smart cities

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Review

Review of Energy Communities: Definitions, Regulations, Topologies, and Technologies

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Highlights:

This paper deals with an overview of energy communities definitions, characterization, architectures and technologies. The energy communities contribute to the decarbonization of the energy sector and are developing all around Europe to transform existing cities towards sustainable and smart cities.

What are the main findings?
- Overview of energy communities: definition and characterization.
- Analysis of technologies and typologies for energy communities.

What are the implications of the main findings?
- Condensed survey of regulations for energy communities.
- Investigation of centralized and decentralized systems for energy communities.

Abstract: The Clean Energy package recognizes and offers a favorable regulatory framework for citizens and energy communities with renewable energy sources. However, various countries' national regulations will be highly important for the successful development of energy communities in existing cities and surrounding areas. Energy communities represent a way in which citizens and local authorities can invest in clean energy sources and energy efficiency, with several benefits in addition to the financial ones, like strengthening the concept of community and individual contributions to reductions in the overall carbon footprint. In this paper, an overview of recent developments in financial incentives in energy communities, their organization, and typologies, as well as benefits shared among the participants, is performed. The overview reveals the potential of energy communities in contributing to the economic, energetic, and social development of cities towards sustainable and smart cities.

Keywords: energy communities; clean energy; renewable energy sources; microgrids; peer-to-peer

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1. Introduction

In the context of the transition to a green future in which the sources of pollution are drastically limited or eliminated, considering the field of electricity generation, electricity production can be achieved without the release of pollutants [1].

According to the regulations imposed by the European Community (Green Deal package), Europe wants to become neutral about polluting emissions by 2050 [2]. Taking into account the influence of the goals set by the European Green Deal package, renewable energy sources (RES), together with energy storage systems (ESSs), are increasingly being used to determine energy communities (ECs), which can be defined as citizen energy communities (CEC) or renewable energy communities (RECs). ECs receive financial support through programs and initiatives worldwide. In Europe, the programs and initiatives that contribute to achieving climate neutrality, energy efficiency and, at the same time, the participation of citizens in the energy transition, to accept the changes for a brighter and cleaner future, are presented in Figure 1 [3–6].

But how do these models differ and what do they reveal about the global energy transition? This paper delves into these questions, uncovering the nuanced definitions, characterizations, and global significance of ECs in driving the energy transition.

RESs are a key component in ECs and the capacity installed in RESs can be chosen according to the needs. These can be installed in the form of power plants (with a large installed capacity) or directly in the space of the domestic consumer (of small sizes). Furthermore, traditional consumers can make the transition to prosumers, thus having the ability to consume and produce power [7]. The capacity installed in the RES depends on the consumption requirement and it is always important to correctly size them: oversizing RESs can lead to the impossibility of injecting the surplus into the public network. RESs have been in constant development and their use is constantly increasing (Figure 2) as a sustainable and environmentally friendly alternative to traditional fossil fuels, contributing to the reduction of greenhouse gas emissions [8]. Many types of RESs have been developed across the centuries up until now; they are enumerated in Figure 3 [9–11].

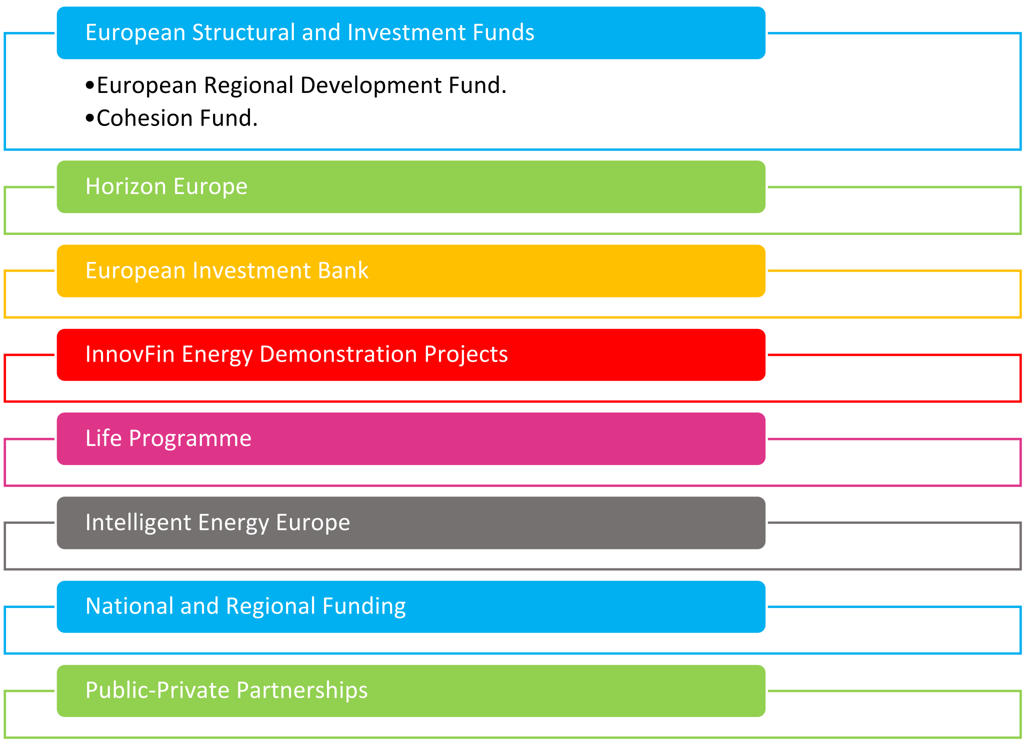

Figure 1. Financial support for energy communities in Europe.

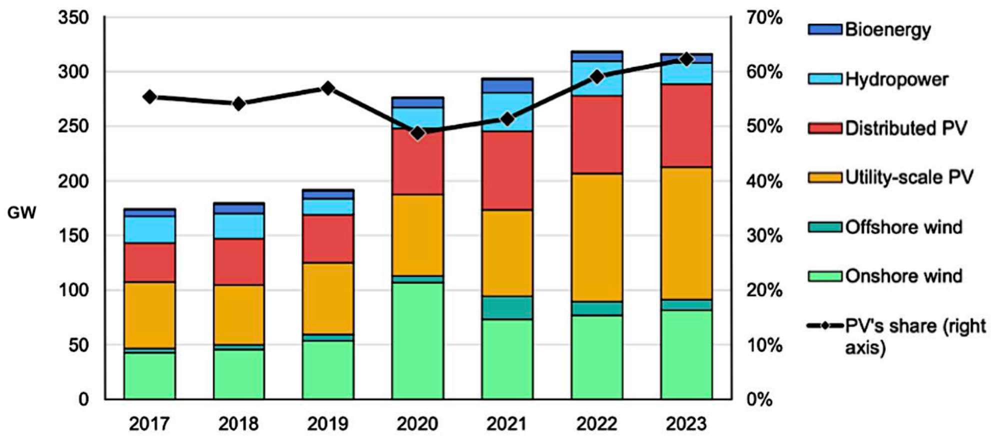

Figure 2. Net RES capacity from 2017 to 2023.

