Heliyon 10 (2024) e28269

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A roadmap for the implementation of a renewable energy community

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ARTICLE INFO

Keywords:
Renewable energy communities
Energy sharing
Energy management
Energy systems
Roadmap of renewable energy community
Energy policies

ABSTRACT

Environmental problems due to climate change, that have been affecting our planet for years, are the main issues which prompted European Union to establish the ambitious target of achieving carbon neutrality by 2050. This occurrence encouraged all Member States to undergo significant changes of their energy sectors, favouring the extensive use of renewable energy sources. In this scenario, the European Union introduced Renewable Energy Communities, innovative energy systems based on a new model of renewable energy production, consumption and sharing, guaranteeing environmental, economic, energy and social benefits. The objective of this paper is twofold: firstly, to examine the regulatory framework of Member States and, secondly, to present a standardized procedure for the implementation of a Renewable Energy Community, an aspect not yet covered in scientific literature. The roadmap includes four main phases: a feasibility study involving an energy analysis of end users' consumption and a general assessment; the aggregation of members as producers, consumers or prosumers forming a legal entity, considering different funding opportunities; the operating phase, involving plant construction and project validation by national authorities; the technical and economic management phase. The dynamic structure of the roadmap allows for adjustments to accommodate different regulatory contexts, member typologies and project aim.

1. Introduction

The current energy crisis encompasses several global issues: the need for many countries to reduce their dependence on natural gas from a few suppliers, the mitigation of climate change, the massive use of renewable energy sources (RESs) and the challenge of addressing energy poverty [1]. For each state, the need to have access to the necessary energy and, therefore, to guarantee its energy security, which is fundamental for technological development and the future of civil society, remains of paramount importance [2]. While the energy sector is crucial for a country's economic balance, it also requires increased attention to environmental and social sustainability [3]. Sustainable development includes support for energy efficiency and new technologies that affect economic growth [4]. Despite the high cost of sustainable innovations begin a reason for the deceleration of sustainable development in some states [5], the last decade has seen a decrease in energy demand in advanced economies countries, with an increase in emerging economies,

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https://doi.org/10.1016/j.heliyon.2024.e28269
Received 19 October 2023; Received in revised form 6 March 2024; Accepted 14 March 2024
Available online 21 March 2024

Nomenclature

a	Discount rate [−]
c	Unitary average cost of electricity [EUR/kWh]
CO_2	CO_2 emissions [tCO_2/y]
DPB	Discounted Pay back [y]
E	Energy [kWh/y]
IN	Income [kEUR/y]
I	Economic incentive for shared energy [EUR/kWh]
IC	Investment cost [kEUR]
k	Year index in the investment horizon [−]
MC	Maintenance costs [EUR/y]
N	Investment horizon [y]
OC	Operating costs [kEUR/y]
P_R	Performance ratio [−]
SPB	Simple pay back [y]
10%	10% indicator [−]

Acronyms

AI	Artificial Intelligence
BEM	Building Energy Modelling
BESS	Battery Energy Storage System
CEA	City Energy Analyst
CEC	Citizen energy community
CEP	Clean Energy Package
CEU	Characterization of energy users
CHP	Combined Heat and Power
CityBES	City Building Energy Saver
c-Si	Crystalline silicon
DSM	Demand Side Management
EU	European Union
EV	Electric vehicle
GHG	Greenhouses Gas
HOGA	Hybrid Optimization by Genetic Algorithms
HOMER	Hybrid Optimization Model for Electric Renewable
HV	High Voltage
IEA	International Energy Agency
IEMD	International Market Energy Directive
KPI	Key Performance Indicator
LA	Local Authorities
Li-ion	Lithium-ion
LV	Low Voltage
mono-Si	Mono-Crystalline silicon
MV	Medium Voltage
PG	Power grid
p-Si	Poli-Crystalline silicon
PV	Photovoltaic
RC	Residential customers
REC	Renewable energy community
RED II	Renewable Energy Directive
RERL	Renewable Energy Research Laboratory
RES	Renewable energy source
SEC	Smart Energy Community
SME	Small and medium enterprise
TEASER	Tool for Energy Analysis and Simulation for Efficient Retrofit
TIAD	Integrated Text Widespread Self-Consumption
TS	Traditional System
UBEM	Urban Building Energy Modelling
UEUM	Urban Energy Use Modeling
UrbanOpt	Urban Renewable Building And Neighborhood optimization

particularly in China and India, with projections indicating a rapid increase by 2030 [1]. The Covid-19 pandemic in 2020 led to a 5.2% reduction in global CO_2 emissions from energy combustion and industrial processes, while they increased by 6% in 2021 compared to the previous year due to economic output growth after the global financial crisis [6]. The need to increase the use of RESs and consequently reduce the impact on the environment concerns especially huge consumption sectors, as the industrial one. A gradual reduction of traditional sources in favour of RESs has been implemented in recent years [7]. Numerous natural disasters are directly associated with greenhouses gas (GHG) emissions in the atmosphere. To counter energy crisis and climate change, many governments have set targets. The European Union (EU) has established key targets to reduce GHG emissions by 55% by 2030 [8]. The COP26 Glasgow Agreement aims to limit the rise of global temperature to 1.5 K [9], building on the goal of the COP21 Paris Agreement, which called for Member States to voluntary limit global warming to below 2 K compared to pre-industrial levels [10]. The United States of America and the EU have committed to achieve carbon neutrality by 2050, while China aims to reach it by 2060 [11]. Energy transition also offers the opportunity for a state to invest in its own energy independence, reducing its economic and geopolitical dependence on others [12]. Energy policies implemented in recent years have been favoured not only by environmental and energy reasons but also economic and political ones, demonstrating the strong interconnection between these issues [13]. The solution to energy crisis involves two main approaches: a top-down approach that focuses on increasing energy production from RESs and reducing fossil fuel demand, and a bottom-up ones that includes the evolution of citizen participation. In the EU the energy production from wind and solar photovoltaic (PV) is rapidly expanding and is estimated to reach 30% and 15% of electricity generation by 2030, respectively [1]. At the same time, energy production from conventional power plants has decreased. While this transformation is advantageous from an environmental point of view, it is crucial to consider its consequences for the power system and electricity market, which must guarantee the security of electricity supply [14]. The introduction of the sharing economy in the energy field has characterized the ecological transition of the last decade. It is a new way to share surplus renewable power from a single building to a group of interconnected buildings within the same micro-grid [15]. This enables the reduction of the impact on the grid caused by the non-programmability of RESs' energy production. In this new energy landscape, the key actor is the prosumer, an end-user who can simultaneously consume and produce energy and strives to minimize the interaction with the grid ensuring the resilience of the power sector. To address the energy crisis, it is also necessary for citizen behaviours to change, encouraging them to consider energy and environmental issues and make changes in their daily routines [16]. All these objectives converge in the concept of Renewable Energy Communities (RECs).

In 2018, the European Commission introduced RECs through the Renewable Energy Directive (RED II). RECs are energy-sharing systems that involve residential customers (RCs), small-medium enterprises (SMEs), and local authorities (LAs) in a specific area. These communities primarily use energy produced by RESs-based plants, resulting in economic, environmental and social benefits for all members. RECs are seen as alternatives to conventional fossil fuels-based energy production in collective systems. Since their introduction, European citizens have considered RECs a democratic and bottom-up solution that allows them to actively participate in energy transition [17]. RECs have a significant social impact as they facilitate access to alternative energy sources for many citizens [11] and help to address energy poverty, a social issue highlighted by the World Energy Outlook 2022 of International Energy Agency (IEA), which projects that around 75 million people will face difficulties paying for electricity due to economic pressures in the next years [1].

2. Literature review

RECs have been widely discussed in scientific literature in recent years. Many research teams have conducted analyses on RECs focusing on legal frameworks, management methods, development guidelines and optimization models based on mathematical algorithms applied to case studies. Table 1 encompasses keywords and the aims of some selected works, providing a broader overview of the main aspects that can be covered by them, including regulatory framework, development and management methodology, business plan. The papers have been carefully selected based on their unique features in addressing the subject and only sources published after 2018 (the year of the REDII publication) have been considered. The selected aspects encompass the optimization of the REC management on an economic, legal and organizational level, which this study aims to analyse comprehensively.

The transposition process of the REC directive has been influenced by geographic, cultural and political factors in every country, so

Greek symbols

α	CO_2 emission factor [$kgCO_2/kWh_{El}$]
η	Efficiency [−]

Superscripts and Subscripts

El	Electric
p	Primary
PG	Power grid
REC	Renewable energy community
RES	Renewable energy source
Sh	Shared
TS	Traditional System
US	User

Table 1
List of selected paper and main aspects considered in each one.

Reference	Keywords	Aim	Regulatory framework	Development and management methodology	Business plan
[18]	Energy communities; European renewable energy directive; Energy democracy; Community energy; Energy justice; Renewable energy clusters.	Policy advice for the effective implementation of RED II in Member States of EU.	X	X	
[11]	Renewable energy community; Diffusion of innovation; Willingness to accept; Segments.	Analysis of willingness of participating in RECs of three groups with different attitudes.		X	
[19]	Energy communities; Multi-agent systems; Demand-side management; Flexibility.	Optimization methods to demonstrate benefits of community from having members with different energy consumption profiles.		X	X
[20]	Energy policies; Energy communities; Renewable energy; Energy market.	To introduce an energy community taxonomy based on spatial factor and purposes of the REC.		X	
[21]	Renewable energy communities; Multi-energy system optimization; Energy transition; Demand side management; Electrification.	Analysis of economic advantages dependence in a REC from multiple interdependent factors and context.			X
[22]	Energy community; Collaborative governance; Energy sharing; Micro energy grid.	Analysis of a REC from an energy, environmental, management and economic point of view, applied to a case study.	X		X
[14]	Energy communities; Self-consumption; Prosumers; Business models.	Analysis of RECs impact on the Power system.	X	X	
[23]	Sector coupling; Positive energy communities; Urban energy district; Smart energy systems; EnergyPLAN; Hydrogen blending.	Investigation of RES excess and combined Power-to-gas, Power-to-Heat and Power-to-Power systems in a REC.		X	X
[24]	Artificial Intelligence; Deep learning; Renewable Energy Community; Battery Energy Storage System management; Model Predictive Control.	Hybrid AI optimal method to improve the efficiency of energy management in a REC.		X	X
[25]	Building energy system; DesignBuilder; Machine learning; PV system; Electric vehicle.	Machine Learning model used to manage a REC in Canada.		X	
[26]	Energy community; Energy storage; Photovoltaic system; Optimization.	Presentation of a methodology to size a solar PV whit BESS based on multicriteria optimization.	X		X
[27]	Smart energy community; Renewable energy community; Biomass-based cogeneration system; District heating network.	Economic analysis of a Biomass-Based REC.	X		X
[28]	Heating and cooling network; Polygeneration system; Geothermal energy community; ORC; Geothermal energy; Energy district.	Energy, Environmental, and Economic Analyses of Geothermal Polygeneration System.			X
[29]	Prosumers; Optimization; Self-consumption; Energy sharing; Economic indicators; Stakeholders.	Analysis of energy management and sustainability assessment of a REC in Italy.	X	X	

these factors were analysed and policy advice was proposed [18]. Participation in a REC requires knowledge of the project and its benefits, starting with the voluntary commitment to increase the consumption of renewable energy. However, this alone may not be enough. The willingness to participate in a REC project has been investigated by analysing the perception level of community identity, altruistic values, and subjective norms among potential members [11]. In addition to these features, the selection of REC members must follow specific criteria to maximize benefits and comply with legal constraints. For example, community benefits could be increased by selecting different types of members with various consumption profiles and optimizing energy management for economic advantages [19]. Different types of RECs can be realized, depending on the project's aim, the typology of included end-users, energy management, or geographical features. Some studies have proposed an energy community taxonomy based on parameters: the first considers a direct spatial correspondence between a specific geographical area and the community itself, the second differentiates between energy-purpose communities and multi-purpose communities [20]. The assessment of REC economic benefits depends on a multitude of interdependent factors, such as electricity tariffs and the electrification ratio in the transport and heating sectors, which vary in each context. These factors also have implications for environmental aspects, including the reduction of GHG emissions [21]. The copious benefits of RECs have been investigated both theoretically through the analysis of legal frameworks and practically through case studies. Environmental benefits of RECs compared to traditional configurations without a sharing approach were highlighted in a case study of a multi-purpose energy community simulated using commercial software. The results demonstrated a reduction of 39.5 t/y of CO_2 emissions with a REC configuration compared to the traditional configuration [22]. The interaction between the power system and RECs is investigated to understand the influence of users' energy exchange and to find the best energy management programs. The electricity fed into the grid, self-consumption, and participation in the electricity market, are just some of the most important aspects of RECs [14]. RES-based energy excess could be used through Battery Energy Storage Systems (BESS), if integrated into the plant, or combined with other energy conversion systems. Some studies examine the combined implementation of RES-based energy surplus with Power-to-Power, Power-to-Gas and Power-to-Heat systems within a REC under different conditions [23]. Models for energy management in a REC seems to be a topic extensively covered in existing literature. Some proposed approaches include hybrid artificial intelligence (AI) based methods to forecast energy fluxes, optimize energy interactions among members and predict BESS operations [24]. A machine learning tool has been used to assess the energy demand or supply within the community and has been evaluated in a cold climate region in Canada [25]. Other studies investigate models for community optimization. A methodology for sizing a solar PV plant based on two Key Performance Indicators (KPIs) evaluated on the energy balance and power flow to or from the grid on an hourly basis, has been presented [26]. Several case studies have investigated various purposes of the community and different RES-based technologies included in the RECs. The biomass-based REC in Tirano (Northern Italy) satisfies approximately 68% of the thermal and electric demand of members and supports the development of a local supply chain based on the maintenance of local forests whose byproducts are used to power biomass plants [27]. An analysis conducted on a geothermal energy community demonstrated not only the economic feasibility but also a reduction in environmental impact, corresponding to $5.49{\cdot}10^3$ t/y of avoided CO_2 emissions and a yearly reduction of 27.2 GWh of primary energy [28]. Economic, environmental, and social analyses are presented through KPIs applied to two different energy sharing configurations in accordance with the Italian regulatory framework [29].

