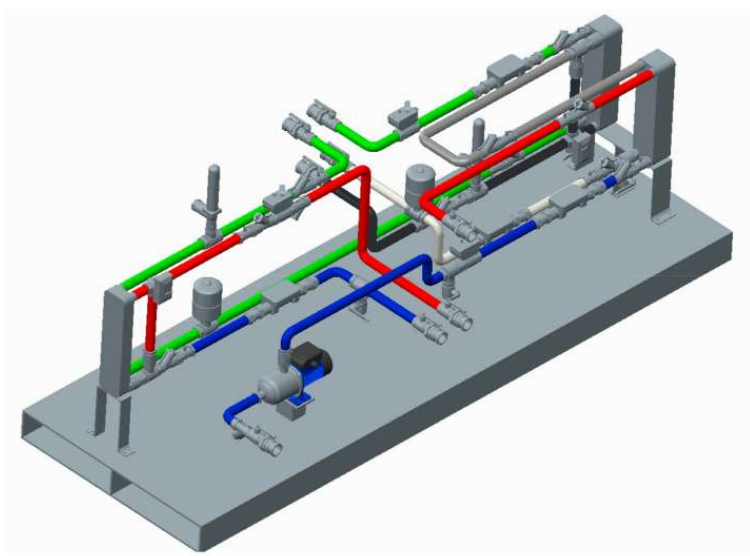


Figure 5. 6 CAD 3D drawing of bidirectional substation prototype [152]

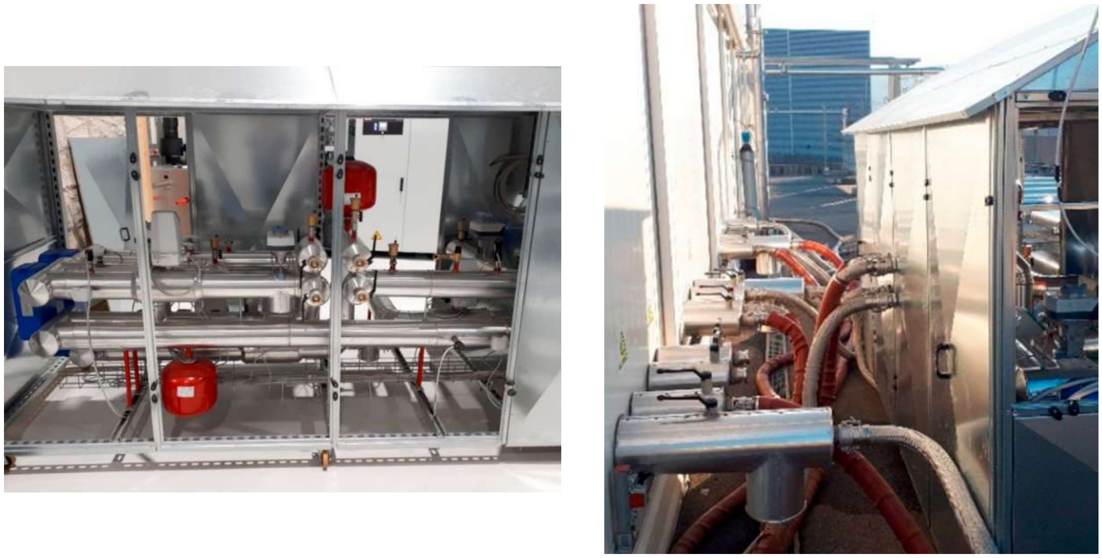


Figure 5. 7 Inside the substation and hydraulic connection to the Energy Exchange lab [152]

The new experimental campaign, conducted at the Energy Exchange Laboratory of EURAC Research, was structured in multiple phases. Phases A to D primarily focused on increasing thermal self-consumption on site. Phase E, subdivided into Phase E1 and Phase E2, focused on the analysis of the substation in the Turin configuration in bidirectional setup. In both phases, the prototype was modified by integrating a 500 L dual-coil thermal storage tank. The lower coil of the tank was connected to the heat exchanger HE2, while the upper coil was connected to HE1. This modification was crucial in replicating both the Turin network layout and the numerical model developed in Dymola, based on the "supply-to-return" configuration. The distinction between the two phases lies in the type of solar collectors used: Phase E1 involved flat-plate solar collectors, while Phase E2 focused on evacuated tube collectors. In both cases, the bidirectional substation was hydraulically connected to the testing facility, which is equipped with a small-scale District Heating Network (DHN). This setup allowed independent control of flow rates and inlet temperatures at four connection points: district heating supply and return, user return, and solar generator supply. Thermal loads from end-users and solar production profiles were dynamically simulated using numerical models, coupled with the entire system in hardware-in-the-loop (HIL) mode, as illustrated in Figure 5. 8, which presents a simplified schematic of the HIL setup.

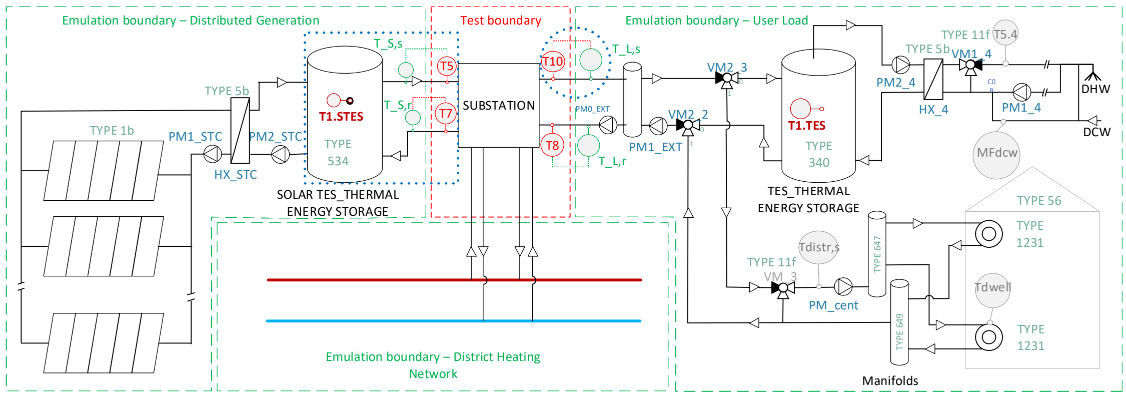


Figure 5. 8 Hardware In the Loop configuration [154]

TRNSYS was the dynamic simulation software utilized to emulate building loads and solar collector generation. Input data for the simulation model were provided by the substation, which measured temperature and flow rate at each data acquisition interval. This setup allowed for real-time coupling of the substation with the building and solar generation models, facilitating the assessment of performance, management, and control characteristics under various operational and dynamic conditions. Table 5. 1 shows the nominal values of main control variables while Table 5. 2 shows the operating temperatures for phase E.

Table 5. 1 Nominal values of main's substation control variables

Control Variable	**Nominal Value**
Solar system flow rate (M5&M7)	3 m^3/h
Flow rate from DHN to HE1 (M1&M2)	1.8 m^3/h
User flow rate (M9&M10)*	4.7-3.7-1 m^3/h
User supply temperature	Variable
Control Variable	Nominal Value
Storage Tank Volume	500 L

* Differentiated by type of load. The three values respectively represent the flow rate when there is a simultaneous request for heating and DHW storage loading, in case of heating only and in case of DHW loading only.

Table 5. 2 DHN temperatures of tested days

	Supply	**Return**
Thermal season (DHW + SH)	80 °C	60 °C
Out of the thermal season (only DHW)	70 °C	50 °C

To evaluate the annual performance of the substation, six representative non-consecutive days were chosen to capture variations in weather conditions during winter and spring, in accordance with the procedure outlined by [178]. Table 5. 3 presents the selected test days, along with their average ambient temperatures, average horizontal surface irradiance, and the number of days associated with each considered cluster.

Table 5. 3 Characteristics of test days

Test days	Average daily temperature [°C]	Average daily radiation on the horizontal surface [W/m²]	Number of days in the cluster
5 January (test 1)	3.7	63	83
21 March (test 2)	9.9	156	42
9 April (test 3)	15.8	243	47
24 May (test 4)	20.1	153	67
1 August (test 5)	24.4	287	74
5 November (test 6)	10.1	58	52

Table 5. 4 presents the energy results from the experimental campaign carried out for Phase E, with a particular focus on the distinction between Phase E1 and Phase E2. For the latter, only two days of testing were considered. The table shows the amount of energy drawn from the DHN to meet the demand for DHW and space heating SH. Additionally, it highlights the amount of useful energy derived from the solar system, distinguishing between the energy self-consumed through the storage tank to cover DHW needs and the energy fed back into the network through the new bidirectional setup. These results provide a clear overview of the system's energy performance and the efficiency of solar integration in both phases.

Table 5. 4 Energy results of the phase E

Test days	Energy form DHN [kWh]	Solar useful energy [kWh]
1 E1	30.9	19.1
1 E2	30.6	134.1
2 E1	36.8	31.7
3 E1	26.5	181.6
3 E2	25.3	341.5
4 E1	36.9	27.3
5 E1	29.9	227.3
6 E1	38.6	10.6

The experimental data collected during Phase E1, with flat-plate solar collectors, was instrumental in the development and validation of the numerical model in Dymola, in terms of energy performance. This data ensured that the model closely aligned with the real-world behavior of the system, providing a robust foundation for future simulations and applications.

5.4 Methodological approach: Numerical Modeling

To develop and simulate the numerical model of the bidirectional substation, Dymola software was utilized, employing the open-source Modelica and IBPSA libraries. A brief overview of the components utilized for modeling the bidirectional substation is provided, while a detailed description of the existing components is presented in section 2.3. To facilitate connections between essential devices and components within the substation, *StaticPipe* models were implemented. For modeling boundary conditions, the *MassFlowSource_T* (mass flow source model) and *Boundary_pT* (model for prescribing pressure and temperature) were employed. In terms of sensors, *TemperatureTwoPort* (temperature sensor) and *MassFlowRate* (mass flow rate sensor) were incorporated. A key component in the design of the bidirectional thermal exchange substation is the heat exchanger, responsible for transferring thermal power between different fluid flows. The ConstantEffectiveness model from the IBSA Fluid library was used to represent this heat exchanger, operating at a constant efficiency. To model and characterize the valves of the substation, the *ThreeWayValveLinear* from the IBPSA library was utilized. In one scenario, the valve regulates the flow rate entering HE1, while in another scenario, it diverts the flow rate from the supply branch of the primary and tertiary circuits toward HE3. A PI regulator controls the valve's opening until the set-point temperature is achieved, and to configure the diverter mode, the flows through the three fluid ports were reversed compared to the standard model.