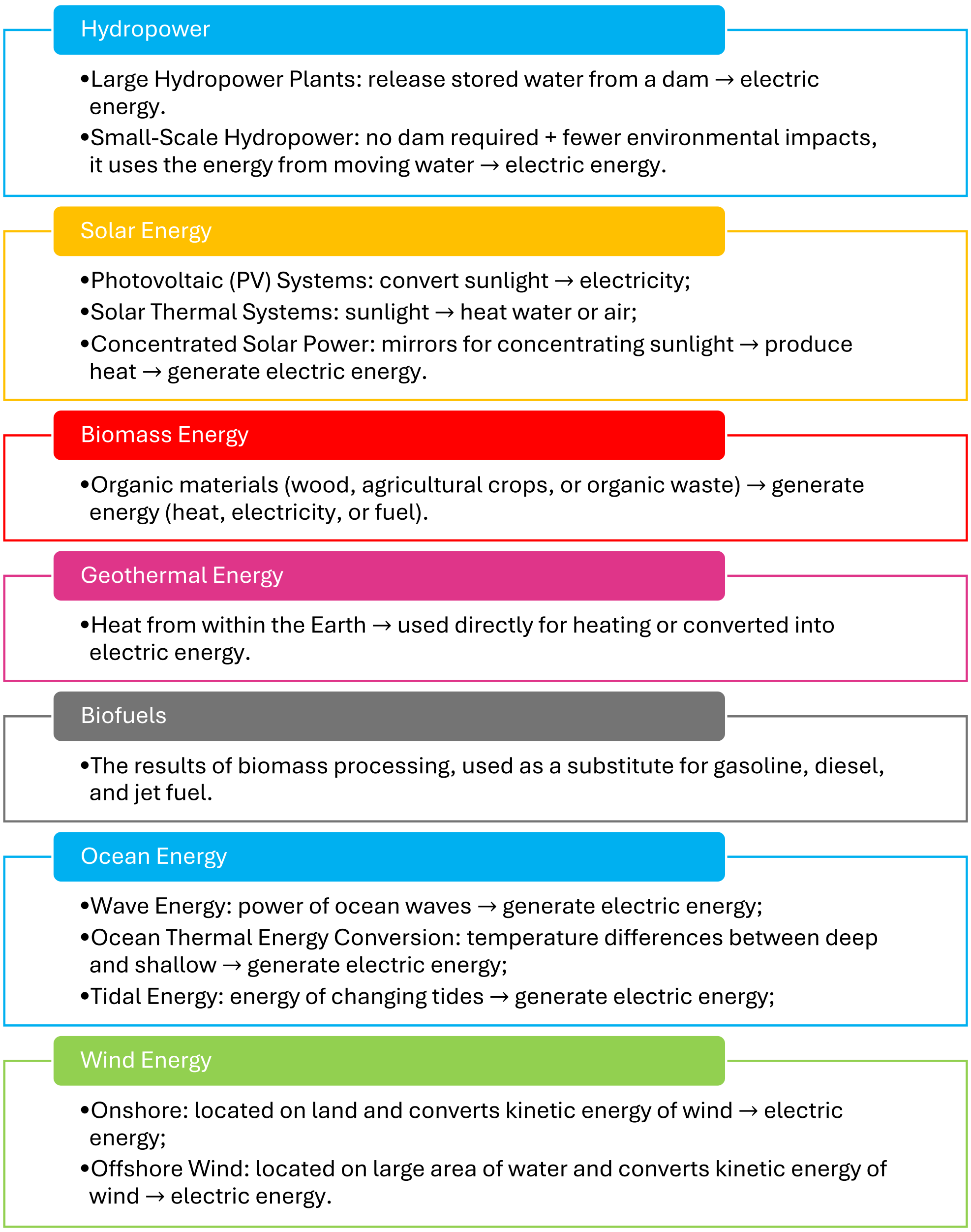

Figure 3. Types of RESs known up to 2024.

RESs have contributed to the transition of the traditional consumer to an active consumer or prosumer who can purchase electricity from the mains based on a contract with a local supplier or can use the electricity produced by their own RESs installed in their house areas. Moreover, through another contract they can sell back to the public grid the energy surplus produced from their own generation sources. The prosumer can use different RESs (PV panels installed on the rooftop of the building, wind turbines if the area has favorable eolian potential) and a storage system used as a power reserve. The consumer can choose if the energy surplus is stored and used later to cover their own consumption or injected into the public grid during peak load periods or when it is considered beneficial from an economic point of view [12–14]. These types of consumers are a key component in ECs. ECs can be defined in many ways; the European Commission describes energy communities as collective and citizen-driven energy actions which contribute to the transition to a greener future and are focused on the well-being of citizens, offering direct advantages to citizens by maximizing energy efficiency, reducing electricity expenses, and creating local job opportunities [15].

Energy communities enhance the well-being of citizens, leading to a sustainable environment, enhanced life quality, smart economy, smart society, and smart governance. In Naples, Italy, the energy community promotes local development and direct involvement of citizens in renewable energy projects, increasing resilience and reducing energy poverty [16]. In Germany, the energy community Energiegenossenschaft Odenwald eG has more than 3000 members and involves municipal actors, and a local bank, and developed more than 80 solar plants, leading to an increase in energy efficiency, a clean energy transition, reduction in energy bills, and improvement of well-being [17]. In Norway, the community in Utsira Island is a testbed for smart renewable energy generation and management and control in weak grids, and the knowledge can be applied to other areas in order to increase resilience and social benefits of energy continuities [18]. In Denmark, Avedøre A.M.B.A is an energy community which is part of the green city goal, using solar panels for heating and charging stations for electric cars [19].