2.1. Aim of the paper

The broad interest of the research community in the development of RECs is confirmed by the extensive literature review in the previous subsection. The REC's concept concerns the sharing of energy choices among more members and is linked with the broader subject of Smart Energy Communities (SECs). SECs, which has been researched since the 70s [30], can be characterized as clusters of energy service providers (whether private, public, or a combination thereof) situated within a defined geographical region. In such communities, end-users (including citizens, businesses, and public administrations) fulfil their energy requirements by embracing a collaborative strategy. This involves the implementation of decentralized energy generation solutions that are often based on RESs-based technologies, but they may also include high-efficiency fossil-based energy conversion systems able to meet both thermal and electric energy community needs. The overarching goal is to derive advantages in terms of cost efficiency, sustainability, and safety. In this scenario, this study is priority referred to a specific subcategory of SEC, that are the RECs as understood in European regulations. In these communities, members share facilities based on RESs for electricity generation, including virtual sharing schemes. This choice has been made to avoid making the discussion too general. Nevertheless, references to examples where the proposed methodology could also apply to cases involving the sharing of thermal energy are included in the paper.

All the references aforementioned in the previous section are listed and categorized in Table 1, where it is evident that no paper covers contemporary the three considered aspects in the table (regulatory framework; development and management methodology, business plan). Thus, this paper aims at bridging such gap by providing the key novel contributions.

- The development of a standardized process outlining the main phases for REC implementation with a realistic approach. This general methodology is applicable in every context, with necessary adjustments based on national regulations. Scientific literature on RECs phases accomplishment mainly focuses on the pre-implementation process, involving the analysis of the regulatory framework, and the post-implementation phase, which includes proposing optimization models to increase benefits and methods to improve the management of energy flows. This standardized method will be beneficial not only for REC developers, but also for stakeholders and key players.
- A comparison of the legal settlement provisions for the transposition of RECs, emphasizing the fundamental scopes and features of different legal forms. This paper expands the analysis of relevant previous works which focus more on the overview of the RECs legislation. This work, instead, compares the different legal settlements allowed by the RECs definition itself through a multidisciplinary approach including energy, economic and legal skills.
- The assessment and comparison of funding opportunities according to the typology of investors and the typology of investments for RECs projects. In the best of Authors' knowledge, no work provides such economic guidelines on RECs implementations.
- The formulation of an energy, environmental, economic and social KPIs to evaluate such different features of RECs. The majority of previous studies on this topic investigate only some of these aspects, avoiding their contemporary implications.

Notably, the insights and outcomes derived from the proposed work may serve as a proactive guide for policymakers, allowing for a more informed assessment of tecno-economic options and legal provisions, potentially influencing decision-making processes for the benefit of advancing REC development.

3. Materials and methods

The paper's structure is illustrated in Fig. 1**.** The introduction presents RECs as instruments against the global energy crisis, followed by a literature review supporting the work's aim in Section 2. Here the novelty of the study is presented. Section 3 provides an overview of the regulatory framework in Europe, focusing on the directives in several Member States. It presents a standardized roadmap that encompasses all the main phases to be followed for REC implementation in each country, with adaptions according to national laws. Each phase is thoroughly examined in a comprehensive way, from the feasibility study to the management of the community. Section 4 discusses the presented method, including its advantages and disadvantages, and proposes case studies analysis. The final section sums up the study and presents future developments.

3.1. Regulatory framework

To achieve the decarbonisation objectives by 2030, the EU revamped its energy policy framework in 2016 with the publication of the "Clean Energy for all European Package" (CEP) [31]. CEP, which came into force only in 2019, consists of eight new laws introducing legislative measures across various sectors: energy performance in buildings, renewable energy, energy efficiency, and the electricity market. Two of these directives are particularly relevant in terms of end-users' role in the transition process: Directive 2018/2001, also known as RED II [32], focuses on promoting the use of energy from RESs and introduces renewable energy self-consumers and RECs. Directive 2019/944, International Market Energy Directive (IEMD) [33], establishes common rules for the internal electric energy market and introduces Citizen Energy Community (CEC). Unlike from RECs, CECs do not have membership restrictions or geographical constrains [34]. RED II sets a binding target of at least 32% share of consumption from renewable energy by 2030, collectively achieved over a decade (2021–2030) by the Member States, based on the gross domestic consumption of the EU. In particular, the Directive aims to promote the development of energy "production" from RESs within the EU by actively involving citizens. It introduces models of participation of increasing complexity, defining and regulating individual self-consumption, collective self-consumption, and RECs. According to RED II, a REC is defined as a legal entity "*based on open and voluntary participation, autonomous and effectively controlled by shareholders or members that are located in proximity of the renewable energy projects that are owned and developed by that legal entity*" [32]. These shareholders or members can be natural persons, SMEs, or LAs, including municipal administrations. The primary objective of the REC is to provide environmental, economic or social benefits to community shareholders or members or to the local areas where it operates, rather than financial profits. The aim of RED II is to support acceptability of RES-based projects among Europeans and in the electricity market, while the IEMD contributes to the completion of internal market. The consumer is at the core of the energy market, and both directives emphasize its central role [35]. By June 2021, European Member States were expected to transpose RED II into national law to introduce common guidelines for establishing RECs, with the aim of removing unjustified regulatory and administrative barriers. However, due to differences among European States in terms of regulatory and cultural aspects, a one-size-fits-all approach was not the best solution.

3.1.1. European context

RECs have played and will continue to play a decisive role in the energy transition in Europe and in achieving Climate Neutrality by 2050. Some Member States have already adopted measures to enable self-consumption and the establishment of RECs in their territories even before the issuance of RED II by the European Parliament [14].

Spain

The Spanish government introduced two forms of self-consumption through Royal Decree 244/2019 [36]: self-consumption with and without surpluses, allowing or disallowing the injection of excess energy into the grid respectively [37]. In 2020, Royal Decree

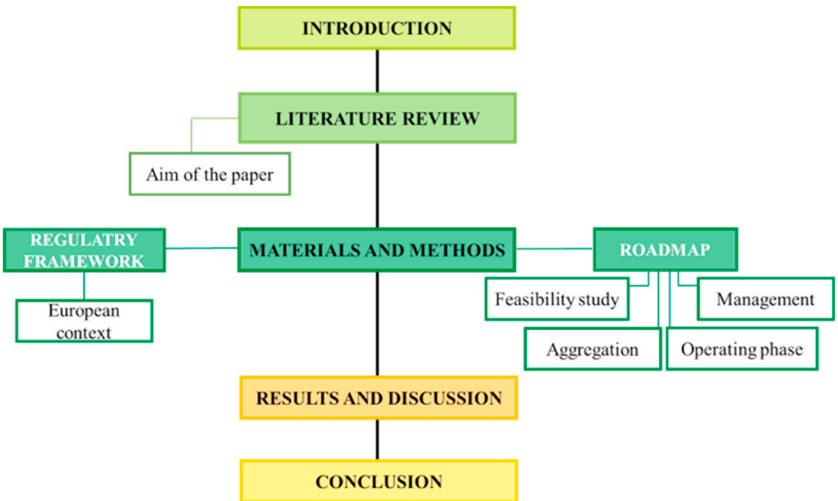

Fig. 1. Paper structure.

23/2020 [38] officially introduced RECs in Spain, with the aim to increase participation in RES-based projects. In April 2023, a public consultation was lunched regarding the new Royal Decree on RECs and CECs.

Germany

Germany currently has the highest number of communities in Europe [39], thanks to the Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG) [40] which introduced incentive tariffs for renewable energy generation lasting 20 years. It has been updated over the years [41]. In Germany, citizens, SMEs or cooperatives which own renewable energy assets are considered RECs and are eligible for incentives or loans [42].

Ireland

The Sustainable Energy Authority of Ireland also provides incentives for renewable energy schemes that include RECs, and it is expected that their number will increase from current 580 to 1500 by 2030 [43]. Irish RECs can include different generation technologies such as Combined Heat and Power (CHP) systems to cover thermal demands of end-users [42].

Greece

Greece introduced a net metering system in 2014 and a virtual one in 2016 for independent producers. Then, Law 4513/18 [44], approved in 2018, made this metering effective for energy communities. Unlike in other European states, RECs in Greece are classified as non-profit organizations without economic distribution among members, or for-profit cooperatives, where economic distribution is possible under certain conditions as long as some conditions are observed [45].

Portugal

The Portuguese Government introduced RECs in Decree Law 162/2019 [46] during October 2019, as a part of the EU framework implementation, and the formalization of RED II, following the previous regulatory framework for individual self-consumption.

Austria

In 2017, the concept of collective-self consumption was introduced for the first time in Austria through the enactment of the Austrian Electricity Act [47]. The transposition of RED II by the Austrian Government took place in July 2021 with the Renewables Expansion Law (Erneuerbaren-Ausbau-Gesetz,EAG) [48], which established that RECs can provide energy services in addition to traditional generation and storage of energy from RESs.

Italy

Italy also introduced self-consumption regulation before RED II, through regional laws [14] in Piemonte, in the North of Italy, in 2018 [49] and in Apulia, in the South of Italy, in 2019 [50]. Between the end of 2019 and 2020, the transposition process of RED II regarding RECs and collective consumption schemes, began in Italy through art. 42 bis of Decree Law Milleproroghe (DL 162/19) [51], then converted in Law No.8/2020 [52]. The introduction of some specific constraints was marked: REC plants must have a maximum power of 200 kW and members must be connected to the same electrical substation MV/LV, from medium (MV) to low voltage (LV). In August 2020, ARERA, the Italian Energy Regulatory Authority, approved Resolution 318/2020/R/eel [53]. The overall transposition of RED II took place with Legislative Decree No. 199 [54] entered officially in force in December 2021, and the constrains were revised: the maximum power of RES plants increased to 1 MW, REC members have to be linked to the same electrical substation HV/MV, from high voltage (HV) to MV and the possibility of access to the REC was extended to religious, third sector and research bodies. In January 2023 ARERA published the Integrated Text Widespread Self-Consumption (TIAD) [55] which introduced an obligation for electricity distribution companies to identify areas underlying the same electrical substation HV/MV and publish them on their websites, with the aim of facilitating the data acquisition by all interested parties.

Latvia

Not all European Member States have introduced national regulations to govern RECs, although in some countries initiatives to promote the use of RES-based plants in a community-based configuration are implemented. In Latvia these initiatives are conducted by citizens' cooperatives or local municipalities for biomass-based plants [42].

Poland

In Poland, energy clusters were introduced by the government in 2016. Members of these clusters could be physical persons, LAs or research institutes linked to the grid with a voltage constrain of 110 kV and a maximum of five communes [56]. Recently, the Polish Parliament received the draft amendment of the Energy Law which was approved by the Council of Ministers and is now under discussion.

Bulgaria

In Bulgaria, to support the use of RESs, the owners of RES plants are allowed to use the generated electricity for self-consumption, facilitated by shorter time limits for connection and no permits required for systems up to 30 kW of peak power. The share of non-self-consumed electricity may be sold to a supplier at a price set by the regulator [57].

The regulatory frameworks in European States have similarities and differences, but more and more countries are introducing legal guidelines to implement RECs on their territories, aiming to make them common instruments to address energy crisis. An overview of the regulation of RECs in some European countries is presented in Fig. 2.

3.2. Roadmap for REC implementation

The complexity of implementing a REC is the reason why there have been several attempts to standardise the essential steps. The goal is to simplify the whole process and make it immediately understandable for anyone interested in getting involved in this ever-changing field. This section proposes a standardized procedure for implementing a REC, which has been developed through a comparison with professionals involved in real projects, taking into account the features and problems they encountered during the creation process. The main phases of the process are: feasibility study, aggregation, operating phase and management. These phases, along with their sub-phases, are presented in Fig. 3. Each step will be analysed in detail within this section. The starting point should certainly be acquiring knowledge of the regulations, analysing the necessary requirements and subsequently being able to operate accordingly.

The phases of this roadmap may vary depending on the country where the process is applied to comply with the local regulatory framework. When a generalized analysis is not possible, Italian laws' application is considered.

It should be noted that the following analysis will generally refer to RES-based technologies, however, in some cases practical experiences will be related to as PV technologies. This choice is due to the widespread adoption of solar energy plants compared to others in REC applications. Indeed, solar energy technologies are among the most commonly used RES-based plants worldwide, and they are expected to become even more widely used in the coming decades [58]. The broad adoption of PV has been influenced by cost reduction and incentivisation policies [59]. Nevertheless, there are no restrictions on the choice of technology to use in a REC, the selection mainly depends on the available resources in the considered area. For example, the REC of Tirano (Northern Italy) is based on a biomass-based plant fed by maintenance of local forests and sawmill waste, offering an advantage to the territory starting from its resources [27]. In a more complex REC managing of energy flows from a combined PV and wind turbine system is achieved using a Power-to-Power hydrogen-based system [60]. However, one of the challenges associated with the use of RES-based plants other than solar PV, such as a wind farms or hydroelectric plants, is their typically larger size and power capacity in the order of MW. Detailed knowledge of the subject has led to the development of the proposed roadmap: a dynamic roadmap that continually evolves through the contribution of experience.

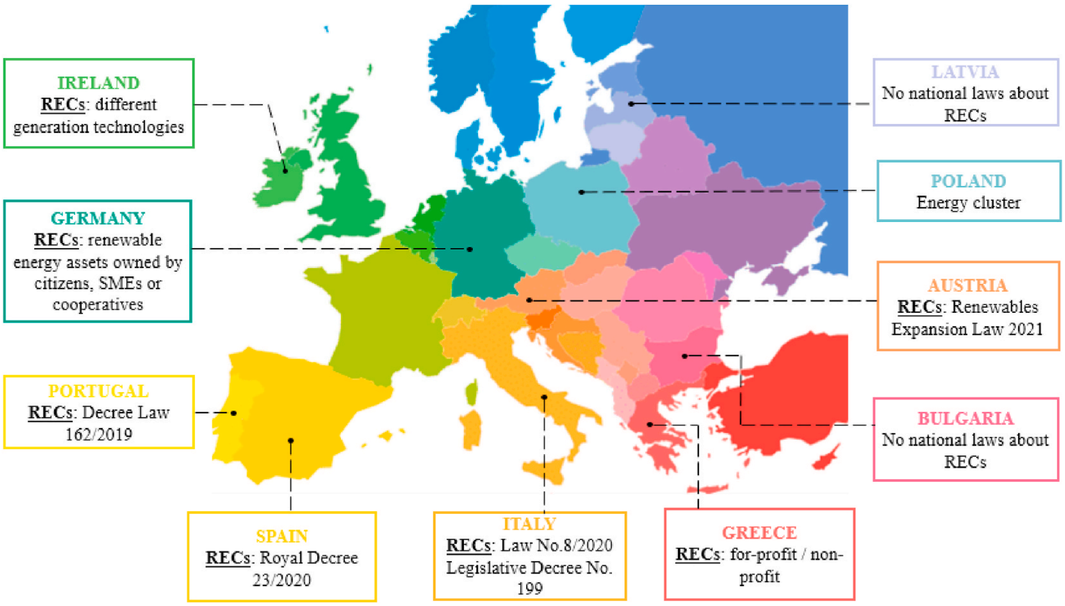

Fig. 2. Overview of the RECS regulation in some European countries.