5.4.1 Tank model with double internal exchange

A crucial element in the development of the bidirectional substation is the storage tank with a double internal heat exchanger. This component is essential for the production of DHW through thermal exchange between the fluid in the tank and the hot flow coming from the supply of the secondary circuit, or from the hot flow generated by the installed solar collectors. Within the Fluid sub-library of IBSA, the most suitable model for this purpose is the *StratifiedEnhancedInternalHex*, which is a storage tank with an integrated heat exchanger. This model includes fluid ports connected to the heat exchanger, allowing the passage of a fluid that transfers thermal power to the stored fluid, similar to a storage tank connected to a solar system. The heat exchanger is configured with an internal flow through a helical coil and a static external fluid, as shown in Figure 5. 9. The parameters describe heat transfer under nominal conditions and the external geometry of the exchanger. This information is used to determine the value of hA for each side of the coil, calculating the heat transfer between the heat exchange fluid and the fluid in the tank through convection.

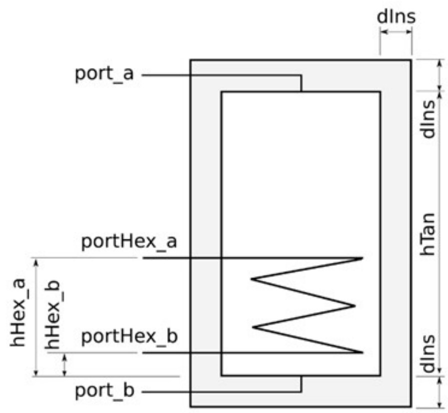


Figure 5. 9 StratifiedEnhancedInternalHex layout [179]

The position of the heat exchanger is parameterized using hHex_a and hHex_b to indicate the heights of the fluid ports a and b, measured from the bottom of the tank. These parameters also determine segHex_a and segHex_b, which represent the segment numbers of the fluid in the tank to which the heat exchanger ports are connected. Optionally, this model calculates a dynamic response of the heat exchanger using the parameters EnergyDynamicsHexSolid, EnergyDynamicsHex, and massDynamicsHex. These parameters approximate the fluid volume and the thermal capacity of the heat exchanger wall (CHex), both dependent on the length (lHex) of the exchanger. The geometry of the heat exchanger is calculated assuming a cylindrical steel exchanger with a diameter equal to half that of the tank (Equation 5.1), and the length of the hex is approximated as shown in Equation 5.2.

$$\mathrm{rHex} = \frac{\mathrm{rTan}}{2} \tag{5.1}$$

$$\mathrm{lHex} = 2 \cdot \mathrm{rHex} \cdot \pi \cdot \mathrm{h} \tag{5.2}$$

where h is the distance between the inlet and outlet of the heat exchanger. To fully understand the operating logic of the present model, it is essential to refer to the inherited classes that extend it: StratifiedEnhanced, PartialStratified, PartialTwoPortInterface, and PartialTwoPort. PartialTwoPort is a partial model that defines an interface for components with two ports, while PartialTwoPortInterface is the component that defines the interface for models that transport a fluid between two ports. PartialStratified is a partial model of the StratifiedEnhanced tank that warrants further elaboration. The latter is a stratified tank for thermal energy storage, divided into several fluid segments numbered from highest (segment 1) to lowest, as illustrated in Figure 5. 10. The model manages heat conduction between the segments through the contained fluid, as well as between the segments and the external environment. Thermal ports, located outside the tank's insulation, allow for the regulation of ambient temperature. In the absence of connections to these ports, adiabatic boundary conditions are applied.

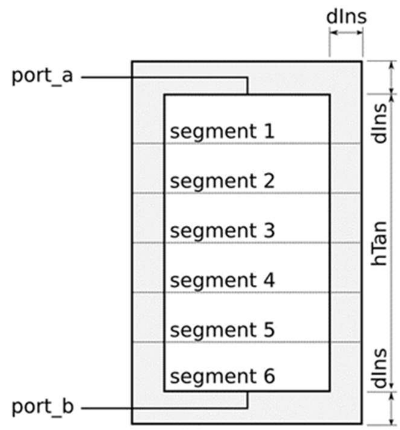


Figure 5. 10 StratifiedEnhancedInternalHex layout segmentation [179]

However, the tank model with an internal heat exchanger is insufficient for simulating the behavior of the bidirectional substation, as it lacks the second coil for supply from the district heating network. Therefore, a new component has been implemented that inherits the same classes as the *StratifiedEnhancedInternalHex* to enable the simultaneous operation of the solar thermal panels and the network for hot water production within the substation model. Specifically, two fluid ports, named a1 and b1, have been integrated into the model for the new heat exchanger, indTanHex1. This was achieved by directly modifying the model's code to define new variables identified with the subscript 1. Additionally, a new representative icon for the new component has been created, as shown in Figure 5. 11.

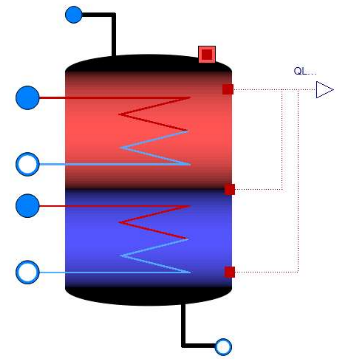


Figure 5. 11 New tank model icon

Figure 5. 12 and Figure 5. 13 illustrate the models corresponding to the StratifiedEnhancedInternalHex and the new tank model with a double heat exchanger, respectively.

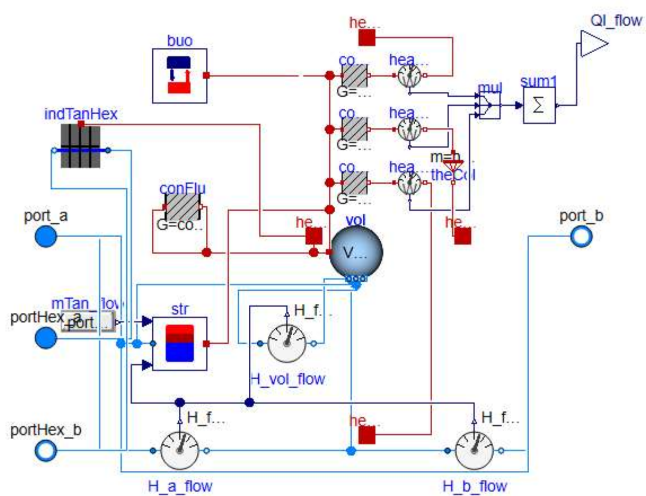


Figure 5. 12 StratifiedEnhancedInternalHex Dymola model

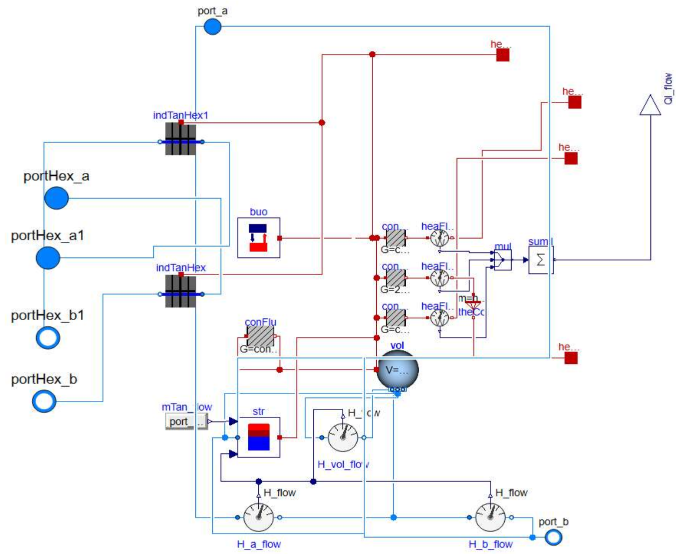


Figure 5. 13 Double Internal Exchanger Dymola model

5.4.2 Bidirectional substation model

The dynamic model of the bidirectional substation for district heating networks in summer configuration is shown in Figure 5. 14. As described previously, all components are sourced exclusively from the Standard Modelica and IBSA libraries or have been specifically created based on components from these libraries. Similar to the layout of the bidirectional substation depicted in the figure, the same colors have been used to represent the branches of the primary, secondary, and tertiary circuits, while dashed lines represent control signals. The dynamic tests consist of simulations carried out by dynamically varying the DHW and/or changing the production profile from the solar generation system; therefore, all necessary control systems have been implemented. Within the control logic, to avoid warning and error situations due to possible fluctuations around the calibration value during the simulation, hysteresis schemes have been adopted. In the model developed in Dymola, a data table is used as an input signal to set boundary conditions that change dynamically over time. The table has two columns: the first column records time in seconds, and the second column records the value of the quantity to be varied.