There are many legal structures under which ECs can be established, associations, cooperatives, partnerships, non-profits, and small-to-medium-sized enterprises, that facilitate collaborative investments in energy assets by citizens and other market participants. The participation in CECs and RECs is voluntary and open, and requires specific governance. The purpose of the energy communities is to bring ecologic, economic, and social advantages to local consumers, with less interest in profit generation at the national level. The energy communities collaborate with distribution system operators which, under an equitable compensation established under regulations emitted by each country's competent authority, facilitate the power flows within the community. In Europe, states are encouraged to incentivize renewable energy communities to allow aggregation services and not to mainly behave as important actors in the energy market.

An investigation of concepts and definitions of energy communities is conducted in [20], revealing the potential gaps and overlap in terms referring to energy communities. The study reveals that a reduction in pollutant emissions is one of the main benefits brought by energy communities. ECs operate as unified entities with access to energy markets, competing fairly with other market players in order to develop a flexible green energy system [21]. The European Parliament offered funding for three different projects (Figure 4) that contribute to the dissemination of best practices and provide technical assistance for the development of ECs across the EU [21].

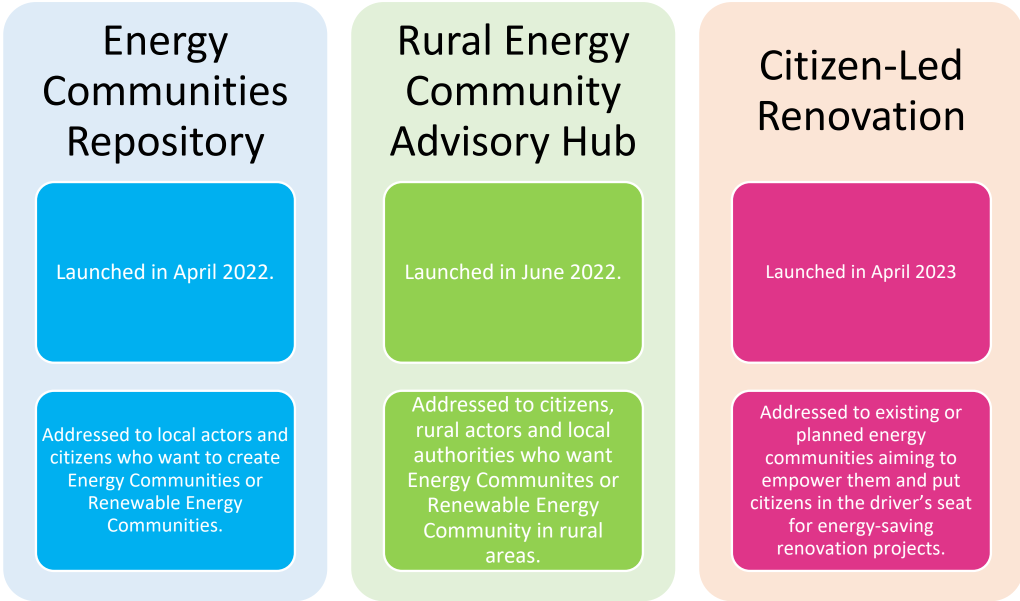

Figure 4. Funding projects for energy communities.

The different types of energy communities (ECs), citizen energy communities (CECs) and renewable energy communities (RECs), describe collective efforts in energy generation and distribution, but each possesses some differences, as presented in Figure 5 [20]. The members of the renewable energy community are located in the vicinity of the renewable energy sources owned by the community. In citizen energy communities, the members are not required to be close to the generation locations; in this way, participants from other geographical areas can also be involved.

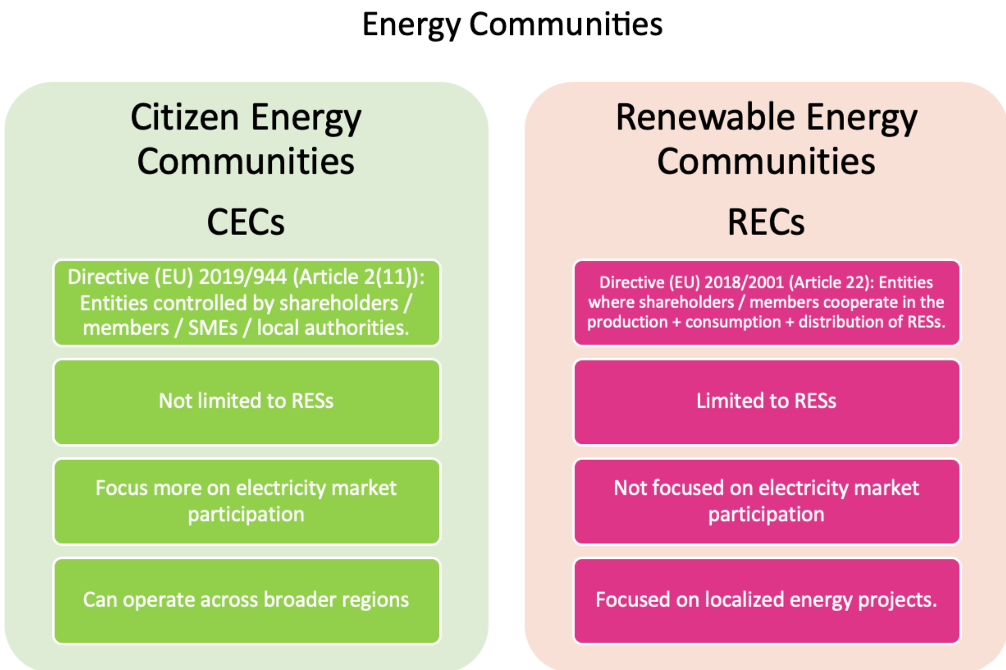

Figure 5. Differences between CECs and RECs.