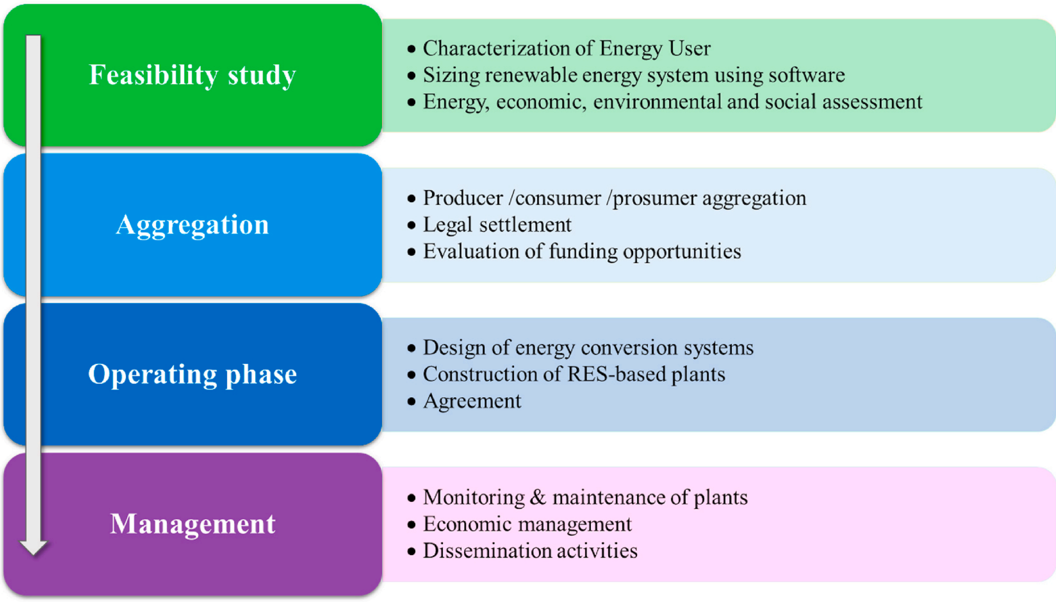

Fig. 3. REC implementation roadmap: phases and sub-phases.

3.2.1. *Feasibility study*

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

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

Additionally, the feasibility study can also serve as a phase for selecting the primary objective of the project.

Social entrepreneurship can also be declined through REC according to aims, forms of governance and ownership, and social impact of the project [61]. Community energy entrepreneurship is rooted in the local context in which it operates. Considering mutualism as a direction of entrepreneurship, the pluralistic and reciprocal character of such partnership projects is referred to as "associative entrepreneurship" [62]. According to the RED II, participants in the REC are voluntary and free [63]. Hence the need to define interaction layers of stakeholders, the roles they can take on and the way in which each of the stakeholders is engaged on the basis of their role and motivations. The involvement of stakeholders through a process of collaborative governance produces value co-creation [64]. In a collaborative context, the amount of added value brought by each member is rarely clearly visible [65]. In addition, other factors affect the behaviour of a community and its ability to generate value [66]. These factors include, e.g., collaboration arrangements, economic interaction of participants, whether they share or trade, centralized or completely decentralized management, and relationships of trust. According to Bovaird and Loeffler, co-creation by users and RECs brings benefits that greatly improve service outcomes and quality, but it is not without costs [67]. Moreover, Dudau et al., have constructed a future research agenda and this study is in coherence with Research Direction 6: "*the utility and applicability of value co-creation-theories to public service ecosystems, hence the prospect for a value creation ecosystems theory*" [68]. However, the latter perspective will need to include further research.

3.2.1.1. Characterization of Energy User. Analysis of end-users' energy consumption during the preliminary phase is undoubtedly approximate, as it depends on the consumers expected to be included in the REC. The process of consumption forecasting is referred to as "Characterization of Energy Users" (CEU). The CEU is useful for accurately assessing the size of the plants serving the community and determining the types of utilities to be included in order to maximize shared energy and, therefore, energy and economic benefits. If the utilities that will be part of the same REC are already known, their energy consumption data can be easily obtained from their bills; in this case, it is possible to use these data as input for the "Sizing renewable energy system using software" phase described in the following section.

Otherwise, if the actual consumption data are not available during the preliminary phase, estimation methods are needed to collect the data for the CEU implementation based on extensive databases with information from different spatial levels and various time resolutions [69]. Since the users' behaviours and occupancy patterns strongly influence the load profiles [70], given the extensive scope of application, one can conduct energy modelling at the level of specific structures, known as Building Energy Modelling (BEM), or on a broader scale within an urban context, referred to as Urban Building Energy Modelling (UBEM). Concerning the spatial domain of RECs, UBEM approaches seem to be most suitable, and are widely discussed in the literature, comprising two categories: top-down and bottom-up models [71]. Top-down models utilize macroeconomic variables and statistical data to make energy forecasts. Conversely, bottom-up models consider and design clusters of buildings sharing similar characteristics (both geometric and non-geometric parameters) across various modelling scales [72]. According to with previous research [73], the bottom-up approach has demonstrated its suitability for conducting thorough analyses of buildings at the urban scale to create load profiles for representative buildings within a specific area over a given period of time.

Among bottom-up UBEM modelling approach three methods can be distinguished: *physics-based*; *data-driven* and *reduced-order*.

The *physics-based* utilizes simulation techniques along with building characteristics, construction details, climate data, and system information to compute end-use energy consumption. Most bottom-up engineering models predominantly utilize distribution, sample, or archetype-based methodologies. The distribution approach evaluates end-use energy consumption by analysing the regional or national distribution of building energy use. In the sample modelling approach, real building data is utilized as input for the model, requiring a comprehensive database to accurately represent the building group. The archetype approach classifies the building stock based on factors such as dwelling types, size, climate, and construction year [74].

The bottom-up *data-driven* approach finds application in urban energy modelling, aiming to forecast and assess building energy consumption while considering fundamental building features. These approaches rely on easily available data, such as building stock datasets, billing details (e.g., electricity, gas), survey data, and socio-economic variables. Broadly speaking, data-driven modelling involves a combination of statistical and AI methodologies [75].

The *reduced-order* methodologies are gaining popularity for swiftly assessing building energy performance, requiring fewer inputs in comparison to physics-based and data-driven approaches. A unique aspect of this approach involves determining model parameter values, and various calculation standards offered by the European Committee for Standardization and the International Organization for Standardization can be applied for estimation. These standardized procedures outline the calculation method through a series of normative statements covering physical building parameters and associated systems tailored to different building types [73].

Over the past decades, there has been substantial growth in studies focused on bottom-up UBEM approaches. Table 2 summarizes some of the most widespread projects or tools referred to the aforementioned UBEM methods categorized according to the stakeholders/target users potentially interested and tools' developers. For each of them, a reference is provided.

3.2.1.2. Sizing renewable energy system using software. The knowledge of available resources and existing infrastructure in a specific territory is crucial for understanding how to make effective changes. The preliminary phase of analysis includes the examining of various constraints, both in terms of size and location.

The analysis of the constraints refers, for example, to the positions of electric substations and the identification of users connected to them, in the case in which the electric energy sharing of end-users is considered. Other constraints could include any landscape-type restrictions that may limit the installation of RES-based plants in certain areas or on buildings subjected to specific regulations. Environmental problems should also be considered: a comprehensive understanding of the hydrogeological structure of the territory helps to avoid potential issues before implementing new installations. RES-based plants are usually considered environmentally friendly due to their contribution to the reduction of GHG emissions during the energy production process. However, they have significant negative impacts. For instance, solar PV installations can impact the visual aesthetics of an area or the building they are installed on and have adverse effects on wildlife resulting in bird fatalities due to the heat generated by solar modules [86]. Similarly,

Table 2
Summary of some bottom-up UBEM projects and tools [76].

Projects/tools	Stakeholders/Target users	Developer	References
physics-based approach			
City Building Energy Saver (CityBES)	Legislators, urban planners	Lawrence Berkeley National Laboratory (LBNL)	[77]
Urban Renewable Building And Neighborhood optimization (UrbanOpt)	Energy management specialists	National Renewable Energy Laboratory (NREL)	[78]
CitySim	Legislators, urban planners	Swiss Federal Institute of Technology Lausanne (EPFL)	[79]
data-driven approach			
UrbanFootprint	Legislators, urban planners	Lawrence Berkeley National Laboratory (LBNL)	[80]
Urban Energy Use Modeling (UEUM)	Legislators, urban planners, designers	Illinois Institute of Technology	[81]
Energy Proforma	Legislators, urban planners, designers	Massachusetts Institute of Technology Department of Urban Studies and Planning	[82]
reduced-order approach			
Tool for Energy Analysis and Simulation for Efficient Retrofit (TEASER)	Energy management specialists	RWTH Aachen University	[83]
Energy Atlas	Legislators, urban planners	Technische Universität München	[84]
City Energy Analyst (CEA)	Legislators, urban planners	ETH Zurich	[85]

wind turbines also have non-negligible impacts, including visual disturbances, human health issues such as hearing loss and sleep disorders due to noise pollution, and effects on wildlife such as bird collisions with the turbine blades [87].

In addition, before proceeding with the design of new plants, it is important to evaluate existing plants within the designated territory. This step is crucial for several reasons. Firstly, it helps avoid the overlap of existing and new facilities powered by the same RES, which may not be available in sufficient quantities to sustain these installations (consider biomass or hydropower, for example). Secondly, assessing existing facilities powered by RESs allows the evaluation of various scenarios for their inclusion within the community. However, the feasibility of this latter option depends on the legislation in force in each country and the legal settlement of the community itself.

On the basis of the CEU conducted through real data or UBEM approaches and according to acquired information about energy and environmental constraints referred to the selected location ad well as the RES availability and existing plants, it is possible to size the RESs-based plants included in the energy community by specific software.

Determining the size of the RESs-based systems is a crucial stage in establishing the capacity of each plant. Inadequate sizing poses a risk of either undersizing or oversizing the system. In addition, the "plants 'sizing problem" is strictly connected to the need in achieving a large self-sufficiency and self-consumption in the REC. Indeed, given the community loads, a large generation facility can increase the self-sufficiency but it generates in some period of the years a surplus of energy that exceeds local storage facilities and must thus be sold on the grid. On the other hand, a smaller generation can be totally self-consumed but is not able to fulfil all community energy needs. A totally self-sufficient and self-consuming community is thus almost unreachable. The plant's size, the storage capacity and their management must be selected to ensure the best solution meeting the maximum REC's self-sufficiency and self-consumption and some software allow to optimize this process increasing the RES's flexibility.

Among the software available for this purpose, one of the most widely used is Hybrid Optimization Model for Electric Renewable (HOMER Pro), it allows for modelling, sizing and optimization of a wide range of RES-based plants as production systems grid connected or off-grid by achieving specific electric or thermal loads as input [88]. TRNSYS stands out as a highly versatile, graphically based software environment employed for simulating the dynamics of transient systems. Its primary focus of simulations revolves around evaluating the efficiency of thermal and electrical energy systems, the software allows users to construct models in a manner that enables the modification of existing components or the creation of new ones [89]. iHOGA/MHOGA represent two iterations of the Hybrid Optimization by Genetic Algorithms (HOGA) designed for simulating and optimizing electric RES-based systems. The HOGA version is intended for systems ranging from a few watts up to 5 MW power, while MHOGA is tailored for power systems in the megawatt range, without any specific limit. The system can incorporate various components, encompassing PV systems, wind turbines, hydroelectric turbines (with or without pumped hydro storage), auxiliary generators (diesel, gasoline, etc.), inverters or inverter-chargers, batteries (both lead-acid and li-ion), chargers, batteries charge controller, as well as hydrogen-related components (electrolyzer, hydrogen tank, and fuel cell) [90]. The Hybrid2 software is a product of the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, USA, with assistance from the National Renewable Energy Laboratory. There are two primary types of simulation models widely employed for hybrid (intended as fossil based and renewable based technologies) systems. The first type is referred to as "logistic" models, primarily utilized for long-term performance predictions and as inputs for economic analyses. Historically, many of these models have been of the time series variety. The second type is known as "dynamic" models, which account for rapid fluctuations and system responses to changes in parameters. Hybrid2 falls into the former category, utilizing statistical analysis to enhance the accuracy of modeling events during a given time step [91]. The RETScreen Clean Energy Project Analysis software serves as a decision support tool crafted through collaborative efforts involving government, industry, and academia. Its global applicability enables users to assess energy production and savings, costs, emission reductions, financial feasibility, and risk associated with diverse RES-based and high energy efficiency technologies [92]. RETscreen employs a five-step analysis for each model: energy model, cost analysis, GHG's analysis and financial summary.

It is important to underline that while traditional software tools are commonly used for technical, economic and environmental analyses, they may not always provide an exhaustive solution to finding the optimal configuration [93]. In some cases, codes written in

Table 3
Pros and cons of software used for sizing process of RES-based plants.

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

dedicated programming languages are employed to solve optimization problems or simulate complex energy plants. The growing interest in using software that provide economic and environmental evaluation, recently has been flanked by the addition of social criteria to evaluate also the social impact of the community [93].

Hereinafter, Table 3 presents a comparison among the aforementioned software used for sizing process of RES-based plants and useful in REC's constitution [94].