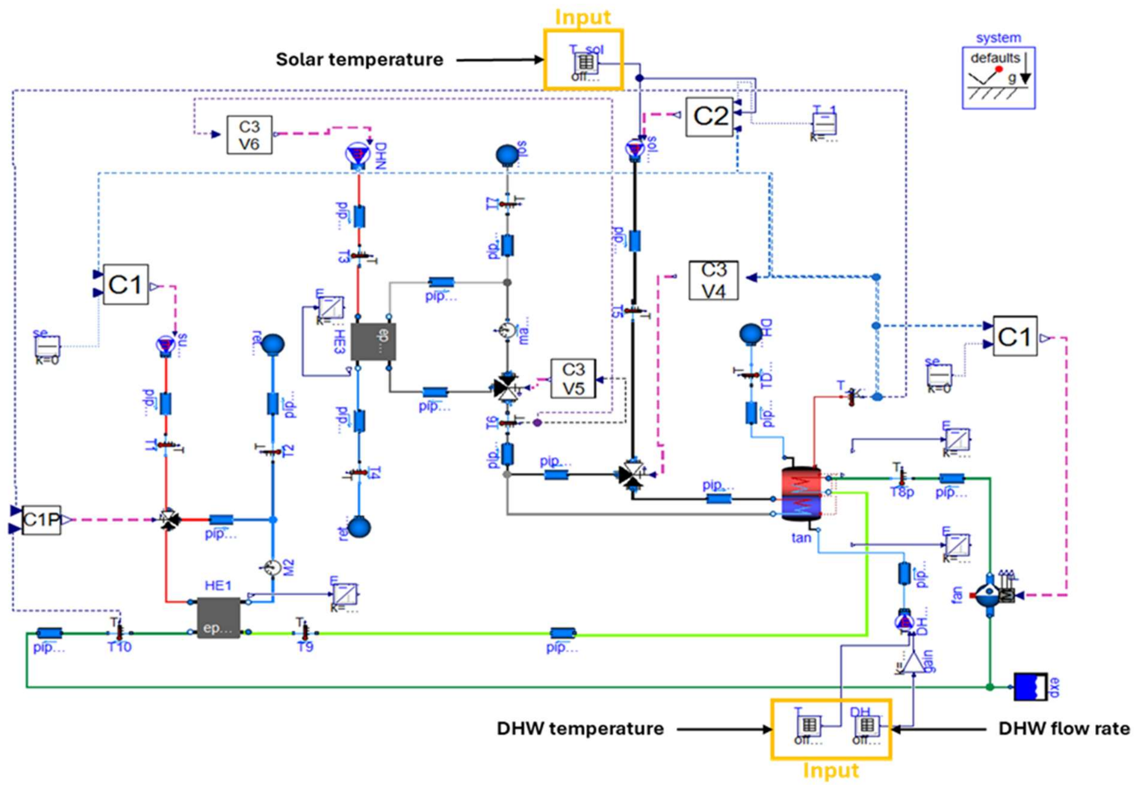


Figure 5. 14 Bidirectional substation Dymola model

The control logics were developed based on the descriptions in the previous chapter, but they have been adapted to the dynamics of the components, focusing on the operational configuration of the substation as determined by the implemented control system. Among the valves mentioned in the previous chapter, only a few were necessary for the development of the numerical model: the three-way valve V4, which diverts the fluid and bypasses the storage tank, and the three-way valve V5, which directs the flow to the heat exchanger HE3. The other controls, managed by the two-way valves V1 and V3, the three-way valve V4, and the pump Pdhw, were implemented by directly adjusting the boundary conditions in sections 1, 3, and 5. The following control logics were confined within control blocks equipped with inputs to receive signals from the reference sensor and outputs to send signals to the corresponding valve or section. The 'switch' component (Figure 5. 15) used in all control blocks assigns y = u1 if the input boolean signal (in fuchsia) is true; otherwise, it assigns y = u2.

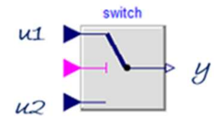


Figure 5. 15 Switch Dymola component

5.4.3 Control blocks

C1 control block

Figure 5. 16 shows an exploded view of control block C1, along with its various components. The control block C1 performs the function of both valve V1 and the circulation pump Pdhw. Specifically, if the heating season is in effect (from October 15 to April 15, between 9:00 and 22:00), or if the temperature of the water in the tank (Ttank) falls below its set point, the flow is drawn from the district heating network supply. As previously mentioned, a hysteresis scheme of 2°C (68–70°C) is applied to mitigate significant fluctuations in the water temperature within the storage tank. The same control block is also used to manage the circulation pump, which sends the secondary supply flow to the upper coil of the storage tank when the tank water temperature is below the set point value.

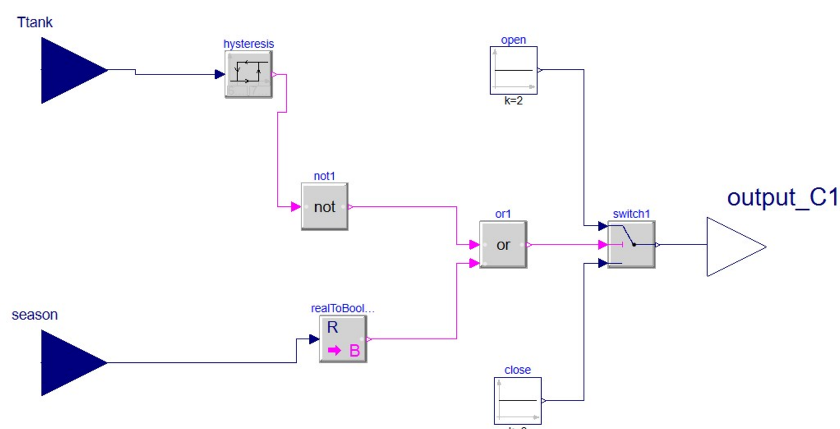


Figure 5. 16 C1 control block model

C2 control block

Figure 5. 17 shows an exploded view of control block C2, along with its various components. The control block C2 serves the function of valve V3. Specifically, if the solar supply temperature (T5) is greater than the tank temperature (Ttank) by more than 5°C, and the water temperature in the tank is below the set point value, or if the solar supply temperature (T5) is greater than the district heating supply temperature (T1) by more than 5°C, then the nominal flow from the tertiary circuit is drawn.

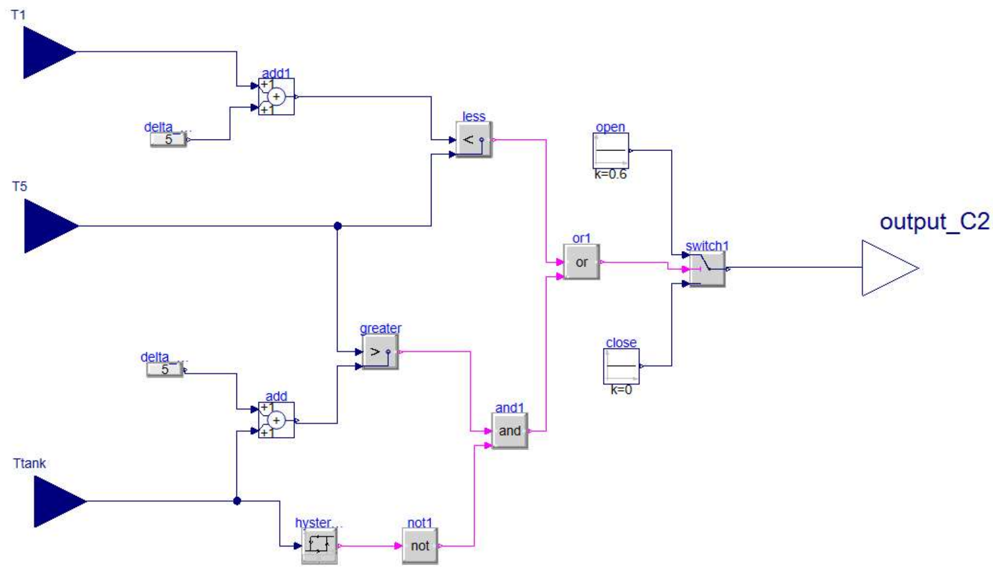


Figure 5. 17 C2 control block model

C3_V4 control block

Figure 5. 18 provides an exploded view of control block C3_V4, illustrating the key components involved. The control block C3_V4 sends a signal to the three-way valve V4, which redirects the flow to bypass the storage tank when the tank has reached its set point temperature (Ttank = T set point).

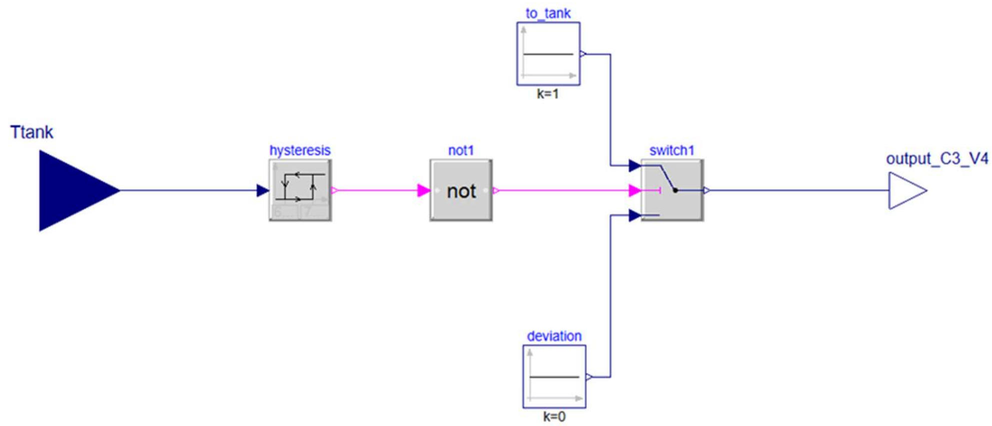


Figure 5. 18 C3_V4 control block model

C3_V5 and C3_V6 control blocks

Figure 5. 19 presents an exploded view of the control blocks, illustrating their interaction with the three-way valve V5. These control blocks, which receive the same input, send a control signal to valve V5, which redirects the flow of the tertiary return to heat exchanger HE3 and section 3, while simultaneously directing the primary flow to heat exchanger HE3. This configuration occurs when the temperature of the generation system, possibly after exchanging thermal energy with the storage tank (T6), exceeds the district heating supply temperature (T1) by 5°C. This mechanism ensures efficient thermal management by prioritizing the heat exchange process when the system temperature surpasses that of the district heating network.