Various investment schemes can be in place in energy communities. The local community members can invest their own funds to purchase the necessary sources and equipment for the local supply and they own the energy system. The barrier is the high initial investment [22,23]. Another possibility for investment is from third-party entities like companies, grid operators, and aggregators, which make profit from the operation of the energy community. The members purchase electricity from the community or from the grid as a function of the electricity prices offered by the two parties [24]. A mechanism based on static/dynamic/hybrid/even sharing coefficients of the produced energy and the expected profits obtained in an energy community is investigated and simulated in [25]. A time-of-use pricing mechanism for energy communities is proposed in [26], where the price of energy varies depending on the time of day or the season for energy consumption in peak and off-peak hours, in order to incentivize consumers to shift or reduce their energy consumption in peak hours. The feed-in tariff schemes applied in energy communities provide financial incentives for community members who produce renewable energy and feed it back into the grid. Ref. [27] analyzes the techno-economic feasibility of buildings operating as single-self consumers and buildings participating in an energy community. Three different redistribution mechanisms for energy community-incurred grid costs are proposed in [28]. Income-based redistribution is focused on the financial burden of low-income households; contribution-based redistribution benefits participants providing PV rooftop systems; while proximity-based redistribution rewards virtual energy flows with short distances from the source to the consumption point. Cost allocation among the community members is investigated in [29]. The Shapley value approach is based on the contribution of each member to the community, but it requires long computational times. The equal allocation of non-separable values compares the gap between each individual's initial energy bill and the community's total bill, and the benefits are shared by dividing the collective savings equally among the participants, thus decreasing individual bills. In a proportional allocation method based on the Nash equilibrium concept, the bill decrease is proportionally assigned based on a comparison among the initial individual bills and their contribution to the community bill. An optimization model can be formulated and resolved for optimized cost allocation, which delivers the prices for the consumption/generation of the energy community (i.e., the meter value). The application of Shapley values in a case study of an energy community in Trondheim is investigated in [30], where flat energy pricing (based on an individual's energy consumption and yearly consumption) and coincident/noncoincident peak consumption of individuals with respect to community power consumption are compared. The remainder of this paper is structured as follows. Section 2 summarizes the regulations at EU level regarding energy communities. Section 3 discusses technologies and system architectures, while Section 4 concludes the overview on energy communities. This paper aims to contribute to the literature by addressing the topic of energy communities from the definition, regulation, technology, and system architecture points of view.

The ultimate goal of energy communities is to provide environmental, economic, or social benefits at the community level to shareholders or members, and they are aimed at supporting the path toward energy transition and emissions reduction.

The topic of energy communities fits well into smart cities. The development of such communities must necessarily pass through a smart grid connecting intelligent buildings that can optimize their consumption. The community grid serves the decentralized, local, and collective energy model, with benefits for the social engagement of participants, clean energy, reductions in energy poverty, and innovation enhancement. Energy communities are a new model and a promising tool for the energy transition process, and are often at the forefront of adopting new technologies that ensure efficient management of energy consumption and distribution. This development model will bring a revolution in terms of digital energy, helping to develop smart cities of any size, to increase people's well-being, making them aware of their energy consumption, and allowing them to optimize it through sharing. Energy infrastructures occupy a central place in the city ecosystem. Urban areas represent one of the main places of energy consumption and consequently are one of the main players in the decarbonization process. Energy infrastructures will be one of the founding pillars on which to develop the smart cities of the future. The public lighting infrastructure is a clear example. Widespread in every city, it can easily integrate solutions capable of covering a wide range of services: traffic management, security, environmental monitoring, wireless connectivity, just to name a few examples.

Finally, according to the International Energy Agency, it is estimated that 1.3–2.6 billion people on the planet suffer from energy poverty, with multiple negative effects on both the socioeconomic sector and the environment [31]. Energy communities allow individuals for whom it would be difficult to invest in the construction of renewable energy facilities to share, instead, the benefits of installing a renewable energy plant and thus to obtain amounts that contribute to reduction in their energy costs.

2. Regulations in ECs

There are many regulations regarding energy communities that are still being developed worldwide. These regulations vary from country to country or region to region within a country. The regulations are determined by the energy policies, the legal framework, and the structure of the energy markets in the respective areas, as shown in Figure 6 [32–36]. In Europe, the regulations forming ECs are primarily governed by the European Union's legislative framework. In Figure 7, the EU directives for ECs are presented along with their schematic description [37–39].

The "Clean Energy for All Europeans Package" was introduced in 2016 and adopted by 2019; the key components of the "Clean Energy for All Europeans Package" are presented in Figure 8 [37].

Electricity Directive (2019/944) [38] introduces the concept of CECs as can be seen in Figure 9. CECs are defined in Article 2(11) from different points of view: they are a legal entity; citizens can voluntarily participate in the community along with individuals, local authorities, and others, having the primary objective of providing environmental, economic, and social community benefits favoring the load coverage in the community with the help of CEC participants. CECs allow members or shareholders to participate in the decision-making process and support distributed generation.

The Renewable Energy Directive (2018/2001/EU), or RED II, was introduced as part of the Clean Energy for All Europeans package and the key aspects are presented in Figure 10 [39].

Figure 6. Worldwide EC regulations.

Figure 7. Directives for energy communities.

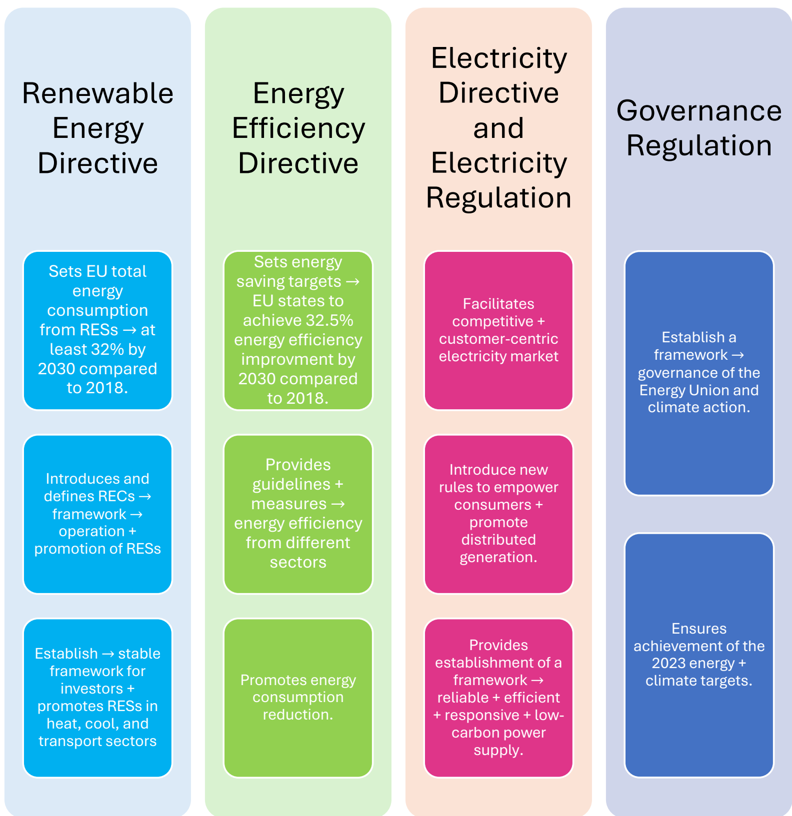

Figure 8. Key components of the "Clean Energy for All Europeans Package" [37–42].