3.2.1.3. Energy, economic, environmental and social assessment. RECs provide people with the opportunity to address energy poverty, support the energy transition from fossil fuels to RESs, mitigate environmental issues, and promote social inclusion in specific areas [95]. While the specific goals of RECs may vary, the consistent aim is to achieve energy and environmental benefits. Furthermore, social objectives, such as combating energy poverty, and economic goals, facilitated by incentives established by European countries regarding shared energy, are pursued. In most countries, remuneration for residential prosumers is not time-dependent, but is based on the time-flexible wholesale price, which already account for realistic future price [96]. To assess the existing system and alternative solutions, an evaluation can be carried out through energy, economic, environmental and social impact assessment. The energy analysis (*i*) allows for a comparison of alternative systems in terms of primary energy conversion efficiency and the environmental impact analysis (*ii*) evaluates the amount of GHG emissions avoided. The economic analysis (*iii*) enables an assessment of whether the proposed solution (REC), allows for the recovery of the investment costs within a reasonable timeframe, as well as the achievement of further benefits through plant operation and incentives related to shared energy. Social analysis (*iv*) considers changes in the energy poverty condition of end-users, whatever they are member of a REC or not. These analyses compare a traditional energy system (TS) with the new REC in terms of energy demanded by users (specifically electric energy), as shown in Fig. 4.

The dependence on the location where the REC is implemented does not allow a general analysis, Therefore certain elements, such as the calculation of energy sharing and economic incentives, will be presented according to the Italian regulations.

The electric energy requested by users is the same in the TS ($E_{El,US}^{TS}$) and in the REC configuration ($E_{El,US}^{REC}$). In the TS, the electric energy is taken from the power grid (PG), where it is produced by using a mix of power plants fed both by fossil fuels and RESs. Thus, the average national efficiency of the PG for the given year, denoted by η_{PG}, varies for each country. In the REC configuration, the electric energy requested by the users during the specific period can be supplied by the RES community plant, if $E_{El,US}^{REC}$ is less than the energy generated by the RES-based plant. However, if $E_{El,US}^{REC}$ exceeds the energy generated by the RES-based plant in the same period, the electric energy can be taken both from it and the PG. In former case, any surplus energy "produced" by the RES-based plant is fed into the PG (E_{El}^{REC-PG}), while in the latter case, the PG compensates for the shortage of energy (E_{El}^{PG-REC}) not supplied by RES-based plant to meet the users demand. The shared energy ($E_{El,sh}^{REC}$) in the REC configuration is evaluated as the minimum value between the energy taken from the PG and the energy "produced" by the REC plant and supplied to the PG within a defined time interval, as illustrated in Equation (1).

$$E_{El,sh}^{REC} = min\left(E_{El}^{PG-REC}; E_{El}^{REC-PG}\right) \tag{1}$$

The primary energy saving (ΔE_p) in a REC configuration compared to the TS can be evaluated by calculating the difference between the electric energy provided by the PG to satisfy user request in TS ($E_{El,US}^{TS}$) and the electric energy provided by PG to compensate for the energy deficiency from the RES-based plant in the REC configuration (E_{El}^{PG-REC}), considering the average national PG efficiency (η_{PG}), as presented in Equation (2). It is important to note that the energy supplied by the PG in the REC configuration is always lower than the

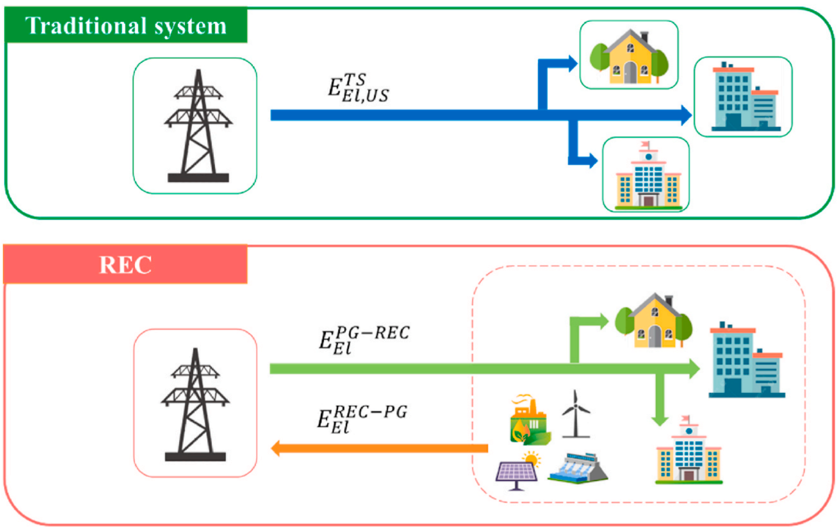

Fig. 4. Layouts of traditional system and REC.

corresponding value in the TS because the community plants have the purpose to fulfil as much of the energy demand from users as possible.

$$\Delta E_p = \frac{\left(E_{El,US}^{TS} - E_{El}^{PG-REC}\right)}{\eta_{PG}} \tag{2}$$

Regarding the environmental analysis, the CO_2 equivalent emissions imputable to the electricity taken from PG, are evaluated by multiplying the electric energy supplied by the PG and the national power grid CO_2 emission factor, represented by the term α_{PG} and measured in gCO_2/kWh_{El}, variable for each country. This evaluation is carried out according to Equations (3) and (4).

$$CO_2{}^{TS} = E_{El}^{TS} * \alpha_{PG} \tag{3}$$

$$CO_2{}^{REC} = E_{El}^{PG-REC} * \alpha_{PG} \tag{4}$$

The difference between the CO_2 equivalent emissions of TS and REC configurations, as shown in Equation (5), represents the avoided GHG emissions (ΔCO_2).

$$\Delta CO_2 = CO_2{}^{TS} - CO_2{}^{REC} \tag{5}$$

With reference to the economic analysis, the yearly operating costs (OC) are evaluated for both configurations in Equations (6) and (7). Yearly operating costs of the TS (OC_{El}^{TS}) are obtained by multiplying the electric energy provided by the PG by the unitary electricity average price $c_{El,PG}$, which is measured in EUR/kWh and varies for each country. The yearly operating costs of the REC layout (OC_{El}^{REC}) are calculated by considering the cost of electricity imported from the grid, maintenance costs (MC) associated with the plants, REC management costs, and income coming from the economic incentive for the shared energy. The last term is calculated by multiplying the shared energy by the economic incentive (I_{sh}^{REC}) established by the national authority.

$$OC_{El}^{TS} = E_{El}^{TS} * c_{El,PG} \tag{6}$$

$$OC_{El}^{REC} = E_{El}^{PG-REC} * c_{El,PG} + MC - E_{El,sh}^{REC} * I_{sh}^{REC} \tag{7}$$

The avoiding cost (ΔOC_{El}) in a REC configuration compared to the TS can be evaluated as the difference between OC of TS and REC, as shown in Equation (8).

$$\Delta OC_{El} = OC_{El}^{TS} - OC_{El}^{REC} \tag{8}$$

Another economic performance indicator that can be evaluated is the number of years necessary to recover the initial investment cost of the RES plant (IC_{RES}) through the annual cash flows of the REC, represented as OC_{El}^{REC}. This indicator, Simple Pay Back (SPB), is calculated by comparing the first and the second term, as shown in Equation (9).

$$SPB = \frac{IC_{RES}}{OC_{El}^{REC}} \tag{9}$$

This method is commonly used to evaluate alternative systems, employing the recovery period as a criteriation for accepting a project. It is typically deemed acceptable if the SPB index is within 5 years.

A more thorough economic indicator is the Discounted Pay Back (DPB) which accounts for the time variation of the value of money. Consequently, the DPB results always higher than the SPB. DBP is calculated comparing IC_{RES} with the discounted annual cash flows of the REC until year N, as reported in Equation (10), where a is the discount rate.

$$DPB = \frac{IC_{RES}}{\sum_{k=1}^{N} \frac{OC_{El}^{REC}}{(1+a)^k}} \tag{10}$$

The social purpose of an energy community is primarily realized by addressing the energy poverty of its members who can be included in the configuration. A quantitative analysis of this condition can be carried out through "10%" indicator. As reported in Equation (11), it is the ratio between the energy cost and the income (IN) of the considered end-user over a specific period of time [97].

$$10\% = \frac{OC}{IN} \tag{11}$$

If the end-users spend more than 10% of their overall income on energy services, they are considered to be in an energy poverty condition. The indicator must be calculated for the end-users, whether they are members of a REC or not, and the results must be compared. Energy, environmental, economic and social assessments conducted during the feasibility study phase are useful for a rough evaluation of the benefits of the REC configuration. However, it is important to repeat the analysis using real consumption and production data.

Concerning the electric energy sharing among REC members, some case studies aimed at the REC analysis have been evaluated in order to provide numerical indications about the reported indices. In a multi-users REC consisting of two restaurants and thirty-six residential buildings located in a town in Southern Italy, the REC achieves 62% of primary energy savings and 38% of CO_2 equivalent emissions avoidance, compared to the a TS configuration [22]. In a residential REC focused on addressing social aims, the 10% index evaluated for the three considered members, moves away from the energy poverty target for one of them when they are all included in a REC compared to the TS configuration, where this does not happen. By comparing these two configurations, a ΔE_p on a yearly basis of 61.6% has been evaluated. Furthermore, the REC ensures a decrease in GHGs emissions up to 64% every year. Finally, SPB is equal to 10 years by considering the REC plant was purchased by members [97].

As mentioned earlier, the energy, environmental and economic assessments have been presented with respect to the electricity sharing scheme exclusively. This approach is prevalent in various EU Member States affected by REC regulation. The electric energy sharing among REC members is often economically incentivized, primarily because it is simpler to share electric energy than thermal energy. This is due to the fact that the electric infrastructure, namely the power grid, is often already in place. In contrast, for thermal or cooling energy sharing, the construction of the infrastructure, such as the district heating and cooling network, where the users are physically connected is required. The use of the virtual scheme may not be possible, and the plant cost could significantly increase, affecting the economic profitability, particularly in low density areas, determining the profitability of the expense only in the high population density areas. However, thermal/cooling energy sharing can also present an opportunity for users' aggregation in a REC, posing a challenge that needs to be addressed in future research work. Below, just an example where this topic has already been covered, is provided. The above-mentioned Biomass based REC of Tirano utilizes a less common RES, as biomass, to supply both electric and thermal energy through a centralized system and a district heating network [27]. On the one hand this represents an advantage, on the other hand the constraints for the members of the REC become severer. The combination of thermal and electric sharing enables a reduction in GHG emissions by 18.5%. In the best-case scenario, biomass utilization covers 68.1% of the total thermos-electric demands [98].

3.2.2. *Aggregation*

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

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

The aggregation of members aims to enhance the RES-based plants efficiency and provide flexibility services to the PG. By optimizing the alignment between actual and planned energy profiles, the community gains economic advantages. This optimization not only benefits the community economically but also environmentally by maximizing the RESs exploitation. Additionally, integrating Electric vehicle (EV) charging services as a point of delivery in a REC offers advantages to the end-consumers, who surely use energy from RESs, strengthens the REC by increasing shared energy, and contributes to the territory by promoting the wider adoption of these services. The subsequent subsections will provide a detailed presentation of the sub-phases related to consumer and prosumer aggregation, legal settlement, and the evaluation of available funds.

3.2.2.1. Producer/consumer/prosumer aggregation. REC participants can belong to different categories. According to RED II a REC is a legal entity "*based on open and voluntary participation, the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities*" [32]. In some instances, the idea of creating a REC may originate from a group of private individuals who decide to pursue a common project. Alternatively, if the REC is initiated by a municipality, an expression of interest is conducted to gather the intentions of private citizens who wish to participate as prosumers or consumers. The CEU analysis, conducted during the feasibility study, allows for the aggregation of the most appropriate types of members, ensuring compliance with the legal proximity constraints and proper design of the RES-based plants.

Individuals interested in joining the same REC project can categorized as.

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

Prosumers play a crucial role in meeting the growing demand for electricity and promoting the use of RESs. Consumers are expected to consume electricity when the plants' producibility is high and reduce their consumption when it is low, possible through with Demand Side Management (DSM). Once the members are established, they reach an agreement to form the community and establish their rules.

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

- Cooperatives, which are most diffused in Northen Europe;
- Association (recognised or unrecognised) or foundations, which are most diffused in Italy [99];
- Social enterprises;
- Benefit companies.

Cooperatives are companies with variable capital set up to manage in common an economic activity aimed to provide members with the desired goods or services and they are registered. Thus, the essential characteristics are about the mutual purpose and the capital increase or decrease depending on the entry or exit of members who may be natural persons or legal entities. It is the most common legal settlement in Germany and Denmark [100].

Associations are collective organizations that have a purpose other than profit. They may perform economic activities incidental to their institutional activity, but may not distribute any profits [101]. They may have legal personality (recognised) or not (unrecognised). Legal personality is matched by perfect patrimonial autonomy: the members' assets are separate from those of the organisation and the latter is always and only liable for its obligations. The patrimonial autonomy of associations without legal personality, nevertheless, is imperfect; the organisation's events also produce effects on the asset of the persons who have acted in its name and on its behalf [102]. For the constitution of unrecognised associations there are no formal constraints and no public deed is required. Recognised associations are constituted by public deed, the memorandum and articles of association must indicate the name, the purpose, the assets adequate to achieve it, the registered office, the rules on organisation and administration, the rights and obligations of members, the conditions of admission.

Social enterprises are based on the principle of addressing social problems by applying market-based solutions. Therefore, they are based on three analytical dimensions: purpose, ownership and embeddedness. It is through market mechanisms that social enterprises are able to sustain themselves and promote their social mission [103]. One of the new forms of ownership is the community-based social enterprise: a form of community enterprise that supports the social mission through a democratic or equity-oriented form of ownership [104]. Embeddedness is a kind of precondition, because enterprises that respond to social needs require a local community that expresses those requirements [105].

Benefit societies are traditional societies with revised obligations that require management and shareholders to meet higher standards in terms of accountability and transparency. They voluntarily pursue one or more mutually beneficial purposes in the conduct of their business, in addition to the for-profit purpose [106]. These societies, in fact, have a different governance, which pursues both goals, and a more extensive and responsible management which, in addition to measuring the public value produced [107], assesses the social impact and communicates it transparently [108].

The decision about legal form is often guided by the need to find a simple and streamlined structure, as a complex organization could raise concerns among potential members and act as a barrier to REC implementation. The reference norms do not impose a particular legal form, but are all consistent in prescribing aims and key characteristics that guide the selection and demarcate the field.