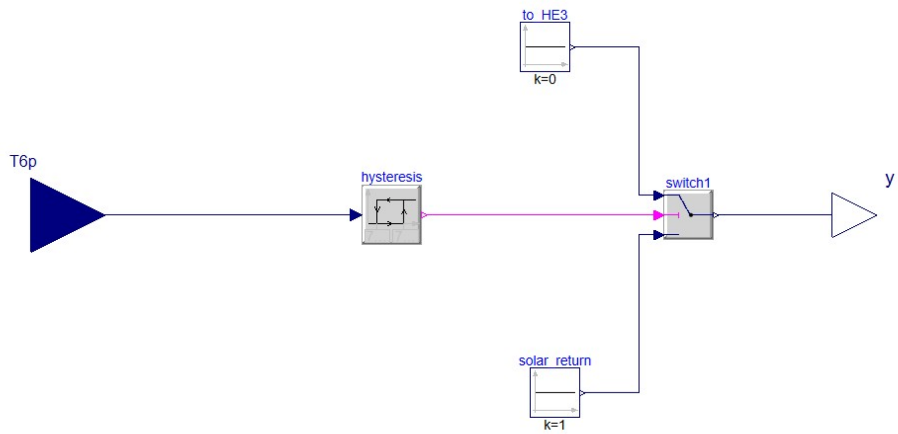


Figure 5. 19 C3_V5 and C3_V4 control block models

5.4.4 KPIs & Scenarios

The configuration conditions, including the input data, were based on a prototype of a bidirectional substation, which was tested at the Energy Exchange Laboratory of Eurac Research. For more detailed information regarding the prototype's specifications and experimental setup, please see [152]. To assess the substation's performance, two representative, non-consecutive days were selected to capture variations in weather conditions, following the procedure outlined in [178]. Table 5. 5 presents the selected test days, their average ambient temperature, average horizontal irradiance, and the number of days in each cluster analyzed.

Table 5. 5 characteristics selected test days

Test days	**Average daily temperature [°C]**	**Average daily radiation on the horizontal surface [W/m²]**	**Number of days in the cluster**
24 May	20.1	153	67
1 August	24.4	287	74

For the comparative analysis of the test days, key performance indicators (KPIs) were calculated daily. These include the self-consumption (SC), which measures the percentage of locally produced thermal energy consumed on-site (Equation 5.3); the self-sufficiency (SS), which reflects the proportion of thermal demand met by local production (Equation 5.4); and the useful energy coefficient (Uec), indicating the percentage of locally generated thermal energy utilized by the user or fed into the grid (Equation 5.5).

$$S_C = 100 \cdot \frac{E_{DG\ to\ user}}{E_{DG}} \tag{5.3}$$

$$S_S = 100 \cdot \frac{E_{DG\ to\ user}}{E_{User}} \tag{5.4}$$

$$U_{ec} = 100 \cdot \frac{E_{DG\ to\ user} + E_{DG\ to\ DHN}}{E_{DG}} \tag{5.5}$$

Where, E_{DG} represents the energy produced by distributed generation, $E_{DG\ to\ DHN}$ refers to the energy generated by distributed systems and fed into the district heating network, $E_{DG\ to\ user}$ indicates the energy produced and consumed by the end-user, and Euser represents the thermal load for the end-user.

5.5 Results & Discussion

To dynamically test the model, daily simulations were performed for the two days described in the previous section. Figure 5. 20 and Figure 5. 21 show the water temperature in the tank in relation to solar temperature, the DHW flow rate requested by the user, and the power exchanged in the heat exchangers HE1, HE2, and HE3, respectively, for the mid-season and summer days. Looking more closely at Figure 5. 20, the first graph at the top displays the solar circuit temperature in orange and the tank water temperature in black, which is evidently influenced by the DHW demand, shown in the second graph in fuchsia. Aside from the initial moments of the simulation, where the starting tank temperature was set to 20°C, there are temperature drops corresponding to DHW requests. According to the control logic described earlier, thermal exchange with the DHN (via HE1) or with the solar collectors (via HE2) occurs when the water temperature in the tank falls below 60°C, which is the selected set point, considering a hysteresis of 2/3°C. Looking at the power exchanged in HE1, represented in blue, it can be observed how its trend follows the tank water temperature. As for HE2, shown in green, it can be seen that only at two points during the day is there both solar energy available and a simultaneous request of thermal power: around 11:00 am, when there is a temperature drop due to DHW demand, and at 3:30 pm, when there is no DHW demand, but the tank water temperature drops below 59°C due to thermal losses. It is also evident that most of the solar power is not used for local self-consumption but, thanks to the bidirectional setup, is fed into the network through HE3 (red line), as the temperature is high enough to exchange with the supply line of the primary circuit.

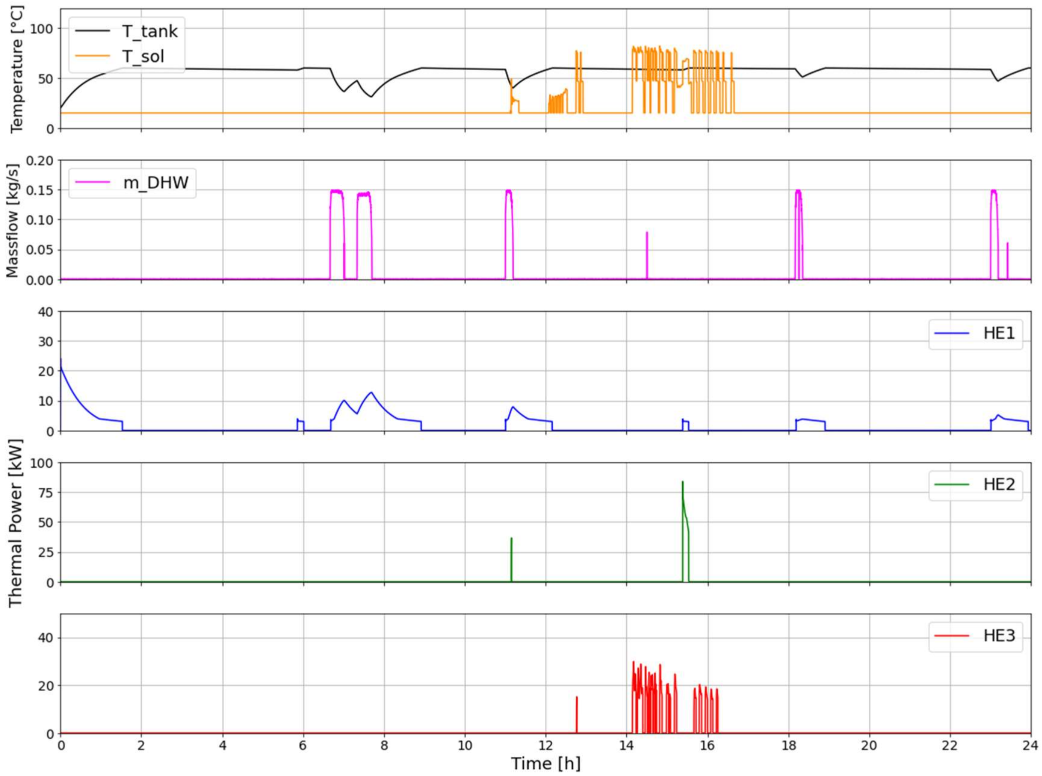


Figure 5. 20 24 May: tank and solar temperature, flow rate required for the DHW, power exchanged in HE1, HE2, HE3

Similar considerations can be made when analyzing the summer day in Figure 5. 21, with the main difference being a significantly higher thermal power production from the solar system. However, this does not lead to a substantial increase in self-consumption, as there are only a few moments when both sufficient solar production and thermal demand occur simultaneously: in the early hours of the morning (around 7:30), between 8:00 and 9:00, and around midday. As a result, a large amount of thermal power is fed into the grid through HE3, taking advantage of the bidirectional setup. For both days analyzed, the increased solar production does not lead to a significant rise in self-consumption. This is because the majority of the domestic hot water demand occurs in the early morning and evening hours, when solar production is either insufficient or entirely absent.

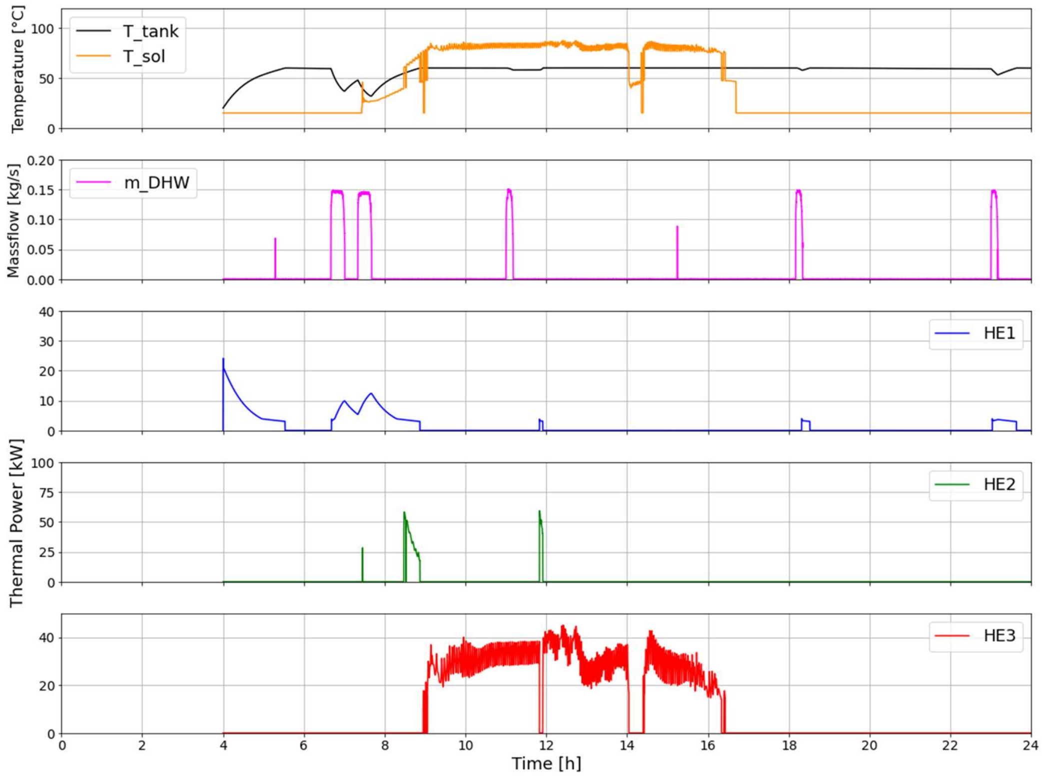
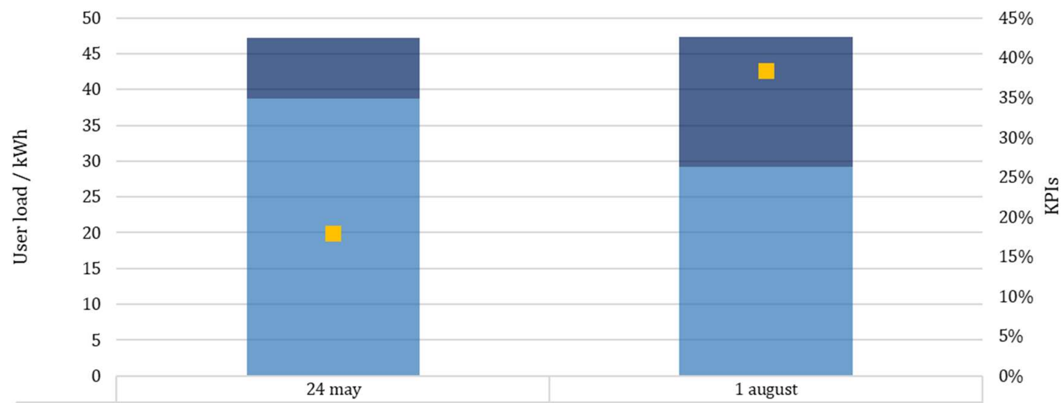