Figure 9. Components of the "Electricity Directive (2019/944)" [39].

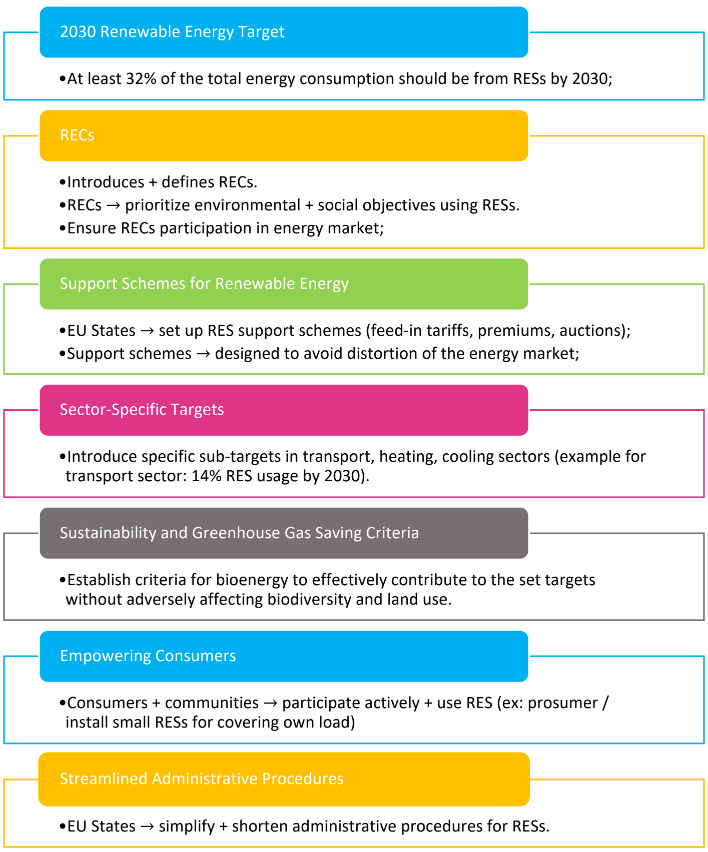

Figure 10. Key aspects of RED II.

3. Technologies and System Architectures

ECs use many different types of technologies to achieve their purpose, which involves providing environmental, economic, and social benefits to their members while promoting RESs, energy efficiency, and energy sharing. Different types of technologies used in ECs are presented in Figure 11 [43,44].

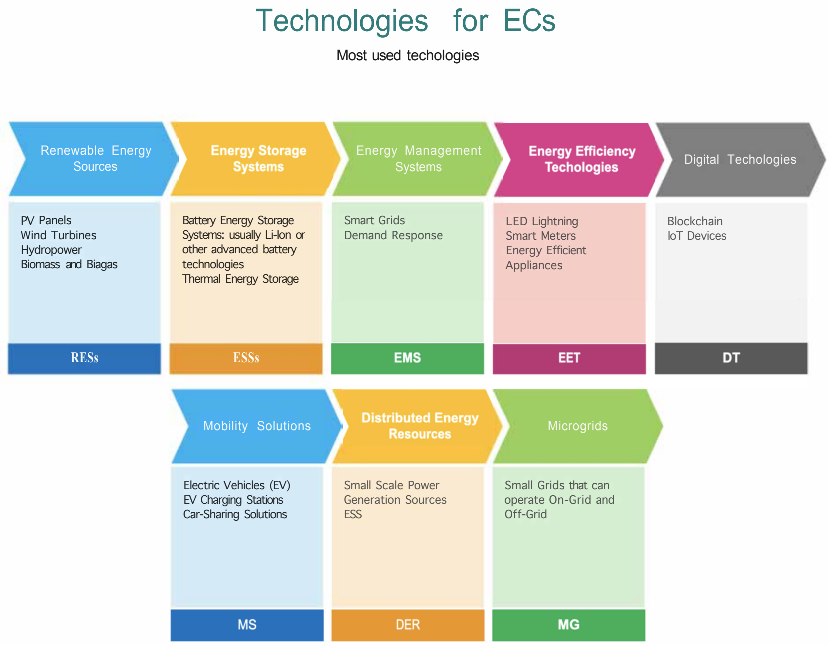

Figure 11. Technologies often used in ECs.

The presented technologies can interact in a diverse and complex manner to meet the growing energy demands. In a broad sense, ECs comprise producers, distributors, and energy consumers, and technologies are developed to extract, convert, distribute, store, and use energy more efficiently and sustainably. The overlapping of technologies present in ECs is shown in Figure 12 through a Venn diagram.

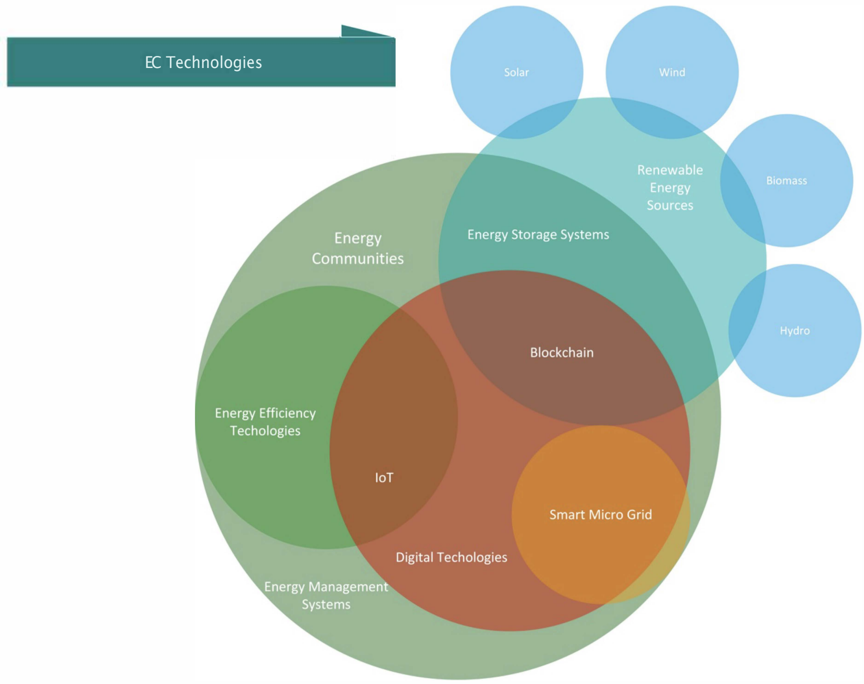

Figure 12. Overlapping of technologies within ECs.