REC must be a legal entity, naturally of a collective type since it is a community: it must be a participated entity, with or without legal personality but with legal subjectivity, e.g. with the capacity to be the holder of subjective legal situations autonomously with respect to members or components, endowed with an organisation and its own organs [109]. In addition, the REC must not have profit as its main purpose. To be prudentially understood both in a subjective sense, as the profit of the members, and in an objective sense as the pursuit of profits; with the clarification that the purpose of giving a benefit to the individual participants in the form of expenses saving, proportional to their capacity for consumption and not in the form of a return on the investment in participation, is a no profit purpose [110]. This leads to the exclusion of entities that are necessarily predominantly for profit (partnerships and corporations), and to the identification as possible legal forms only those that have or may have a main purpose other than profit.

However, the characteristics, number and type of members of a REC can take on different compositions. The sharing economy applied to the REC concept shows that, autonomous and heterogeneous actors, can share and exchange energy from RESs in a localized market both for-profit and non-profit [111].

The drafting phase of the contractual relationship involves the definition of the relationships among members, such as establishing regulations, agreements on the division of the maintenance and management costs for REC plants, and agreements on the allocation of the incentives on shared energy. During the establishment of the REC all the aforementioned rules are specified in the Constitutive Act, the Statute and the Operating Regulations.

Statutes of a REC, necessary for the legal creation, must fulfil the following requirements and contents [112].

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

3.2.2.3. Evaluation of funding opportunities. The economic aspects of establishing a REC should be defined during the initial phases of the project. Funding opportunities can come from different paths, and the opportunity of receiving funds through European or national projects often encourages those interested in carrying out a feasibility study for implementing REC. The evaluation of funding opportunities is applicable when the REC or a LA economically support the plant installation. Alternately, a REC member may choose to participate to the investment costs and subsequently obtain a remuneration, as set out in the Constituent Act.

In general, the most plausible financing opportunities are equity financing, debt financing and grants. The complexity of these types is reflected in the REC's activities, and for these reasons each funding opportunity is analysed in depth.

Firstly, equity financing is a form of self-financing through which each new member brings new capital into the REC [113]. This is a mutualistic situation in which the partners incur a long-term debt and, in the meantime, gain the power of control by becoming co-owners [114]. They also receive a share of the project's available profits, e.g. through a dividend every economically positive year. Shareholders may recover their invested capital in compliance with the rules laid down in the contract or the articles of association. Typically, in the aggregation and management stage of a REC, equity financing is widespread. As in all projects, the initial phase is where the greatest risks and uncertainties arise, therefore there are very few investors and convincing financiers is very difficult. Initially, after the first contribution, there will be negative cash flows in the business model for expenses to be incurred. The way in which shares are used by RECs can vary. However, while quotas are a valid way to plan REC participation, they still hinder inclusion and engagement, notably if the money required is excessive [18]. An issue that many RECs are currently struggling with is finding out a way to guarantee destitute families the appropriate services and, at the same time, safeguarding sufficient funding [115]. An alternative to entering equity capital is to apply for funding from a capital fund [116]. Particularly, these are financing instruments that pool collective investments. In this scenario, the cash flows might be different depending on whether it is an institutional fund or private funds. Indeed, the latter often only disburse financial resources on a constant basis over time by reaching set milestones. A disadvantage of this method is the time-consuming administrative work that, depending on the terms of the fund, can be costly. Moreover, the major advantage is that investing in equity means sharing ownership [117]. Equity funds can be utilized for both aggregation, construction and management phase.

Secondly, the other possibility is debt financing, which differs from equity financing in the investor's intention [118]. Players financing through equity believe in the project and are also satisfied with receiving a modest remuneration. Contrarily, debt-financing actors examine the REC from a dual perspective: risk and return [119]. Once the debt has been repaid, the paths part again and there is no longer any relationship. The actors in debt financing are mainly the banks but can also be citizens. In the initial stages, especially in the operation phase, debt financing may be a simpler and more immediate source. However, the collateral to be given to banks may be substantial. In fact, it allows for positive cash flows which, however, will have to be repaid and this will generate a financial burden on future business plans. Nevertheless, banks provide short-term financing solutions. If one needs specialized support for joining or setting up a REC, the bank can refer qualified companies and technical partners, which offer services for the installation of the equipment, setting up and administrative management of the REC.

Thirdly, grants do not provide for repayment as in the previous two forms of fundings opportunities [120]. Public grants are offered from European to national, regional and municipal level. Naturally, it is necessary to apply for tenders through a project indicating the activities that will be carried out with the grant. Financial support from a public partnership is considered relevant for the promotion of RECs by many stakeholders [121]. In addition, a system could be established to receive donations and keep abreast of the different possibilities [122]. The common factor is the need for time to fulfil administrative requirements.

For the sake of comparison, the below Table 4 explains the three crucial funding opportunities.

The decision on the type of funding opportunity may affect the independence of the REC. In a REC totally financed by private citizens, the power of control over all activities and strategic decisions resides with the members [123]. Additional investors may inevitably decrease citizens control or ownership. Indeed, external parties investing in the debt financing of the project may demand that their requirements be met, therefore the higher the exposure to debt financing, the greater the impact of foreign players. Thus, it is necessary to carefully choose the correct type of financing for each activity in which funds are raised. Subsidies never have an impact on ownership, but they often involve some bureaucracy.

3.2.3. *Operating phase*

Once the feasibility study and aggregation phase are completed, the project can progress to the operating phase, which involves implementing the previously simulated plan. This phase follows a technical path aimed at defining the operational parameters. In

Table 4
Funding opportunities.

	Equity financing	Debt financing	Grants
Investors	Citizens, municipalities, SMEs	Typically banks and funds, but also citizens, municipalities and SMEs	Public authorities, charities, funds, companies, citizens
Investor becomes a member	Yes	No	No
Deadline	Long-term	Short-term	Variable
Investor benefits	Power of control. Dividend.	Financial remuneration for lending capital	Nothing
Benefits compared with other forms	More flexible and cheap. Control remains with the energy community	Bigger group of potential investors. Potential fast provision.	Free funding
Investor risks	In the event of bankruptcy, it is the last to be reimbursed	In the event of bankruptcy, it is the first to be reimbursed	Misappropriation
Forms	Share	Loan, bond	Loan, bond

contrast to the feasibility phase, real end-users consumption data are collected here, subsequent to the aggregation of the members. The operating phase is further divided into sub-phases.

- Design of energy conversion systems: it involves considering the evaluation done during the feasibility phase on available resources and RESs to be used. Data collected during the preliminary phase, such as available surfaces for systems installation, serve as a starting point for the technical design. This phase entails careful planning, including determining the power for each plant, selecting and determining the number of modules, selecting and determining the RES technology, configuring their connections to the users and to the PG, choosing inverters if necessary, and possibly incorporating a BESS. It also involves creating an economic plan.
- Construction of RES-based plants: it entails implementing what was established during the design phase. Collaborating with local resources is crucial to promote employment opportunities within the respective territories. Constructing a RES plant requires specialized personnel in the sector. The construction phase concludes with the connection and operational launch of the plant. After commissioning, actual production profiles are compared with the expected profiles from the simulation phase.
- Agreement: it involves the verification of the REC project by the national competent authority. It ensures compliance with all legal constraints and checks the design and commissioning of the RES plant. If all requirements are met, the shared energy is calculated on an hourly basis, and incentives are disbursed. This process requires providing necessary data about the legal entity, production plants, and all REC members.

Fig. 5 presents some possible REC configurations based on REC typology, plant size, plant ownership, and RES plant typology, including.

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

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

3.2.4. Management

The final phase involves the management of the REC, which extends throughout the entire lifespan of the community. The sub-phases encompass the main aspects.

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

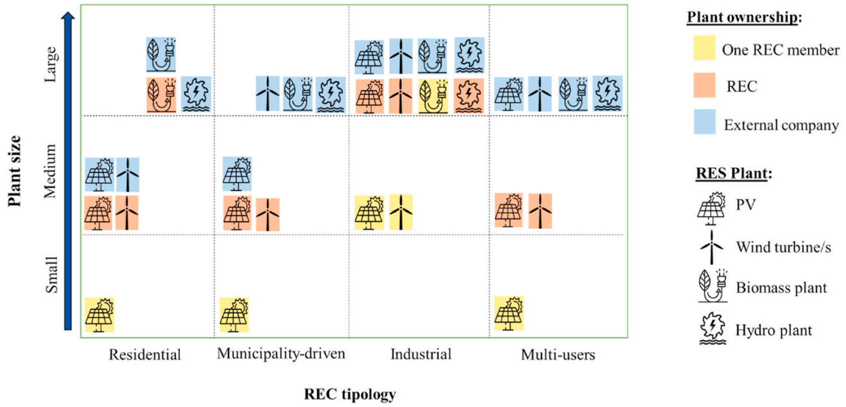

Fig. 5. Potential REC configurations.

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

3.2.4.1. Monitoring & maintenance of plants. Monitoring of plant performance involves analysing and evaluating plants are operating efficiently. Monitoring is especially crucial during the early years when the decrease in production rate due to aging is relatively limited, but it can also extend throughout the plant's entire lifespan. RES-based plants are subject to environmental stress, which can lead to long-term performance and reliability degradation. For example, PV systems are affected by high temperatures and humidity, which impact energy yield [124]. The performance ratio (P_R), ratio between final and reference yield of a PV system, is the primary index used to assess its energy production. It is expressed as a percentage on an annual basis [125]. Climate conditions in the installation area significantly influence the P_R. A comparison of five crystalline silicon (c-Si) PV modules installed in Singapore (tropical rainforest climate) revealed degradation rates ranging from 0.03%/y to 0.47%/y [126]. In contrast, polycrystalline silicon (p-Si) and monocrystalline silicon (mono-Si) PV modules installed in the Gobi Desert of Mongolia (cold-dry climate) showed degradation rates of 1.28%/y and 0.86%/y, respectively [127]. An investigation of over 2000 PV installations worldwide reported different degradation rates, with an average of 0.8%/y [128]. Operating conditions beyond standard parameters affect also the lifespan of wind turbines, typically sets at 20 years. Factors such as wind shear, ambient turbulence, additional wake turbulence, and wind speed significantly affect their durability [129]. The BESS included as a backup system to address potential unavailability of the considered RES, must also undergo monitoring. Its lifespan is mainly influenced by the number of charge/discharge cycle, discharge depth and operating conditions [130]. Among the various types of BESS associated with RES technologies, Lithium-ion (Li-ion) BESS are most prominent due to their excellent dynamic response, high energy density, high efficiency and durability. However, they are sensitive to extreme temperature ranges, impacting power output, capacity, self-discharge rate and thermal losses [131]. Nevertheless, BESSs play a positive role in enhancing network stability during fault conditions, especially in large-scale plants like wind generators [132]. The estimation of the state of health for a BESS in a REC is more complex as it depends on a broader set of variables.

Maintenance, necessary operation for any industrial plant, is often categorized into ordinary and extraordinary. Ordinary maintenance is typically conducted annually and involves the replacement of accessory components as a preventive measure. Extraordinary maintenance instead, has a ten-year cycle and entails replacing components that require temporary shutdown of the production plant. This may include the replacement of the inverter, which has a useful life of around ten years. The allocation of maintenance costs depends on the agreements established during the REC constitution phase. These costs may be borne by the plant owner, the municipality, or the entire REC.

The members are free to join or leave REC, but such decision results in changes to energy and economic flows. When users join an established REC, the assessments of the REC plant are needed. Depending on the chosen RES technology and the significance of the additional members, repowering the plant may be considered, leading to an increase in the energy produced and available for sharing. Therefore, the energy produced and available for sharing increases. Economic benefits have to be recalculated too. From perspective of the individual member, as the number of users increases, the savings decrease because, although both shared energy and the incentives increase, they are distributed among more users, reducing the share of each individual user [133].

Conversely, if the number of REC members decreases, the energy available will be greater than estimated. Consequently, the energy sold to the network increases. DSM techniques can be implemented to guide users to concentrate their loads in the hours of maximum producibility of the plants.

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

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

In addition to these, a portion of the recognised incentives is typically used to cover REC maintenance and management expenses.

The social purpose of the REC should be clear from the preliminary phase. The COVID-19 pandemic and energy conflicts have led to an increase of people experiencing energy poverty in Europe. Installing solar PV systems on available surfaces of non-profit associations could contribute to addressing this social issue, providing significant savings on energy bills through self-consumption. Another possibility is to include vulnerable families among the consumers, as they may afford essential energy services like heating and cooling in order to ensure good thermo-hygrometric conditions in environments and do not have health problems.

A case study of three residential users shows that none of them is in energy poverty condition if they are members of a REC, considering that an end-user is in this condition if he spends for energy more than 10% of his income [97]. Participation in a REC to address energy poverty is an aspect of the broader energy justice concept, which is still considered marginal in many countries. It has been proven that innovative energy systems have the potential to reduce these phenomena [134]. Municipal administrations may play a crucial role in identifying families facing energy poverty and providing them with necessary information on REC membership, as they might otherwise remain unaware of such opportunities.

In the management phase, some specialized organizations usually provide technical assistance through their legal, commercial, financial and technical expertise to reduce costs as well as contractually complex risks, thus creating replicable and financeable business models. These organizations can provide reduction of transaction costs that would normally be incurred by both the customer and the producer to perform the contract, cost negotiation by facilitating and coordinating transactions and ultimately reduction of information asymmetries between all stakeholders.

3.2.4.3. Dissemination activities. The dissemination activities carried out by REC promoters, either directly or through third parties, aim to raise awareness of these projects within the territory. It involves implementing various communication and outreach strategies to inform and engage stakeholders, including members of the REC, local residents, businesses, and other relevant parties. Dissemination activities may include organizing events, conducting educational campaigns, participating in conferences or exhibitions, and utilizing online platforms to share information about the REC's activities and achievements. The objective is to stimulate the conception, development, and participation in governance models of distributed generation and to promote new technologies for the use of RESs. RECs are also considered instruments to address social acceptability issues related to RES plants and to create employment opportunities in the relevant territories. By promoting community activities and publicly disseminating the results, they can inspire others to become potential members of the same project or to create new.