Figure 5. 21 1 August: tank and solar temperature, flow rate required for the DHW, power exchanged in HE1, HE2, HE3

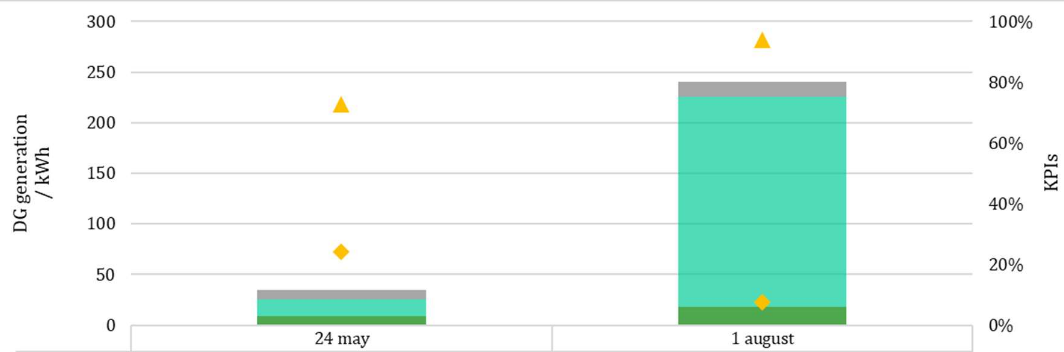
Figure 5. 22 and Figure 5. 23 illustrate the energy flows and KPIs for the mid-season and summer days. Specifically, Figure 5. 22 shows the total daily DHW load, with energy supplied by the network in light blue and energy from the solar collectors in dark blue. It is clear that on both days, the user's load was mainly satisfied by the DHN, particularly in May, where the self-sufficiency rate (Ss)was 18%. This rate increased to 38% in August, due to the significant rise in solar production on that day. Figure 5. 23 show the total daily energy production, with unused energy shown in gray, energy fed into the network in light green, and energy used by the user in dark green. A notable increase in production is observed in August, with a corresponding rise in energy fed into the network compared to May. In both days, the self-consumption rate (Sc), which considered the only energy used by user for DHW remained low, with 24% of the produced energy being used in May and only 8% in August. However, when considering also the energy fed into the network through HE3, the useful energy coefficient (Uec) reaches much higher values, allowing 73% of the energy produced in May and 94% in August to be utilized, significantly reducing unused energy. These results highlight the significant contribution of the bidirectional setup in maximizing the utilization of solar energy, especially in the summer, where

despite low self-consumption, the system effectively feeds surplus energy into the grid, minimizing energy waste and enhancing overall system efficiency.



	24 may	1 august
from DG	8.5	18.1
from DHN	38.7	29.1
Ss	18%	38%

Figure 5. 22 User load energy flows and KPIs



	24 may	1 august
DG not used	9.6	14.3
to DHN	17.0	207.9
to user	8.5	18.1
Sc	24%	8%
Uec	73%	94%

Figure 5. 23 Local generation energy flows and KPIs

5.6 Energy data validation

The energy validation of the model showed a high level of consistency with the experimental results, with minimal discrepancies in the energy flows. Specifically, when analyzing the day of May in Figure 5. 24, the energy drawn from the DHN to meet the DHW demand was slightly higher in the numerical model compared to the experimental prototype. Conversely, the useful solar energy — that is, the energy used locally through HE2 for DHW or fed into the network via HE3 — was higher in the numerical model, with an error of 6.1%. During the day of august in Figure 5. 25, these discrepancies were further reduced, with an error of 2.5% for the energy drawn from the network and 0.6% for the useful solar energy. Some of the differences observed in the useful energy, particularly through the HE2 heat exchanger of the tank, also affect the thermal exchange with HE1. It is important to note that accurately replicating the fluid dynamics of the experimental tank in the numerical model presents inherent challenges. Key factors influencing the accuracy of the tank model include:

- Position of the temperature sensor
- Thermal stratification
- DHW outlet and recirculation inlet placement
- Internal coil geometry

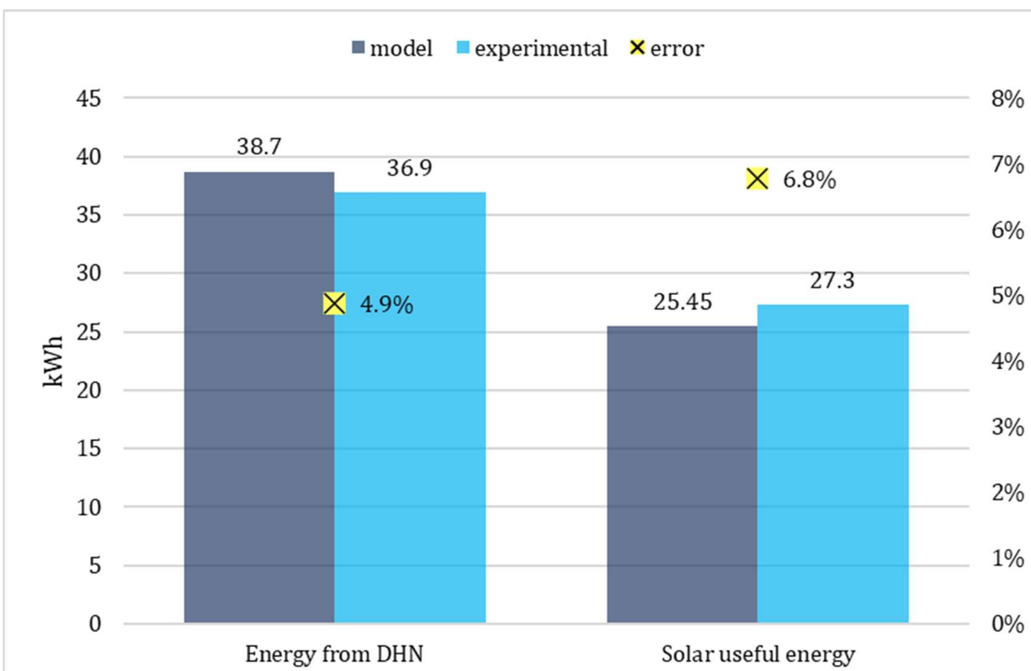


Figure 5. 24 day of 24 may: energy model validation

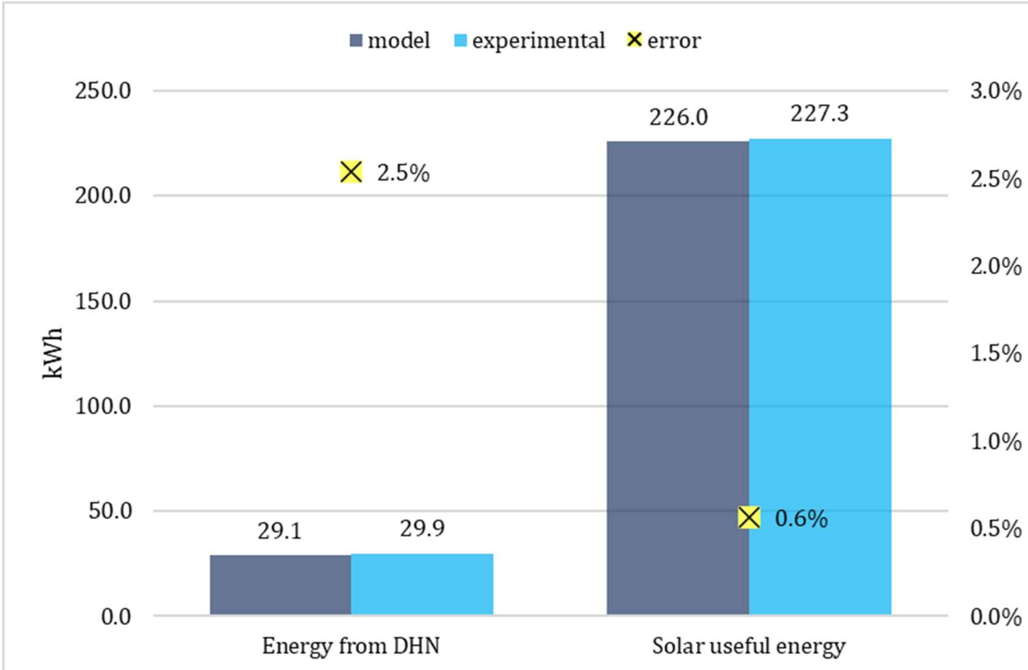


Figure 5. 25 day of 1 august: energy model validation

Despite the inherent challenges in replicating the fluid dynamics and thermal characteristics of the experimental tank, the numerical model achieved a satisfactory alignment with the experimental data. This consistency suggests a solid foundation for further refinement and application in similar contexts.