3.1. Energy Storage Systems

Energy storage systems (ESSs) manage RES generation and ensure a reliable and resilient energy supply. By using ESSs, ECs can store energy excess generated by RESs (e.g., solar panels or wind turbines) and use it during periods of high demand or when RES production is low. Different types of energy storage technologies can be used (e.g., batteries, pumped hydro storage, compressed-air energy storage, or thermal energy storage) depending on the specific needs and resources of the EC—if a community has access to a nearby water source, pumped hydro storage can be a solution that can be taken into account for ESSs and also for generation. Using ESSs concomitantly with RESs can help ECs to become more self-sufficient and ensure a more reliable energy supply. ESSs can help ECs to participate in demand management programs, where they can provide energy to the grid during times of peak demand or when there is a shortage of power supply [43,44]. ECs combined with ESSs can enhance local self-sufficiency by mitigating the challenges posed by the variability in RESs' impacts on power flows. However, in case of unavailability of local generation (variability in renewable energy production, discharge of battery) and high consumption, the main grid is required to supply the demand.

3.2. Demand Management

The demand management in ECs can be adopted to provide flexibility to the system by proper management of dispatchable and controllable electric loads. An overview of demand-side management, demand response, and smart loads can be found in [45]. Demand management is a strategy used by utilities and grid operators to reduce or shift energy demand during certain times of peak loads, usually encouraging customers to reduce their energy consumption or by increasing the use of RESs. By participating in demand management programs, ECs can play an active role in managing the energy grid and reducing the dependence on traditional power plants that use fossil fuels. An EC with a PV system can cover the EC demand by producing during peak demand hours during hot summer afternoons to help reduce strain on the grid. ECs can also benefit from demand management incentives offered by utilities and grid operators. These incentives can be used to help offset the cost of installing RESs or other technologies that are used in ECs. By participating in demand management programs, ECs can also help to stabilize energy prices and reduce their overall energy costs [46–49].

3.3. Internet of Things

Internet of Things (IoT) and other equipment that supports IoT in ECs can be interconnected to increase energy efficiency and ease the integration of RESs into the system. IoT devices can be used for data acquisition (e.g., for energy consumption and production), thus community members can monitor their energy demand and make informed decisions regarding their energy consumption. To justify the previous statement, it is important to discuss smart meters that support IoT. These smart meters can register the energy consumption in real time and can provide users with information (e.g., feedback) to help them reduce energy consumption. Sensors that support IoT can also be considered and installed in buildings to monitor temperature, humidity, or other parameters of interest in the respective area or building to improve energy efficiency and reduce energy consumption. Moreover, IoT technologies are a key component for implementing virtual power plants by helping the EC to coordinate energy production and consumption in real time. IoT technologies can monitor energy production from energy sources such as PV panels, wind turbines, and classical energy sources found within the EC concomitant with energy demand, also within the EC, thus the production of energy can be controlled to match the demand. This can provide a more reliable and sustainable energy supply for the EC while reducing the use of fossil fuels if RESs are used [50,51].

3.4. Blockchain

To have a secure and transparent transaction between parties for a functioning and efficient EC, blockchain technology is needed, thus individuals and organizations can buy and sell energy while reducing energy costs, facilitating the increase in using RESs. Blockchain technology allows a secure and transparent transaction without the need for intermediaries (e.g., banks or governments) and tracks energy production and consumption concomitant with facilitating peer-to-peer energy trading and community-based energy management. The secure and transparent transactions can be made in real time [52,53]. A review of microgrid energy markets and blockchain technology is conducted in [54], where an evaluation of the case study of the Brooklyn microgrid (a blockchain-based microgrid energy market in Brooklyn, New York) is carried out.

3.5. Digital Technologies

The use of digital twins allows energy communities to be modeled by reproducing their behavior, starting from hourly or 15 min values, on historical or real-time datasets of consumption curves, production, and electrical storage. Thus, the possibility to evaluate the impact of the energy community in terms of indicators and performance (energy fed into and withdrawn from the grid, direct self-consumption, shared energy, self-sufficiency, etc.) can be carried out. This is useful in the community design and management phase, making it possible to evaluate different possible scenarios and their optimization [55]. The intent is to predict, with a good degree of approximation, the trends in the community indicators when some parameters change, such as the number of participants or the installed power.

The acquisition and monitoring of actual electricity consumption and estimated electricity production allows the evaluation of the direct self-consumption associated with common utilities and the shared energy related to the community apartments, therefore monitoring the progress of possible economic incentives, to evaluate strategies for involving community members (user engagement), to adopt measures for improving demand response on energy consumed and to implement periodic actions to improve the self-consumption of ECs.

Various forecasting methods applied to energy communities, like moving average, seasonal naive, hot winters, prophet, least absolute shrinkage and selection operator, and K-nearest neighbors, are investigated in [56] from the points of view of forecast quality (accuracy, bias, or reliability) and forecast value (self-sufficiency, cost of energy, and fairness among community members). The mean absolute percentage error and mean absolute scaled error as a function of community size (from 2 to 95 members) for different forecasting methods are analyzed using 100 real-world load profiles for one year with a 15 min resolution. Machine learning techniques for load consumption forecast were applied to the data of seventy-two council buildings gathered by smart meters with a 30 min resolution from 2 October 2006 until 8 February 2020, and various metrics like mean squared error, root mean squared error, mean absolute error, etc., were evaluated in [57]. Forecasting the generation of renewable energy sources is a difficult task and many scientific papers have proposed various methods with different models. Many methods were physical-, statistical-, artificial intelligence- or hybrid-based. Experimental data of PV production recorded with a 15 min resolution for a series of months in Belgium were used in a multi-objective artificial hummingbird algorithm to forecast the PV production [58]. The accuracy of the forecast was evaluated using various quality criteria and was compared with the experimental results, leading to interesting results.