4. Results and discussion

The aim of this study is to present a standardized procedure for implementing a REC anywhere in Europe. The implementation of these innovative energy systems is not possible in all Member States yet. In some of them the absence of legal definition and therefore,

Table 5
Phases of the implementation process of existing RECs.

	Feasibility study	Aggregation	Operating phase	Management
COMMON LIGHT: Renewable Energy Community of Ferla	Feasibility study realized through a collaboration between the Municipality of Ferla, the University of Catania, and interdepartmental research project TREPESL (Energy Transition and New Models of Participation Local Development), organized and funded by the same university. Detailed data are not available.	−5 members (municipality, 2 citizens, 2 commercial activities); - unrecognised association; - Funding: Operative Plan FESR Sicilia 2014–2020.	−20 kW PV plant installed on the roof of City Hall of Ferla. The municipality is the owner of the plant; −20 kW PV plant installed on the roof of City Hall of Ferla; - National authority approved.	- data not available; - Distribution of incentives: 20% of the share granted to all members, 30% in proportion to the percentage of energy shared by each member, the remaining 50% is granted only to producers, in this case the Municipality of Ferla, which allocates them to other green initiatives or to reinvestment in other plants, thereby generating collective benefits. - dissemination activities throughout the country.
ENERGY CITY HALL: Renewable Energy Community of Magliano Alpi	Feasibility study realized by Energy Center of Polytechnic University of Turin. Detailed data are not available.	−7 members: 3 related to the Municipality (one is a prosumer), 2 artisan businesses, 2 citizens; - unrecognised association; - Funding: grant for less than 5000 inabithants Municipalities (Legge Fraccaro), used for the REC.	−20 kW PV plant installed on the roof of City Hall of Magliano Alpi. The municipality is the owner of the plant; −20 kW PV plant installed on the roof of City Hall of Magliano Alpi; - National authority approved.	- Local chain of management and maintenance of plants; - data not available; - dissemination activities throughout the country.
Energy and fair Community of Napoli Est	Project stakeholders: Social company "Fondazione Famiglia di Maria"; no-profit organization "Fondazione con il Sud"; environmentalist association "Legambiente Campania"; Technical partner "3E–Italia Solare". REC born to pursue social objectives. Detailed data are not available.	−40 families in energy poverty condition; - unrecognised association; - Funding: by "Fondazione per il Sud".	−55 kW PV plant installed on the roof of "Fondazione Famiglie di Maria". −55 kW PV plant installed on the roof of "Fondazione Famiglie di Maria". - PV plant total investment equally distributed between "Fondazione con il Sud" and funding through eco-bonus through a discount on the invoice and the assignment of credit to the companies involved.	- data not available; - a tangible benefit for the participating families, with an annual saving of about € 300 for the energy costs of each family; - dissemination activities throughout the country.

the lack of economic incentives, disadvantage their development. This entails a reduction in the diffusion of RES-based plants aimed at achieving the common European target of climate neutrality by 2050. In other European countries, such as Portugal, Spain, Italy and Austria, it is possible to implement a REC, despite differences in national regulatory framework. The presented roadmap includes the main phases required to carry out a community project focusing on energy, environmental, economic and social aspects. Each aspect can have varying importance depending on the members' priorities. The procedure may need to be adjusted to comply with the legal framework of the specific country where the REC is being implemented. Phases can be moved forward or postponed as necessary. The roadmap can also be expanded if additional steps are deemed necessary by the designer, or some others can be omitted if they are not required by the relevant authority or considered unnecessary in the specific context.

While qualitative methods excel in investigating our selected research question, our study has inherent limitations. The qualitative approach falls short in encompassing the complete range of perspectives and experiences, making statistical generalization of results challenging. Concentrating on the roadmap for REC's constitution does not assure specific outcomes but rather indicates potential results. Nonetheless, the presented methods remain applicable to comparable scenarios and hold significance for policymakers and researchers addressing challenges impeding RECs opportunities for an equitable and inclusive energy transition. Furthermore, these findings should be viewed as a catalyst for applying the methodology to extensive real case studies.

Having a standardized procedure to follow provides an advantage to stakeholders, public administrators, and citizens interested in REC implementation. The possibility to replicate already realized and successful projects allows to speed up and streamline the preliminary phases of the new REC, trying to highlight the strengths and avoid mistakes made in already implemented projects. However, there is a potential disadvantage in following a fixed procedure, as it may lead to the homogenization of projects with predetermined structures, potentially discouraging the emergence of innovative projects with new features compared to existing ones. Each innovative project represents an enrichment and can draw inspiration for future RECs. These have to use the most RESs in the area, trying to use technologies with a higher rate of national component, and offer as many benefits as possible to members. The research is in fact focusing on the study of projects which include the thermal vector, also through the use of geothermal source-based plants. The importance of balancing standardisation with adaptability, allowing for local customization while maintaining core principles and objectives, must always be considered.

To substantiate the proposed methodology, some existing RECs case studies have been examined, and their implementation process been analysed to distinguish, where possible, the phases proposed in the roadmap of this study. These case studies pertain to three Italian RECs, realized following the Italian transposition of RED II. The first case study involves the "Common Light Renewable Energy Community" of Ferla, a small village in the south of Sicily. "Energy City Hall", the first energy community in Italy, is located in Magliano Alpi, a village in northern Italy. Both are municipality-driven projects. The third case study is the solidarity REC carried out in a popular district of the city of Naples. Available details for each analysed REC are reported in Table 5 [135]. Information is provided wherever possible for each phase of the roadmap.

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

5. Conclusions

The regulatory framework in Europe introduced Renewable Energy Communities through the RED II, which provides common guidelines for Member States. However, the current transposition process reveals that rules for RECs vary significantly across the EU Member States due to geographic, cultural, economic, and political factors. In this scenario, the aim of this paper is to implement a standardized process for a Renewable Energy Community. It has been conducted a comprehensive analysis of the current state of RECs to identify widely discussed topics and gaps in scientific literature. The procedure for implementing a REC in Europe, including detailed explanations of all the main phases, represents an innovative aspect that has not been thoroughly investigated in the literature. The investigation has been conducted by including multidisciplinary aspects which belong to the economic, legal and energy field. The roadmap for Renewable Energy Community constitution, which is completely general and applicable to its widespread definition, is composed by four phases. The first one is the feasibility study, which focuses on characterizing energy users, sizing RES-based plant using dedicated software and assessing the project's impact in terms of primary energy savings, reduction of carbon dioxide equivalent emissions, cost avoidance and social purposes compared to conventional systems. The second phase is the aggregation, which involves bringing together Renewable Energy Community's members who can be producers, consumers, or prosumers. This phase also includes the legal establishment of the entity and exploring potential funding opportunities for public-driven projects or private members. The third phase of the roadmap is the operating phase, which encompasses the design and construction of production plants and the agreement phase between the REC and the national competent authority. During this phase, constraints are assessed, and incentives are dispensed. Different Renewable Energy Community' s configurations are possible, including variations in plant typology, size, ownership and renewable energy sources exploitation. The final phase is management, which involves not only the economic aspects of the Renewable Energy Community but also includes monitoring and maintenance of the plants and dissemination activities.

The proposed qualitative method has limitations in capturing a comprehensive array of perspectives and experiences, posing challenges for statistically generalizing results. In this work, the general roadmap for the establishment of RECs is primarily focused on the European case to provide concreteness to the discussion. Only a few case studies of already established Renewable Energy Communities in Europe are presented, and in future works, it would be desirable to introduce new case studies based on real-world applications developed following the proposed roadmap. Secondly, further improvements of the proposed work could be attained by including uncertainties related to the entry and exit of community members in an already constituted Renewable Energy Community. The application of the roadmap to the European context has led to the determination of an energy model primarily based on the virtual sharing of electric energy among community members. Although the work has provided insights and indications regarding the sharing of thermal energy in such case studies, it would be useful in future research to investigate, on one hand, the influence that electric storage systems could have on the flexibility of renewable energy communities, and on the other hand, the introduction of thermal sharing through district heating and cooling technologies.

Furthermore, this paper highlights the lack of robust coverage in the business economics literature of stable strategic stakeholder mapping processes that allow the use of value-added services for both for-profit and non-profit organizations. Performance measurement will be identified by future research as one of the success factors that facilitate social impact, so as to be able to reconfigure energy decision-making processes by policy makers, especially in contexts characterized by energy poverty.

Data availability statement

No data was used for the research described in the article.

Ethics declaration

Informed consent was not required for this study.

CRediT authorship contribution statement

Paolo Esposito: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elisa Marrasso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiara Martone:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giovanna Pallotta:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlo Roselli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maurizio Sasso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Massimiliano Tufo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was developed in the framework of the research activities carried out within the PRIN 2022 PNRR project: "NETPLUS – Neighborhood Energy Transition: towards Positive energy baLance and carbon neUtral diStricts", funded by the Italian Ministry of University and Research (MUR).

References

[1] IEA, World Energy Outlook 2022, 2022. https://www.iea.org/reports/world-energy-outlook-2022/key-findings/. (Accessed 25 January 2023).
[2] J. Brodny, M. Tutak, Assessing the energy security of European Union countries from two perspectives – a new integrated approach based on MCDM methods, Appl. Energy 347 (2023) 121443, https://doi.org/10.1016/j.apenergy.2023.121443.
[3] T. Ahmad, D. Zhang, A critical review of comparative global historical energy consumption and future demand: the story told so far, Energy Rep. 6 (2020) 1973–1991, https://doi.org/10.1016/j.egyr.2020.07.020.
[4] J.C. Smolović, M. Muhadinović, M. Radonjić, J. Đurašković, How does renewable energy consumption affect economic growth in the traditional and new member states of the European Union? Energy Rep. 6 (2020) 505–513, https://doi.org/10.1016/j.egyr.2020.09.028.
[5] J. Brodny, M. Tutak, Assessing the energy and climate sustainability of European union member states: an MCDM-based approach, Smart Cities 6 (2023) 339–367, https://doi.org/10.3390/smartcities6010017.
[6] IEA, Global, Energy Review: CO2 Emissions in 2021, 2022. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2. (Accessed 25 January 2023).
[7] J. Brodny, M. Tutak, Analysis of the efficiency and structure of energy consumption in the industrial sector in the European Union countries between 1995 and 2019, Sci. Total Environ. 808 (2022) 152052, https://doi.org/10.1016/j.scitotenv.2021.152052.