5.7 Conclusion

Integrating thermal prosumers into District Heating Networks through bidirectional substations enhances the use of renewable energy and promotes thermal energy sharing at the community level. This section presents a method for retrofitting traditional thermal substations, based on existing networks, with bidirectional heat exchange technology. A dynamic model of such a substation was developed and tested under different configurations, simulating two typical days: one in mid-season (May) and one in summer (August), characterized by varying levels of solar irradiation. The results demonstrate that the majority of the DHW demand is predominantly met by the district heating network through the HE1 exchanger, primarily due to the mismatch between user demand and solar production. Since much of the DHW demand occurs in the early morning and evening, the tank's solar heat exchanger HE2 operates below its potential during peak solar production hours. However, the installation of the new bidirectional heat exchanger HE3 allows the surplus thermal energy to be fed into the network, especially in August, where solar production is highest. Overall, the bidirectional setup significantly improves the energy performance of the substation, particularly on days with high solar radiation, where previously much of the energy would have gone unused. In the summer day this optimization increases the self-consumption rate from 8% to a useful energy coefficient of 94%.

CONCLUSION

The transformation of energy systems, driven by the widespread adoption of distributed generation from renewable sources and the rise of prosumers, has introduced significant challenges and opportunities to global energy landscapes. In this evolving context, the concepts of energy sharing and prosumer involvement have gained considerable attention, as users are increasingly able to participate in energy distribution through decentralized grids and systems. In recent years, energy community initiatives have gained significant momentum across Europe as a means of achieving energy transition goals, enabling citizens to engage in the production, consumption, and distribution of energy. In this context, the potential for sharing energy generated by production plants represents a new paradigm for renewable energy generation and usage.

In light of these developments, the European Union introduced two key directives in 2018 and 2019, namely the REDII and IEMD directives. These marked a transformative step in formally recognizing energy sharing projects and promoting collective self-consumption and the establishment of energy communities within European legislation. In particular, following the adoption of the 2018 REDII directive, renewable energy communities and collective self-consumption projects have rapidly expanded across the continent, demonstrating their potential to create sustainable local energy systems.

However, the multidisciplinary nature of this field, which encompasses technical, regulatory, and social aspects, makes it challenging to fully grasp the various approaches researchers take in analyzing and developing these new European entities. To address these challenges and explore key issues related to energy communities, a systematic literature review has been conducted. By focusing on different areas and levels of investigation, the study has identified strengths and limitations in understanding energy communities, a complex subject that requires support from both European and national policies for effective implementation. This has been achieved through the development of a framework to categorize academic literature, analyzing over 100 scientific articles published in journals using Scopus as a search engine. The framework, which has included a set of structural dimensions and analytical categories, has allowed the authors to analyze the evolution and key features of studies on energy communities.

The review has yielded several key insights, showing that these communities have been widely studied from a social and political perspective rather than a technological one, with a strong focus on economic and financial aspects that are critical to their operation. Most studies have focused primarily on electricity, often linked to photovoltaic systems, as national regulatory frameworks have historically promoted electricity-based initiatives through financial incentives. In contrast, studies on communities based on the production and sharing of thermal energy are still quite limited. Energy sharing is a central theme, as the review revealed that the management of these communities mainly revolves around the equitable distribution of the benefits derived from shared energy. Furthermore, it has emerged that most studies focus on individual countries, although comparative analyses between different geographic areas are essential to capture similarities and differences among communities. The development of these models is influenced by regulatory, financial, and management challenges that require appropriate legal and institutional frameworks. In this regard, Italy's early adoption of the EU directives in 2020 has led scholars to test the potential of these policies ahead of other European countries, resulting in the highest number of studies focused on Italy.

Thanks to this experimental regulatory framework, it has been possible to analyze and test the practical application of an energy community in Italy, integrated with a district heating network. The aim was to improve both overall energy performance and economic benefits by maximizing internal energy sharing, which benefits from the new incentive tariff. Specifically, the potential to use excess solar energy from local rooftop photovoltaic installations to power a heat pump has been tested. This system could then provide useful heat to the local district heating network during the winter months. The related scenarios have been compared with the existing network and two relevant alternatives: one considering the use of absorption chillers for summer cooling to maximize the use of cogeneration units, and another considering the simple installation of photovoltaic panels without a heat pump.

The results indicate that the system's performance can be improved with the proposed design, leading to significant reductions in energy demand, emissions, and system costs: compared to the reference case, the use of photovoltaics reduces primary energy demand by approximately 11%, while the addition of the energy community configuration allows for an emissions reduction of nearly 12%, with no additional investments. This study demonstrates how establishing an energy community makes it advantageous to invest in heat pumps, promoting the decarbonization of the district heating network and fully leveraging the incentive tariff on shared energy within the community. However, the economic benefits of shared energy are considered at the community level, rather than the individual level. Consequently, it is difficult to determine the exact benefit for each prosumer. This challenge is due to the fact that Italian legislation, in line with other European countries, has adopted a virtual energy-sharing model, which does not allow for tracking the actual energy exchanges between users. The absence of a unified methodology for the equitable distribution of economic benefits from shared energy poses a challenge, as it does not ensure full transparency and fairness, potentially limiting participant engagement.

This lack of clarity prompted further exploration of the concept of shared energy within a virtual model, aimed at optimizing the allocation of the benefits derived from energy sharing in energy communities. To achieve this, four ad hoc algorithms have been developed for dynamic sharing keys based on participants' contributions to the community: a key proportional to consumption (M1), a key based on the Pearson correlation coefficient (M3) to assess the synchronization between electricity drawn from the grid and the surplus fed into it, a key based on the balance between energy purchased and fed into the grid (M4), and a combination of the previous two keys (M5). A simulated energy community has been created, consisting of eight representative users, using real hourly energy consumption and production profiles. The goal was to conduct an annual comparative analysis of the developed methods and identify the different amounts of shared energy allocated to each user based on their contribution, highlighting strengths and limitations.

The results show that, except for users with higher consumption, methods M2, M3, M4, and M5 tend to distribute energy more evenly among community members. Users with higher annual consumption are favored by method M1, which allocates them a greater amount of shared energy. However, M1 can overestimate the assigned energy, as it does not consider the distribution of consumption hours relative to the hours of energy fed into the grid. It is essential to incentivize those who consume energy when the community produces an excess from renewable sources (M3), encouraging more sustainable behavior. At the same time, users should keep their consumption equal to or lower than the amount of energy available within the community (M4), avoiding increases compared to the previous configuration.

The algorithms developed in this work can also be applied to a thermal energy community, extending the concept of shared energy to thermal flows. Although the REDII directive allows for the sharing of all forms of renewable energy, including thermal energy, studies analyzing energy communities from this perspective are still limited. This is particularly relevant given that thermal and cooling energy consumption in Europe accounts for more than half of the total energy demand, with limited contributions from renewable sources. In this scenario, the concept of efficient district heating, as defined by the European EED directive, is gaining increasing importance, offering a key opportunity to promote the decarbonization of the thermal sector. Active district heating, still relatively underutilized, could play a fundamental role in the development of thermal energy communities. Thanks to its infrastructure, district heating enables the efficient integration of renewable sources and thermal prosumers, who can not only consume but also produce and share locally generated thermal energy with other users connected to the network.

Therefore, this work proposes an innovative approach aimed at establishing a pre-commercial setup for retrofitting traditional substations into bidirectional substations for district heating networks. These devices allow prosumers to actively consume thermal energy for their own needs and to share any surplus with the network. Based on an existing network in northern Italy, an optimized layout in a "supply-to-return" configuration has been proposed. The system includes a heat exchanger between the end user and the network (HE1), which manages space heating and domestic hot water production through a thermal storage unit (HE2), which can also be charged by local generation sources. A second heat exchanger (HE3) allows the excess locally produced thermal energy to be fed back into the network.

To evaluate the performance and potential of the proposed bidirectional device, a detailed numerical model of the substation has been developed using the Dymola software for multi-domain simulations. The model has been designed to analyze the system's behavior under conditions where only domestic hot water (DHW) demand is present, considering both a mid-season day and a summer day. Custom systems and control logics based on standard library models have been used to accurately reproduce the substation's performance under specific conditions. Experimental tests conducted by EURAC Research in their laboratories provided essential input data for this process, and the collaborative approach facilitated the energy validation of the model, enhancing its robustness.

The results show that most of the DHW demand is primarily met by the district heating network through heat exchanger HE1, due to the mismatch between user demand and solar production. Since DHW demand is higher in the early morning and evening, the thermal power exchange between the solar circuit and the storage tank is limited during peak solar production hours. However, the introduction of the new bidirectional heat exchanger HE3 allows excess thermal energy to be fed into the network, especially in the summer months, such as August, when solar production is higher. Overall, the bidirectional configuration significantly improves the substation's energy performance, particularly on days of high solar radiation, where previously much of the energy produced would have been wasted. In the summer, this optimization increases the self-consumption rate from 8% to a useful energy coefficient of 94%. The energy validated by the model showed good consistency with the experimental results, with minimal discrepancies in energy flows. In particular, the useful solar energy in the numerical model was slightly higher than the experimental data, with an error of 6.1% in May and reduced to 0.6% in August, primarily due to challenges in accurately replicating the fluid dynamics of the storage tank.

Overall, this work explores the topic of sharing electrical and thermal energy within energy communities, a field that has recently become crucial in the transition toward decarbonization. The European regulatory framework provides clear guidelines and boundaries for these initiatives, encouraging the growth of energy communities. The aim of this research is to address certain knowledge gaps. First, it examines the scientific community’s approach to these new entities. Next, it assesses the potential of energy communities through case study analysis, aiming to maximize the overall amount of shared energy. The study also delves into the distribution of benefits among individual community members, which is essential for fostering participation and encouraging the expansion of energy communities. Finally, it explores the extension of the concept of energy sharing to thermal flows, laying the foundations for the development of future thermal energy communities, still not widespread in the European context.