3.6. Energy Management Systems

ECs can participate in electricity markets (EMs), where the energy surplus can be sold for a monetary benefit. The distributed energy resources (DERs) must be allowed to participate in the EM. Another positive financial aspect that appears using EM is that of the possibility to offset the cost of investing in the equipment. Through EMs, the EC can participate in demand-response programs and other grid services (e.g., an EC with a large energy-storage-capacity cloud can participate in frequency regulation to help stabilizing the grid). For an effective functionality of the EC along with the EM, a partnership should be considered with third-party aggregators or service providers due to the fact that participating in EMs is a complex activity that requires a certain level of technical expertise [59,60].

Electric vehicles (EVs) require investment in charging infrastructure in order to increase electric mobility movement. Charging stations can be installed in public areas or in residential buildings in order to facilitate the change to green cars and to reduce the carbon footprint, promoting environmentally friendly practices to increase sustainability and reduce greenhouse gas emissions associated with transportation [61,62]. Car-sharing programs can be implemented in ECs, this being another aspect that can help promote the reduction of dependence on fossil fuels and improve energy efficiency [63]. The optimized energy management of energy communities with prosumers/consumers and electric vehicles, considering sharing mechanisms and network stability, is investigated in [63], taking as objective functions self-consumption and the grid-balancing factor.

Mathematical modeling and the definitions of the self-consumption objective and grid-balancing factor functions are proposed and presented in detail in [64] and applied to a community in Naples (Italy). The results reveal that the optimized energy management allows maximization of self-consumption and the integration of the network-balancing factor strategy determines the achievement of grid balancing, which is highly important in energy communities. A mixed binary non-linear programming model is proposed in [65] for scheduling the pricing and demand to maximize the total benefit to home participants in an energy community. The optimal scheduling for charging/discharging electric vehicles and energy exchange among homes is modeled towards determining the trading price between homes and producers of heat and power. Ref. [66]proposes a distributed and centralized charging of electric vehicles in an optimization problem to minimize the net load variability of residential consumers under forecasting of PV production and considering electric vehicles' energy demand and periodic movements. In case of multiple houses in an energy community, the PV power is shared among the various residents, leading to improvements in self-consumption and determining economic benefits to the participants.

The optimal network improvement of a radial distribution system, minimizing energy losses, for integrating electric vehicle charging stations at a residential location is carried out in [67]. The results reveal that maximum vehicle loads can be allocated when the energy savings are shared between off-peak hours. However, important investments are required to develop the existing power system for energy communities with a high number of electric vehicles.

A coalition game-theory approach can be applied to energy communities for distributing the total payoffs among all participants, contributing to peak shaving and valley filling, with important advantages for the power system [68].

A novel community-aware real-time pricing scheme is proposed in [69]to reduce the system energy costs by around 10% without affecting the users' benefits. The obtained gains are distributed fairly between the participants and energy savings can be achieved. An algorithm for the creation of energy communities is proposed, leading to interesting results. Ref. [70] proposed a mathematical model for sizing and locating renewable installations, as well as for the development of energy communities for consumers participating within energy efficiency programs towards cost reduction and increased sustainability of energy communities.

The planning and design of carbon-neutral energy communities is carried out in [71] for the case of Saudi locations under different energy efficiency scenarios, grid electricity prices, and capital costs of the renewable energy sources. The integration of incentives for renewable energy source installation, the application of feed-in tariff schemes, and grid electricity prices can lead to achieving carbon-neutral energy communities within the analyzed location. An overview of the positive roles of buildings and the transactions of electric vehicles towards decarbonization, digitalization, and decentralization of the energy demand, leading to transactive energy communities, is presented in [72], with a survey of blockchain-based transactive energy for the cross-sector local community. An optimization model is formulated in [73] for automated scheduling of network resources in a local electricity market of an energy community using Internet of Things devices.

Energy communities use various topologies, depending on technology, regulations, and community objectives [74,75]. Energy interaction strategies among a load-serving entity and an energy community are mathematically formulated and solved to determine the benefits to the social welfare under centralized and decentralized coordination schemes. In [76], an energy community consisting of a university campus is proposed and analyzed considering various technologies and operating scenarios, analyzing the economic aspects and benefits to the residents. In Figure 13, different topologies for energy communities are presented, with green text representing the advantages and red the disadvantages for the respective topology.

3.7. Smart Grids

ECs and P2P (Figure 14) can be in place for decentralized energy systems (Figure 15), which is in contrast with centralized generation systems (Figure 16). Centralized generation refers to large-scale energy production at a single location or a few locations (coal, natural gas, nuclear, large hydroelectric power plants) while decentralized generation/distributed generation involves producing electricity at or near the point of use and comprises a wide range of small-scale generation systems (solar panels, wind turbines, and small hydroelectric generators).

Multi-agent management of an integrated energy system with centralized and distributed energy generation is proposed in [77] and tested on a real system placed in Russia. The analysis investigated the costs of supplying electricity and heat to the local consumers using centralized, distributed generation. A theoretical overview of centralized/distributed generation, renewable generation, and energy communities is conducted in [78], discussing the advantages at consumer level and at society level of these aspects. The differences and synergies between microgrids and local energy communities are presented in detail from the point of view of their benefits, stakeholders, technical characteristics in [79]. The microgrid communities of Simris village in Sweden, which is supplied with renewable energy sources (PV and wind) and different storage systems, and of Blue Lake Rancheria in the USA, supplied with PV systems and Li-ion storage systems, were presented in depth from the point of view of implementation and the importance of synergy among communities and utilities in [80].