[8] European Council, in: European Council of the European Union, 2021. Fit for 55, https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition. (Accessed 20 March 2023).
[9] COP26, in: The Glasgow Climate Pact, 2021. https://ukcop26.org/the-glasgow-climate-pact. (Accessed 25 January 2023).
[10] United nations Climate Change, in: The Paris Agreement, 2015, in: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/. (Accessed 26 January 2023).
[11] J. Wang, F. Liu, L. Li, J. Zhang, More than innovativeness: comparing residents' motivations for participating renewable energy communities in different innovation segments, Renew. Energy 197 (2022) 552–563, https://doi.org/10.1016/j.renene.2022.07.141.
[12] M. Tutak, J. Brodny, Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment and conventional energy sources. A 20-year perspective, J. Clean. Prod. 345 (2022) 131076, https://doi.org/10.1016/j.jclepro.2022.131076.
[13] M. Papież, S. Śmiech, K. Frodyma, Determinants of renewable energy development in the EU countries. A 20-year perspective, Renew. Sustain. Energy Rev. 91 (2018) 918–934, https://doi.org/10.1016/j.rser.2018.04.075.
[14] M.L. Di Silvestre, M.G. Ippolito, E.R. Sanseverino, G. Sciumè, A. Vasile, Energy self-consumers and renewable energy communities in Italy: new actors of the electric power systems, Renew. Sustain. Energy Rev. 151 (2021) 111565, https://doi.org/10.1016/j.rser.2021.111565.
[15] P. Huang, M. Han, X. Zhang, S.A. Hussain, R.J. Bhagat, D.H. Kumar, Characterization and optimization of energy sharing performances in energy-sharing communities in Sweden, Canada and Germany, Appl. Energy 326 (2022) 120044, https://doi.org/10.1016/j.apenergy.2022.120044.
[16] M. Ram, D. Bogdanov, A. Aghahosseini, A. Gulagi, A.S. Oyewo, M. Child, C. Upeksha, K. Sadovavskaia, J. farfan, L.S.N.S. Barbosa, M. Fasihi, S. Khalili, C. Breyer, Global Energy System Based on 100% Renewable Energy, 2019. http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf.
[17] M.A. Heldeweg, S. Saintier, Renewable energy communities as 'socio-legal institutions': a normative frame for energy decentralization? Renew. Sustain. Energy Rev. 119 (2020) 109518 https://doi.org/10.1016/j.rser.2019.109518.
[18] C.E. Hoicka, J. Lowitzsch, M.C. Brisbois, A. Kumar, L.R. Camargo, Implementing a just renewable energy transition: policy advice for transposing the new European rules for renewable energy communities, Energy Pol. 156 (2021) 112435, https://doi.org/10.1016/j.enpol.2021.112435.
[19] I.F.G. Reis, I. Gonçalves, M.A.R. Lopes, C.H. Antunes, A multi-agent system approach to exploit demand-side flexibility in an energy community, Util. Pol. 67 (2020) 101114, https://doi.org/10.1016/j.jup.2020.101114.
[20] S. Moroni, V. Alberti, V. Antoniucci, A. Bisello, Energy communities in the transition to a low-carbon future: a taxonomical approach and some policy dilemmas, J. Environ. Manag. 236 (2019) 45–53, https://doi.org/10.1016/j.jenvman.2019.01.095.
[21] A. Felice, L. Rakocevic, L. Peeters, M. Messagie, T. Coosemans, L.R. Camargo, Renewable energy communities: do they have a business case in Flanders? Appl. Energy 322 (2022) 119419 https://doi.org/10.1016/j.apenergy.2022.119419.
[22] F. Ceglia, P. Esposito, A. Faraudello, E. Marrasso, P. Rossi, M. Sasso, An energy, environmental, management and economic analysis of energy efficient system towards renewable energy community: the case study of multi-purpose energy community, J. Clean. Prod. 369 (2022) 133269, https://doi.org/10.1016/j.jclepro.2022.133269.
[23] L.M. Pastore, G. Lo Basso, G. Ricciardi, L. De Santoli, Synergies between Power-to-Heat and Power-to-Gas in renewable energy communities, Renew. Energy 198 (2022) 1383–1397, https://doi.org/10.1016/j.renene.2022.08.141.
[24] F. Conte, F. D'Antoni, G. Natrella, M. Merone, A new hybrid AI optimal management method for renewable energy communities, Energy and AI 10 (2022) 100197, https://doi.org/10.1016/j.egyai.2022.100197.
[25] R. Zahedi, M.H. Ghodusinejad, A. Aslani, C. Hachem-Vermette, Modelling community-scale renewable energy and electric vehicle management for cold-climate regions using machine learning, Energy Strategy Rev. 43 (2022) 100930, https://doi.org/10.1016/j.esr.2022.100930.
[26] A. Cielo, P. Margiaria, P. Lazzeroni, I. Mariuzzo, M. Repetto, Renewable Energy Communities business models under the 2020 Italian regulation, J. Clean. Prod. 316 (2021) 128217, https://doi.org/10.1016/j.jclepro.2021.128217.
[27] F. Ceglia, E. Marrasso, C. Roselli, M. Sasso, G. Coletta, L. Pellegrino, Biomass-based renewable energy community: economic analysis of a real case study, Energies 15 (2022) 5655, https://doi.org/10.3390/en15155655.
[28] F. Ceglia, A. Macaluso, E. Marrasso, C. Roselli, L. Vanoli, Energy, environmental, and economic analyses of geothermal polygeneration system using dynamic simulations, Energies 13 (2020) 4603, https://doi.org/10.3390/en13184603.
[29] E. Cutore, R. Volpe, R. Sgroi, A. Fichera, Energy management and sustainability assessment of renewable energy communities: the Italian context, Energy Convers. Manag. 278 (2023) 116713, https://doi.org/10.1016/j.enconman.2023.116713.
[30] D. de São José, P. Faria, Z. Vale, Smart energy community: a systematic review with metanalysis, Energy Strategy Rev. 36 (2021) 100678.
[31] European Commission, Clean Energy for All Europeans Package, 2019. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en. (Accessed 8 February 2023).
[32] RED II, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=%20uriserv:OJ.L_.2018.328.01.0082.01.ENG.
[33] IEMD, Directive (EU) 2019/944 of, 2019 the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0944.
[34] E. Neska, A. Kowalska-Pyzalska, Conceptual design of energy market topologies for communities and their practical applications in EU: a comparison of three case studies, Renew. Sustain. Energy Rev. 169 (2022) 112921, https://doi.org/10.1016/j.rser.2022.112921.
[35] J. Lowitzsch, C.E. Hoicka, F.J. van Tulder, Renewable energy communities under the 2019 European Clean Energy Package – governance model for the energy clusters of the future? Renew. Sustain. Energy Rev. 122 (2020) 109489 https://doi.org/10.1016/j.rser.2019.109489.
[36] Royal Decree 244/2019, Ministerio para la Transiciòn Ecològica, 2019, https://climate-laws.org/geographies/spain/policies/royal-decree-244-2019-regulating-the-administrative-technical-and-economic-conditions-of-the-self-consumption-of-electric-energy. (Accessed 22 March 2023).
[37] D. Frieden, A. Tuerk, J. Roberts, S. D'Herbemont, B. Komel, Overview of emerging regulatory frameworks on collective self-consumption and energy communities in Europe, in: 16th International Conference on the European Energy Market (EEM), Ljubljana, Slovenia, 2019, pp. 1–6, https://doi.org/10.1109/EEM.2019.8916222.
[38] Ministerio para la Transiciòn Ecològica, Real decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, t'ecnicas y economicas del autoconsumo de energía el'ectrica, Boletín Oficial del Estado, 2020. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-5089. (Accessed 22 March 2023).
[39] R.J. Hewitt, N. Bradley, A.B. Compagnucci, C. Barlagne, A. Ceglarz, R. Cremades, M. McKeen, I.M. Otto, B. Slee, Front. Energy Res. 7 (2019) 31, https://doi.org/10.3389/fenrg.2019.00031.
[40] Budesministerium fur Wirthscaft und Klimaschutz, Das Erneuerbare-Energien-Gesetz, 2000. https://www.erneuerbare-energien.de/EE/Redaktion/DE/Dossier/eeg.html. (Accessed 16 February 2023).
[41] Agora Energiewende, Understanding the Energiewende. FAQ on the Ongoing Transition of the German Power System, 2015. https://www.agora-energiewende.de/fileadmin/Projekte/2015/Undestanding_the_EW/Agora_Understanding_the_Energiewende.pdf. (Accessed 16 February 2023).
[42] M. Haji Bashi, L. De Tommasi, A. Le Cam, L. Sánchez Relaño, P. Lyons, J. Mundó, I. Pandelieva-Dimova, H. Schapp, K. Loth-Babut, C. Egger, M. Camps, B. Cassidy, G. Angelov, C.E. Stancioff, A review and mapping exercise of energy community regulatory challenges in European member states based on a survey of collective energy actors, Renew. Sustain. Energy Rev. 172 (2023) 113055, https://doi.org/10.1016/j.rser.2022.113055.
[43] Government of Ireland, Climate Action Plan 2021, 2021. https://www.gov.ie/en/publication/6223e-climate-action-plan-2021. (Accessed 22 March 2023).
[44] Government of Greece, Energy Communities and Other Provisions, Law 4513/2018, 2018. https://www.taxheaven.gr/law/4513/2018. (Accessed 16 February 2023).
[45] D. Frieden, A. Tuerk, A.R. Antunes, V. Athanasios, A.G. Chronis, S. d'Herbemont, M. Kirac, R. Marouço, C. Neumann, E.P. Catalayud, N. Primo, A.F. Gubina, Are we on the right track? Collective self-consumption and energy communities in the European union, Sustainability 13 (2021) 12494, https://doi.org/10.3390/su132212494.

[46] Presidency of the Council of Ministers, Decreto-Lei n.° 162/2019, de 25 de outubro, 2019. https://dre.pt/dre/detalhe/decreto-lei/162-2019-125692189. (Accessed 16 February 2023).
[47] Government of Austria, Bundesrecht konsolidiert: Gesamte Rechtsvorschrift für Elektrizitätswirtschafts- und-organisationsgesetz, 2017. https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20007045. (Accessed 16 February 2023).
[48] Government of Austria, Erneuerbaren-Ausbau-Gesetz – EAG; Erneuerbaren-Ausbau-Gesetzespaket – EAG-Paket (58/ME), 2021. https://www.parlament.gv.at/gegenstand/XXVII/ME/58. (Accessed 16 February 2023).
[49] Consiglio Regionale Piemonte, Legge regionale n∘12 del 3 agosto 2018 sulla promozione dell'istituzione delle comunità energetiche, 2018. http://arianna.consiglioregionale.piemonte.it/iterlegcoordweb/dettaglioLegge.do?urn.Legge=urn:nir:regione.piemonte:legge:2018;12@2023-5-2. (Accessed 16 February 2023).
[50] Consiglio Regionale Puglia, Legge Regionale n∘45 del 9 agosto 2019 sulla Promozione dell'istituzione delle comunità energetiche, 2019. https://trasparenza.regione.puglia.it/provvedimenti/provvedimenti-della-giunta-regionale/135439. (Accessed 16 February 2023).
[51] Parlamento italiano, DECRETO-LEGGE 30 Dicembre 2019, 2019, 162, https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legge:2019-12-30;162~art19-com3. (Accessed 16 February 2023).
[52] Parlamento italiano, LEGGE 28 Febbraio 2020, 2020 n. 8, https://www.gazzettaufficiale.it/eli/gu/2020/02/29/51/so/10/sg/pdf. (Accessed 16 February 2023).
[53] ARERA, in: Delibera 04 Agosto, 2020, 318/2020/R/eel, https://www.arera.it/it/docs/20/318-20.htm#:~:text=Il%20presente%20provvedimento%2C%20in%20attuazione,conversione%2028%20febbraio%202020%2C%20n. (Accessed 16 February 2023).
[54] Decreto Legislativo 199, in: Attuazione della direttiva (UE) 2018/2001 del Parlamento europeo e del Consiglio, dell'11 dicembre 2018, sulla promozione dell'uso dell'energia da fonti rinnovabili, 2021. https://www.gazzettaufficiale.it/eli/id/2021/11/30/21G00214/sg. (Accessed 17 February 2023).
[55] ARERA, Testo integrato delle disposizioni dell'autorità di regolazione per energia reti e ambiente per la regolazione dell'autoconsumo diffuso, 2023. https://www.arera.it/allegati/docs/22/727-22alla.pdf. (Accessed 17 February 2023).
[56] I. Surwillo, Energy clusters in Poland: towards diffused green energy communities, in: Energy Transition in the Baltic Sea Region, first ed., Routledge, London, 2022, pp. 185–204, https://doi.org/10.4324/9781032003092.
[57] D. Frieden, A. Tuerk, C. Neumann, S. d'Herbemont, J. Roberts, Collective Self-Consumption and Energy Communities: Trends and Challenges in the Transposition of the EU Framework, 2020, https://doi.org/10.13140/RG.2.2.25685.04321.
[58] B.K. Sovacool, M.L. Barnacle, A. Smith, M.C. Brisbois, Towards improved solar energy justice: exploring the complex inequities of household adoption of photovoltaic panels, Energy Pol. 164 (2022) 112868, https://doi.org/10.1016/j.enpol.2022.112868.
[59] F. Egli, B. Steffen, T.S. Schmidt, A dynamic analysis of financing conditions for renewable energy technologies, Nat. Energy 3 (12) (2018) 1084–1092, https://doi.org/10.1038/s41560-018-0277-y.
[60] G. Raimondi, G. Spazzafumo, Exploring renewable energy communities integration through a hydrogen power-to-power system in Italy, Renew. Energy 206 (2023) 710–721, https://doi.org/10.1016/j.renene.2023.02.074.
[61] S. Becker, C. Kunze, M. Vancea, Community energy and social entrepreneurship: addressing purpose, organisation and embeddedness of renewable energy projects, J. Clean. Prod. 147 (2017) 25–36, https://doi.org/10.1016/j.jclepro.2017.01.048.
[62] M. Scott Cato, L. Arthur, R. Smith, T. Keenoy, Entrepreneurial Energy: Associative Entrepreneurship in the Renewable Energy Sector in Wales, 2007, https://doi.org/10.2139/ssrn.1970251.
[63] J. Kotcher, E. Maibach, W.T. Choi, Fossil fuels are harming our brains: identifying key messages about the health effects of air pollution from fossil fuels, BMC Publ. Health 19 (1) (2019) 1–13, https://doi.org/10.1186/s12889-019-7373-1.
[64] C. Conteh, B. Harding, Boundary-spanning in public value co-creation through the lens of multilevel governance, Publ. Manag. Rev. 25 (1) (2023) 104–128, https://doi.org/10.1080/14719037.2021.1942529.
[65] S. Nathaniel, O. Anyanwu, M. Shah, Renewable energy, urbanization, and ecological footprint in the Middle East and North Africa region, Environ. Sci. Pollut. Res. 27 (2020) 14601–14613, https://doi.org/10.1007/s11356-020-08017-7.
[66] E. Ferlie, Concluding discussion: key themes in the (possible) move to co-production and co-creation in public management, Pol. Polit. 49 (2) (2021) 305–317, https://doi.org/10.1332/030557321X16129852287751.
[67] T. Bovaird, E. Loeffler, From Engagement to Co-production: How Users and Communities Contribute to Public Services. New Public Governance, the Third Sector, and Co-production, s.l.: Routledge, 2021, pp. 53–78, https://doi.org/10.1007/s11266-012-9309-6.
[68] A. Dudau, R. Glennon, B. Verschuere, Following the yellow brick road? (Dis)enchantment with co-design, co-production and value co-creation in public services, Publ. Manag. Rev. 21 (11) (2019) 1577–1594, https://doi.org/10.1080/14719037.2019.1653604.
[69] L. Bottaccioli, S. Di Cataldo, A. Acquaviva, E. Patti, Realistic multi-scale modeling of household electricity behaviors, IEEE Access 7 (2018) 2467–2489, https://doi.org/10.1109/ACCESS.2018.2886201.
[70] J. Widén, E. Wäckelgård, A high-resolution stochastic model of domestic activity patterns and electricity demand, Appl. Energy 87 (2010) 1880–1892, https://doi.org/10.1016/j.apenergy.2009.11.006.
[71] A. Grandjean, J. Adnot, G. Binet, A review and an analysis of the residential electric load curve models, Renew. Sustain. Energy Rev. 16 (2012) 6539–6565, https://doi.org/10.1016/j.rser.2012.08.013.
[72] M. Muratori, M.C. Roberts, R. Sioshansi, V. Marano, G. Rizzoni, A highly resolved modeling technique to simulate residential power demand, Appl. Energy 107 (2013) 465–473, https://doi.org/10.1016/j.apenergy.2013.02.057.
[73] T. Hong, Y. Chen, X. Luo, N. Luo, S.H. Lee, Ten questions on urban building energy modeling, Build. Environ. 168 (2020) 106508, https://doi.org/10.1016/j.buildenv.2019.106508.
[74] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sustain. Energy Rev. 13 (8) (2009) 1819–1835, https://doi.org/10.1016/j.rser.2008.09.03.
[75] N. Abbasabadi, M. Ashayeri, Urban energy use modeling methods and tools; a review and an outlook for future tools, Build. Environ. 161 (2019) 106270, https://doi.org/10.1016/j.buildenv.2019.106270.
[76] U. Ali, M.A. Shamsi, C. Hoare, E. Mangina, J. O'Donnell, Review of urban building energy modeling (UBEM) approaches, methods and tools using qualitative and quantitative analysis, Energy Build. 246 (2021) 111073, https://doi.org/10.1016/j.enbuild.2021.111073.
[77] T. Hong, Y. Chen, S.H. Lee, M.A. Piette, Citybes: a web-based platform to support city-scale building energy efficiency, in: Proc. Of 5th International Conference Urban Computing Workshop at San Francisco, 2016. August.
[78] B. Polly, C. Kutscher, D. Macumber, M. Schott, S. Pless, B. Livingood, O. Van Geet, From Zero Energy Buildings to Zero Energy Districts, NREL, Golden, CO, USA, 2016. National Renewable Energy Laboratory, No. NREL/CP-5500-66292.
[79] T. Vermeulen, J.H. Kämpf, B. Beckers, Urban form optimization for the energy performance of buildings using citysim, in: Proceedings of CISBAT 2013 - September 4-6, 2013 - Lausanne, Switzerland, 2013.
[80] Analytics, C., The ultimate technical guide to urbanfootprint. Available online: https://urbanfootprint.com/. (accessed 16 January 2024).
[81] N. Abbasabadi, M. Ashayeri, R. Azari, B. Stephens, M. Heidarinejad, An integrated data-driven framework for urban energy use modeling (UEUM), Appl. Energy 253 (2019) 113550, https://doi.org/10.1016/j.apenergy.2019.113550.
[82] Clean Energy City Energy Proforma. Available online: http://energyproforma.mit.edu/webtool3/home. (accessed 16 January 2024).
[83] P. Remmen, M. Lauster, M. Mans, M. Fuchs, T. Osterhage, D. Müller, Teaser: an open tool for urban energy modelling of building stocks, Journal of Building Performance Simulation 11 (1) (2017) 84–98, https://doi.org/10.1080/19401493.2017.1283539.
[84] R. Kaden, T.H. Kolbe, City-wide total energy demand estimation of buildings using semantic 3d city models and statistical data, in: Proc. Of the 8th International 3D GeoInfo Conference, 2013.
[85] J.A. Fonseca, T.A. Nguyen, A. Schlueter, F. Marechal, City energy analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts, Energy Build. 113 (2016) 202–226, https://doi.org/10.1016/j.enbuild.2015.11.055.