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Appendix A

Table A. 1 Main features of energy community members

REC members	Users classification	Prosumer	Description	Consumption [kWh/y]
u1	Hotel	Yes	38 room - 1400mq	109,491
u2	Hotel	No	80 seats	123,869
u3	Hotel	No	100 seats	195,349
u4	Hotel	No	-	130,942
u5	Hotel	No	120 seats	117,674
u6	Hotel	No	120 seats	55,360
u7	Hotel	No	-	52,659
u8	Residence	Yes	160 seats - 40 rooms	84,127

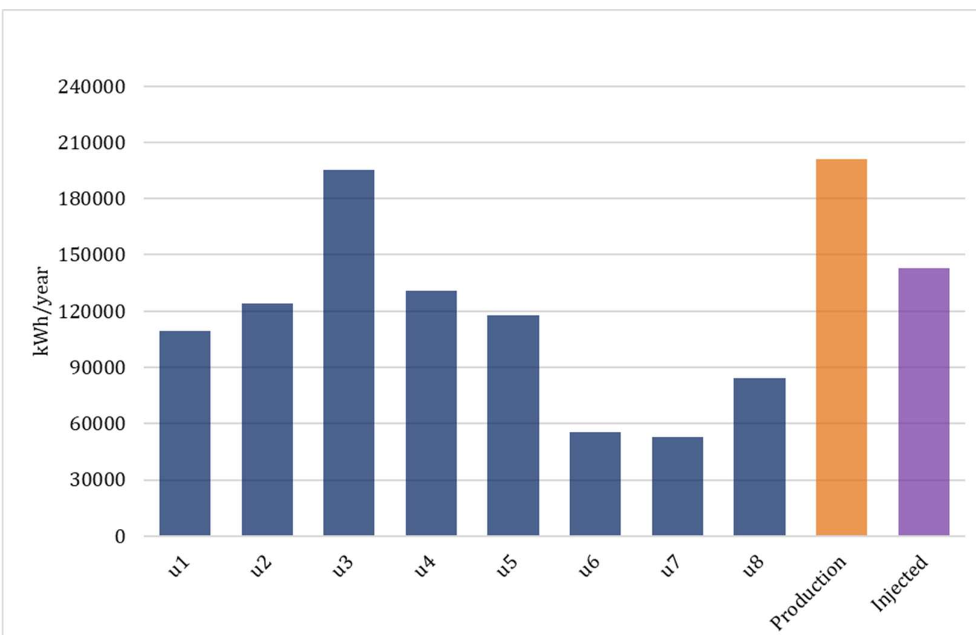

Figure A. 1 EC member's energy flows

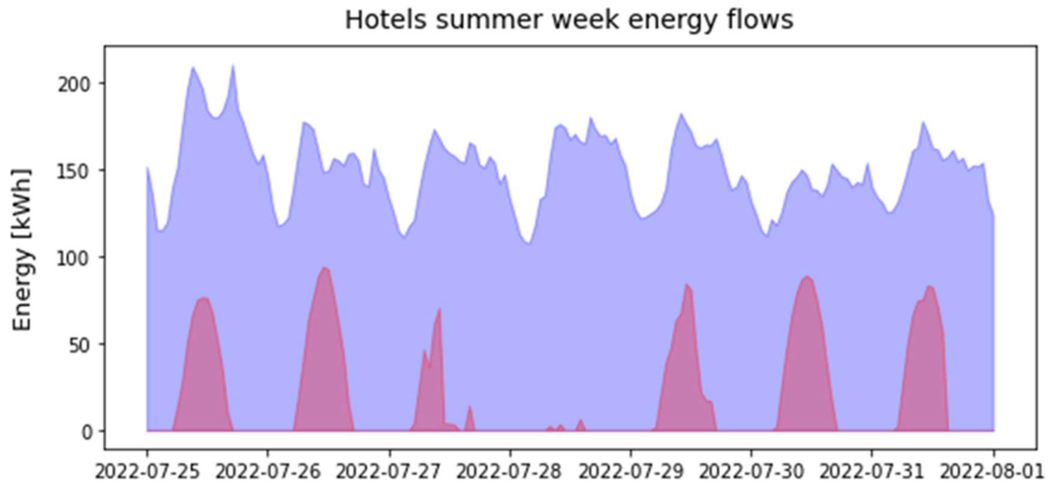

Figure A. 2 Weekly profiles of energy purchased and fed into the grid for all users (summer)

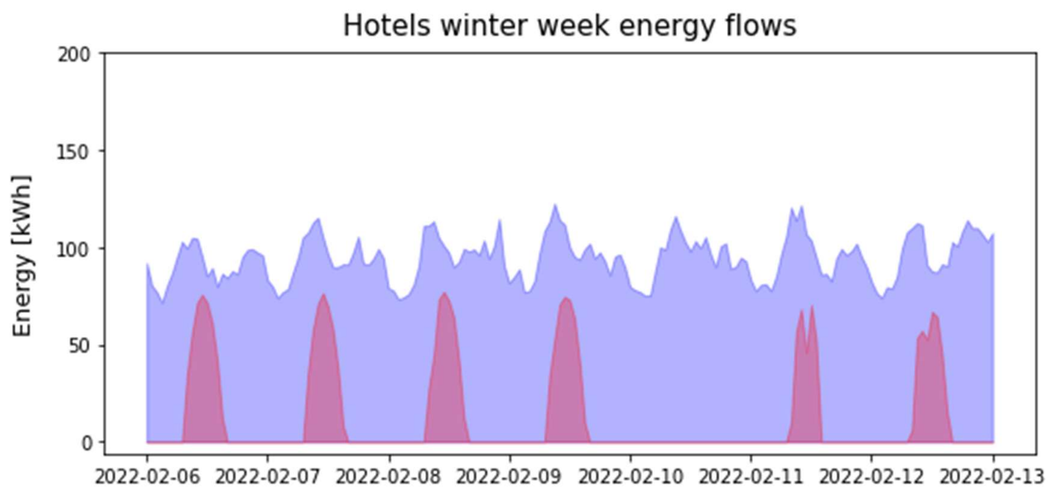

Figure A. 3 Weekly profiles of energy purchased and fed into the grid for all users (winter)

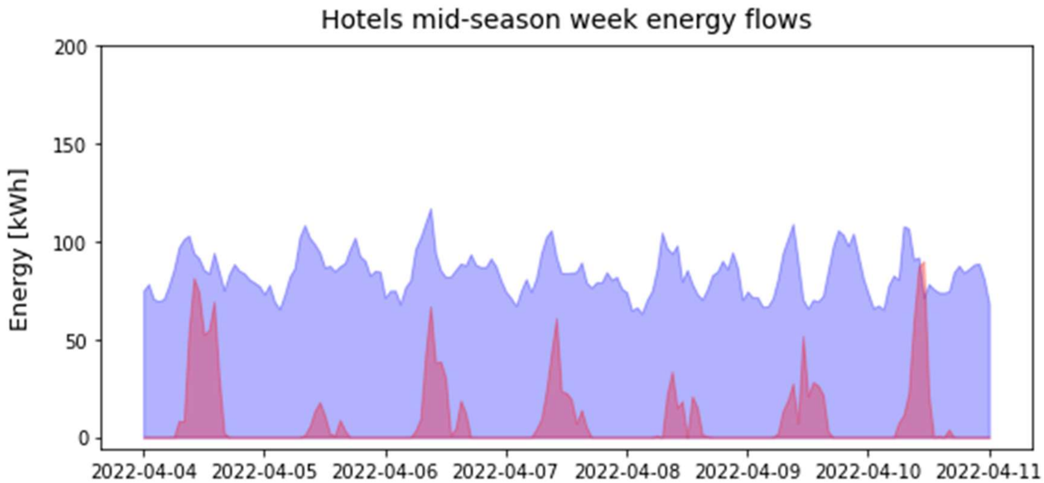

Figure A. 4 Weekly profiles of energy purchased and fed into the grid for all users (mid-season)

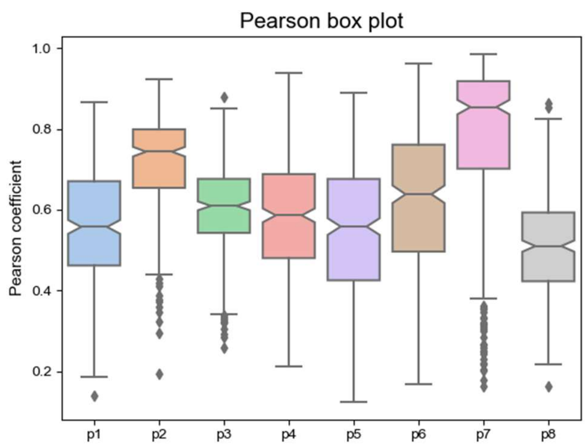

Figure A. 5 Notched box plot of daily normalized Pearson correlation coefficient

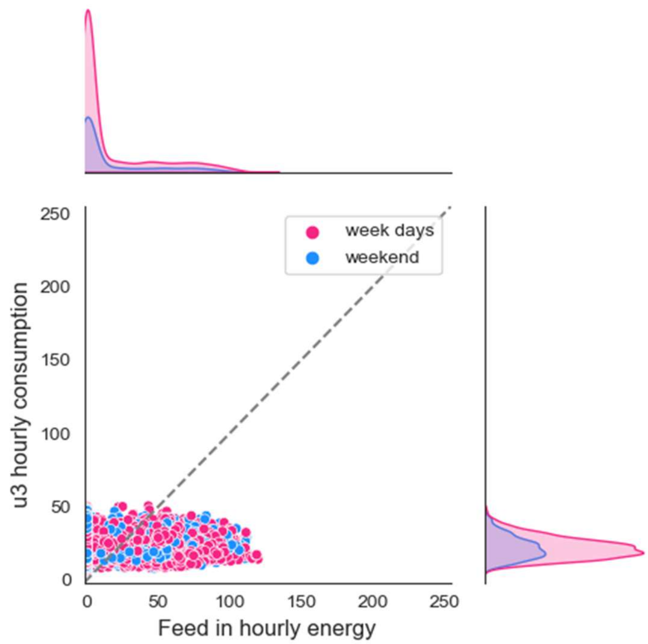

Figure A. 6 Distribution of consumption hours compared to feed in hours for user u3

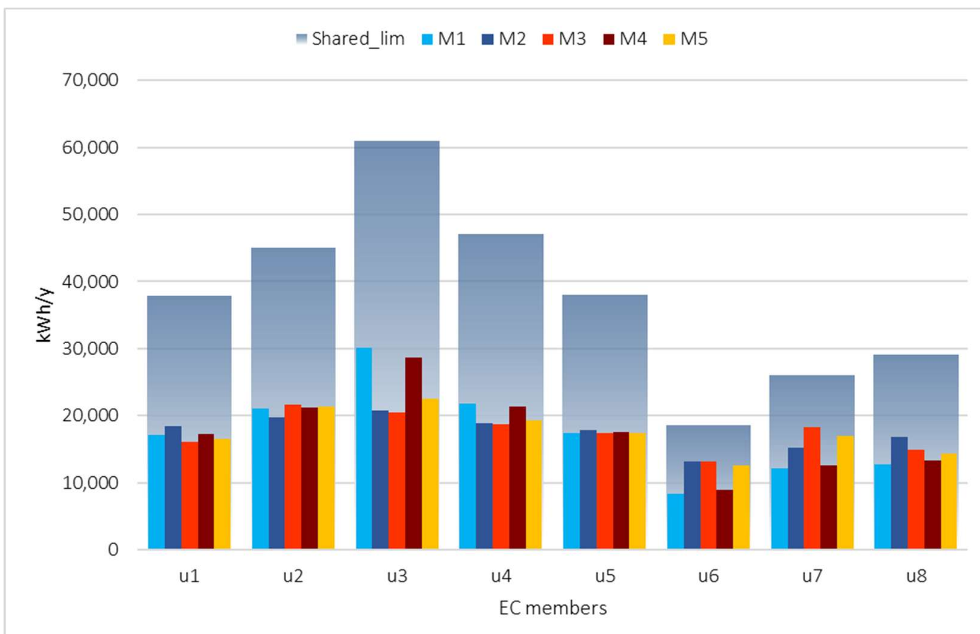

Figure A. 7 Comparative analysis of the methods used for the allocation of shared energy with respect to total consumption

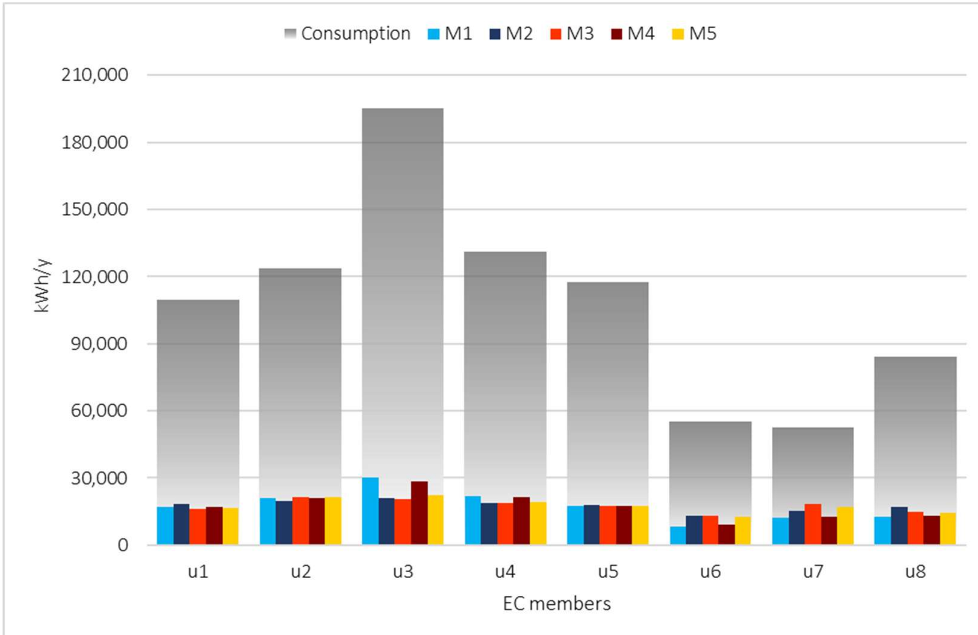

Figure A. 8 Comparative analysis of the methods used for the allocation of shared energy with respect to the shared energy limit

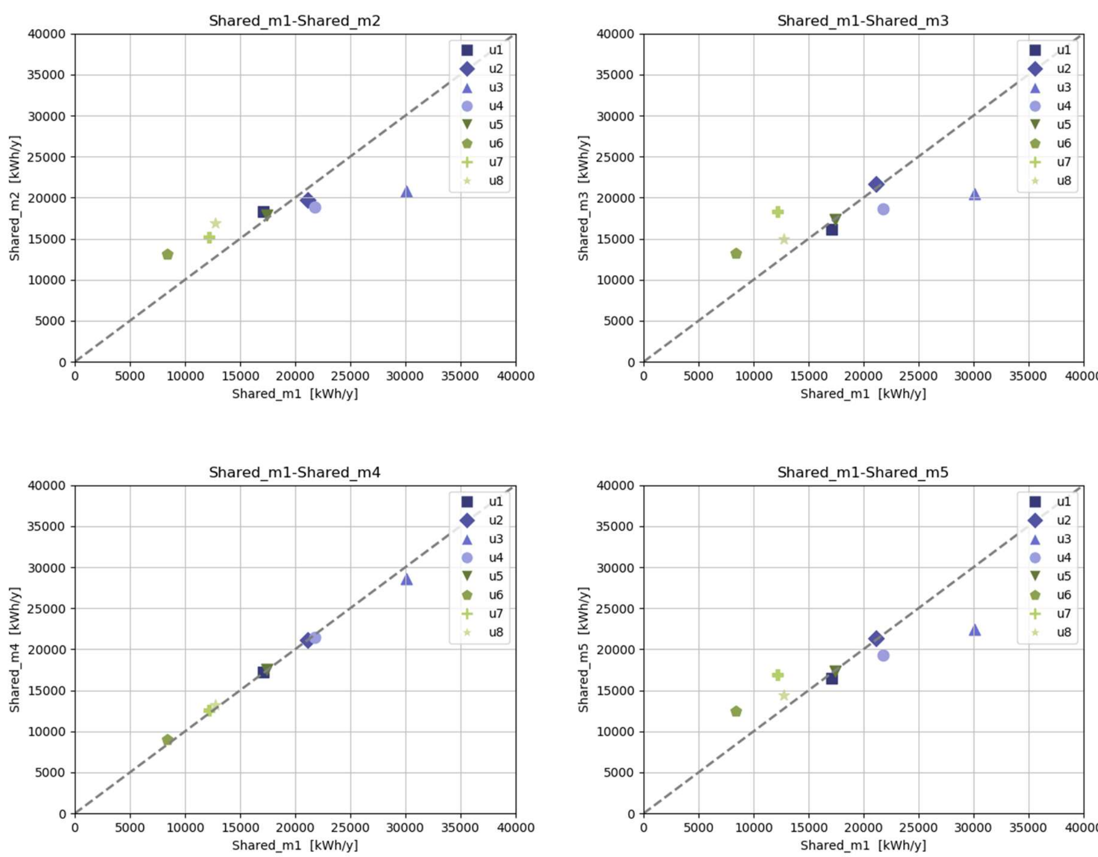

Figure A. 9 Comparison between the shared energy assigned by M1 and other methods

Appendix B

Figure B. 1 Photograph of one analyzed buildings equipped with solar collectors

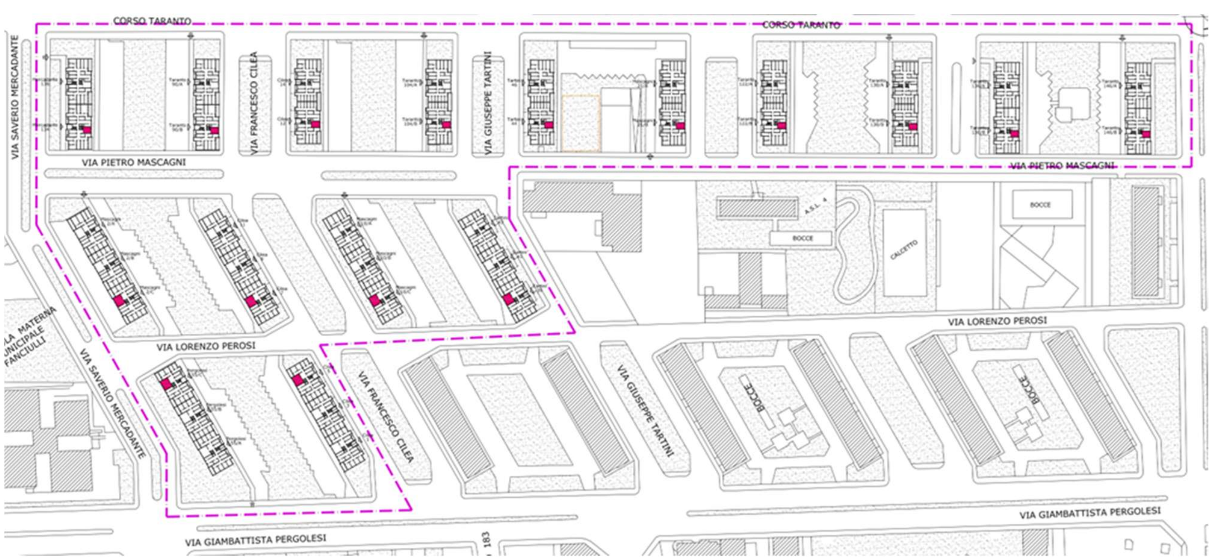

Figure B. 2 Indication of the substation room of analyzed buildings

Figure B. 3 Focus on heat exchanger and the flow and return manifolds for RISC and DHW in the substation room

Figure B. 4 Focus on thermal storage system in the substation room

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