[86] A. Rahman, O. Farrok, M.M. Haque, Environmental impact of renewable energy source based electrical power plants: solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic, Renew. Sustain. Energy Rev. 161 (2022) 112279, https://doi.org/10.1016/j.rser.2022.112279.
[87] M.S. Nazir, A.J. Mahdi, M. Bilal, H.M. Sohail, N. Ali, H.M.N. Iqbal, Environmental impact and pollution-related challenges of renewable wind energy paradigm – a review, Sci. Total Environ. 683 (2019) 436–444, https://doi.org/10.1016/j.scitotenv.2019.05.274.
[88] Homer Pro, Homer Software, 2023. https://www.homerenergy.com/products/pro/index.html. (Accessed 16 March 2023).
[89] Trnsys, Trnsys–- Transient System Simulation Tool, 2023. Available online: https://www.trnsys.com/. (Accessed 20 March 2023).
[90] IHOGA/MHOGA Simulation and optimization of stand-alone and grid-connected hybrid renewable systems. Available online: https://ihoga.unizar.es/en/ (accessed 16 January 2024).
[91] Hybrid2: The Hybrid System Simulation Model. Available online: https://www.nrel.gov/docs/legosti/old/21272.pdf. (accessed 16 January 2024).
[92] RETScreen Clean Energy Project Analysis Software. Available online: https://www.energyplan.eu/othertools/allscales/retscreen/. (accessed 16 January 2024).
[93] M. Cuesta, T. Castillo-Calzadilla, C. Borges, A critical analysis on hybrid renewable energy modeling tools: an emerging opportunity to include social indicators to optimise systems in small communities, Renew. Sustain. Energy Rev. 122 (2020) 109691, https://doi.org/10.1016/j.rser.2019.109691.
[94] C. Ammari, D. Belatrache, B. Touhami, S. Makhloufi, Sizing, optimization, control and energy management of hybrid renewable energy system—a review, Energy and Built Environment 3 (4) (2022) 399–411, https://doi.org/10.1016/j.enbenv.2021.04.002.
[95] V. Casalicchio, G. Manzolini, M.G. Prina, D. Moser, From investment optimization to fair benefit distribution in renewable energy community modelling, Appl. Energy 310 (2022) 118447, https://doi.org/10.1016/j.apenergy.2021.118447.
[96] J. Radl, A. Fleischhacker, F.H. Revheim, G. Lettner, H. Auer, Comparison of profitability of PV electricity sharing in renewable energy communities in selected European countries, Energies 13 (19) (2020) 5007, https://doi.org/10.3390/en13195007.
[97] F. Ceglia, E. Marrasso, S. Samanta, M. Sasso, Addressing energy poverty in the energy community: assessment of energy, environmental, economic, and social benefits for an Italian residential case study, Sustainability 14 (2022) 15077, https://doi.org/10.3390/su142215077.
[98] F. Ceglia, E. Marrasso, C. Roselli, M. Sasso, Energy and environmental assessment of a biomass-based renewable energy community including photovoltaic and hydroelectric systems, Energy 282 (2023) 128348, https://doi.org/10.1016/j.energy.2023.128348.
[99] Gruppo Professione Energia, Autoconsumo collettivo e comunità dell'energia – Manuale operativo, 2020 vol. 1, http://www.enusyst.eu/documents/ManualeOperativoV1.0.pdf.
[100] M. Koltunov, S. Pezzutto, A. Bisello, G. Lettner, A. Hiesl, W. van Sark, A. Louwen, E. Wilczynski, Mapping of energy communities in Europe: status quo and review of existing classifications, Sustainability 15 (10) (2023) 8201, https://doi.org/10.3390/su15108201.
[101] P.D. Conradie, O. De Ruyck, J. Saldien, K. Ponnet, Who wants to join a renewable energy community in Flanders? Applying an extended model of Theory of Planned Behaviour to understand intent to participate, Energy Pol. 151 (2021) 112121, https://doi.org/10.1016/j.enpol.2020.112121.
[102] A. Crespo Márquez, A. de la Fuente Carmona, S. Antomarioni, A process to implement an artificial neural network and association rules techniques to improve asset performance and energy efficiency, Energies 12 (18) (2019) 3454, https://doi.org/10.3390/en12183454.
[103] T. Bauwens, B. Huybrechts, F. Dufays, Understanding the diverse scaling strategies of social enterprises as hybrid organizations: the case of renewable energy cooperatives, Organ. Environ. 33 (2) (2020) 195–219, https://doi.org/10.1177/1086026619837126.
[104] G. Surie, Creating the innovation ecosystem for renewable energy via social entrepreneurship: insights from India, Technol. Forecast. Soc. Change 121 (2017) 184–195, https://doi.org/10.1016/j.techfore.2017.03.006.
[105] S. Becker, C. Kunze, M. Vancea, Community energy and social entrepreneurship: addressing purpose, organisation and embeddedness of renewable energy projects, J. Clean. Prod. 147 (2017) 25–36, https://doi.org/10.1016/j.jclepro.2017.01.048.
[106] Z. Yousaf, M. Radulescu, C. Sinisi, A.A. Nassani, M. Haffar, How do firms achieve green innovation? Investigating the influential factors among the energy sector, Energies 15 (7) (2022) 2549, https://doi.org/10.3390/en15072549.
[107] P. Esposito, P. Ricci, How to turn public (dis) value into new public value? Evidence from Italy, Publ. Money Manag. 35 (2015) 3 227–231, https://doi.org/10.1080/09540962.2015.1027499.
[108] P. Esposito, V. Brescia, C. Fantauzzi, R. Frondizi, Understanding social impact and value creation in hybrid organizations: the case of Italian civil service, Sustainability 13 (7) (2021) 4058, https://doi.org/10.3390/su13074058.
[109] J. Roberts, What are energy communities under the EU's clean energy package? Renewable Energy Communities and the Low Carbon Energy Transition in Europe (2021) 23–48, https://doi.org/10.1007/978-3-030-84440-0_2.
[110] M.L. Bassani, The prosumer legal protection in Latin America: a requirement for an energy transition, in: The Regulation and Policy of Latin American Energy Transitions, 2020, pp. 117–132.
[111] K.O. Adu-Kankam, L.M. Camarinha-Matos, Renewable energy communities or ecosystems: an analysis of selected cases, Heliyon 8 (2) (2022) 12617, https://doi.org/10.1016/j.heliyon.2022.e12617.
[112] F. Envall, D. Andersson, J. Wangel, Gridlocked: sociomaterial configurations of sustainable energy transitions in Swedish solar energy communities, Energy Res. Social Sci. 102 (2023) 103200, https://doi.org/10.1016/j.erss.2023.103200.
[113] M. Rezec, B. Scholtens, Financing energy transformation: the role of renewable energy equity indices, Int. J. Green Energy 14 (4) (2017) 368–378, https://doi.org/10.1080/15435075.2016.1261704.
[114] L. Holstenkamp, Financing consumer (co-) ownership of renewable energy sources, Energy Transition: Financing Consumer Co-Ownership in Renewables (2019) 115–138, https://doi.org/10.1007/978-3-319-93518-8_6.
[115] F. Hanke, R. Guyet, M. Feenstra, Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases, Energy Res. Social Sci. 80 (2021) 102244, https://doi.org/10.1016/j.erss.2021.102244.
[116] L. Byrnes, C. Brown, J. Foster, L.D. Wagner, Australian renewable energy policy: barriers and challenges, Renew. Energy 60 (2013) 711–721, https://doi.org/10.1016/j.renene.2013.06.024.
[117] S.S. Gao, S. Heravi, J.Z. Xiao, 2005. Determinants of corporate social and environmental reporting in Hong Kong: a research note, Accounting Forum, Elsevier 29 (2) (2015) 233–242, https://doi.org/10.1016/j.accfor.2005.01.002.
[118] Y.A. Daiyabu, N.A.A. Manaf, H. Mohamad Hsbollah, Extending the theory of planned behaviour with application to renewable energy investment: the moderating effect of tax incentives, Int. J. Energy Sect. Manag. 17 (2) (2023) 333–351, https://doi.org/10.1108/IJESM-11-2021-0011.
[119] S. Salm, S.L. Hille, R. Wüstenhagen, What are retail investors' risk-return preferences towards renewable energy projects? A choice experiment in Germany, Energy Pol. 97 (2016) 310–320, https://doi.org/10.1016/j.enpol.2016.07.042.
[120] M. Krug, M.R. Di Nucci, M. Caldera, E. De Luca, Mainstreaming community energy: is the renewable energy directive a driver for renewable energy communities in Germany and Italy? Sustainability 14 (12) (2022) 7181, https://doi.org/10.3390/su14127181.
[121] K. Standal, M.D. Leiren, I. Alonso, I. Azevedo, I. Kudrenickis, P. Maleki-Dizaji, E. Laes, M.R. Di Nucci, M. Krug, Can renewable energy communities enable a just energy transition? Exploring alignment between stakeholder motivations and needs and EU policy in Latvia, Norway, Portugal and Spain, Energy Res. Social Sci. 106 (2023) 103326, https://doi.org/10.1016/j.erss.2023.103326.
[122] Á. Manso-Burgos, D. Ribó-Pérez, M. Alcázar-Ortega, T. Gómez-Navarro, Local energy communities in Spain: economic implications of the new tariff and variable coefficients, Sustainability 13 (19) (2021) 10555, https://doi.org/10.3390/su131910555.
[123] J. Lowitzsch, Consumer stock ownership plans (CSOPs)—the prototype business model for renewable energy communities, Energies 13 (1) (2019) 118, https://doi.org/10.3390/en13010118.
[124] S. Regondi, H. Hanif, J. Schneider, Modeling and simulation of the influence of interconnection losses on module temperature in moderate and desert regions, IEEE J. Photovoltaics 9 (5) (2019) 1449–1455, https://doi.org/10.1109/JPHOTOV.2019.2924406.
[125] D.H. Daher, L. Gaillard, C. Menézo, Experimental assessment of long-term performance degradation for a PV power plant operating in a desert maritime climate, Renew. Energy 187 (2022) 44–55, https://doi.org/10.1016/j.renene.2022.01.056.

[126] W. Luo, Y.S. Khoo, P. Hacke, D. Jordan, L. Zhao, S. Ramakrishna, A.G. Aberle, T. Reindl, Analysis of the long-term performance degradation of crystalline silicon photovoltaic modules in tropical climates, IEEE J. Photovoltaics 9 (1) (2019), https://doi.org/10.1109/JPHOTOV.2018.2877007.

[127] B. Bayandelger, Y. Ueda, B. Batbayar, A. Adiyabat, N. Enebish, K. Otani, Long-term performance and degradation rate analyses of photovoltaic modules exposed in the Gobi Desert, Mongolia, Jpn. J. Appl. Phys. 57 (2018) 08RG07, https://doi.org/10.7567/JJAP.57.08RG07.

[128] D.C. Jordan, S.R. Kurtz, The dark horse of evaluating long-term field performance—data filtering, IEEE J. Photovoltaics 4 (1) (2014) 317–323, https://doi.org/10.1109/JPHOTOV.2013.2282741.

[129] J. Zhang, H. Zuo, S. Zhu, J. Yang, L. Lu, Fatigue degradation of wind turbines considering dynamic wake meandering effects, Eng. Struct. 300 (2024) 117132, https://doi.org/10.1016/j.engstruct.2023.117132.

[130] Md M. Islam, C.H. Dagli, Z. Sun, A model to estimate the lifetime of BESS for the prosumer community of manufacturers with OGS, Proc. Comput. Sci. 168 (2020) 186–194, https://doi.org/10.1016/j.procs.2020.02.274.

[131] A. Vazquez-Rodriguez, A. Michiorri, G. Kariniotakis, Integrating thermal properties and degradation modelling of batteries into the scheduling of hybrid power plants with photovoltaics, J. Energy Storage 73 (2023) 108782, https://doi.org/10.1016/j.est.2023.108782. Part A.

[132] E. Šunj, M. Šarić, J. Hivziefendic, Wind generator transient response analysis and improvement using BESS, IFAC-PapersOnLine 55 (2022) 322–327, https://doi.org/10.1016/j.ifacol.2022.06.053.

[133] RSE, Assolombarda, COMUNITÀ ENERGETICHE RINNOVABILI Quali opportunità per le imprese, Dispensa n°20/2023, https://www.rse-web.it/wp-content/uploads/2023/12/5_12_2023-Vademecum-Comunita-energetiche-rinnovabili.pdf.

[134] J. Ehnberg, H. Ahlborg, E. Hartvigsson, Approach for flexible and adaptive distribution and transformation design in rural electrification and its implications, Energy for Sustainable Development 54 (2020) 101–110, https://doi.org/10.1016/j.esd.2019.10.002.

[135] L. De Vidovich, L. Tricarico, M. Zulianello, Community Energy Map Una ricognizione delle prime esperienze di comunità energetiche rinnovabili, FrancoAngeli, 2021.