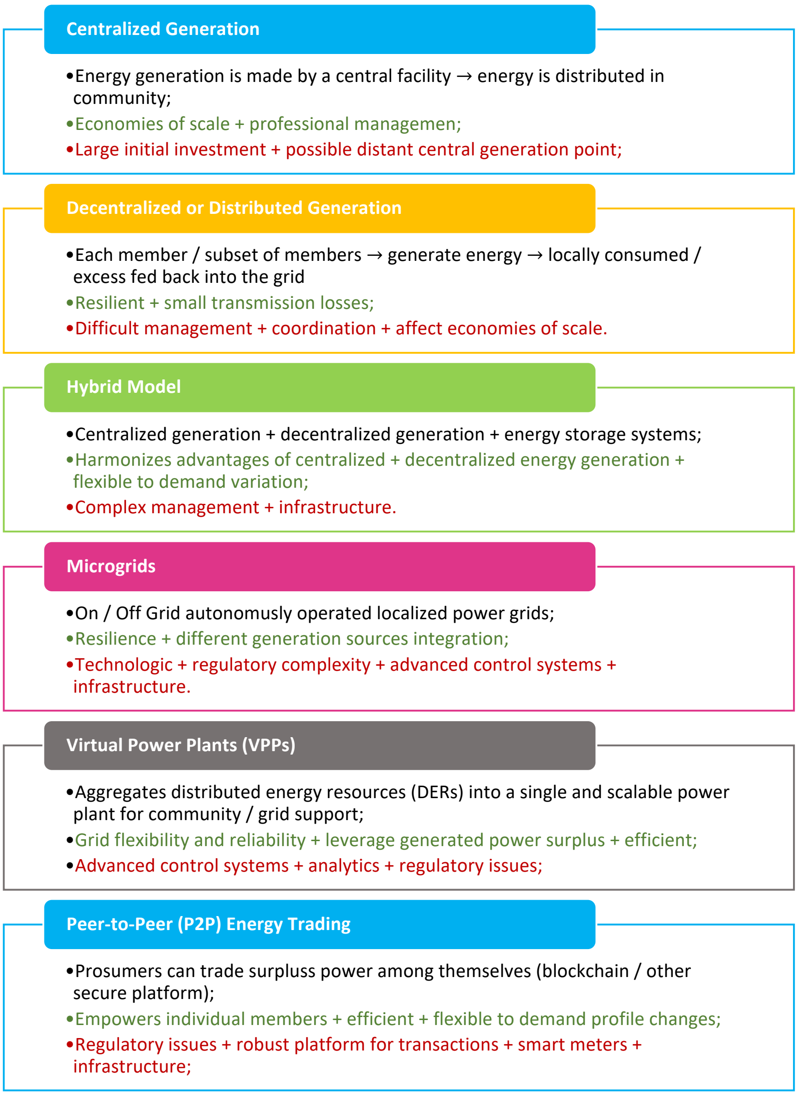

Figure 13. Types of topologies for ECs.

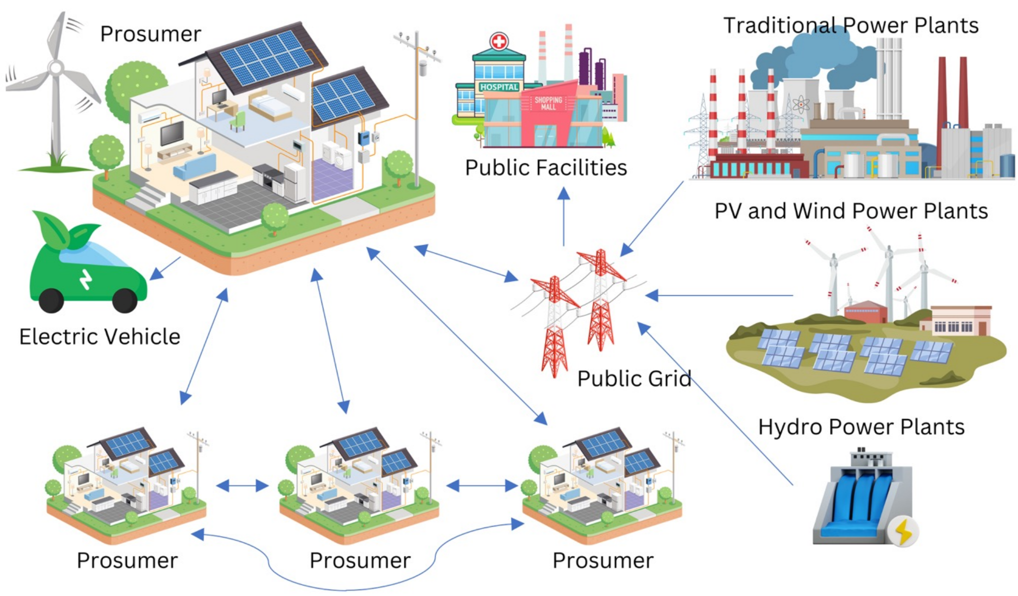

Figure 14. Schematic of peer-to-peer system.

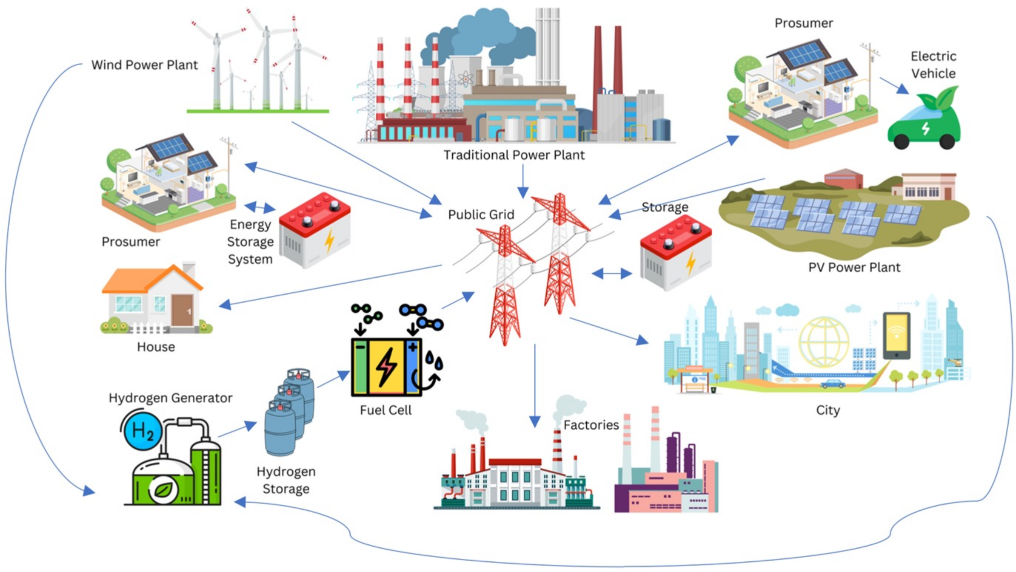

Figure 15. Schematic of decentralized energy systems.

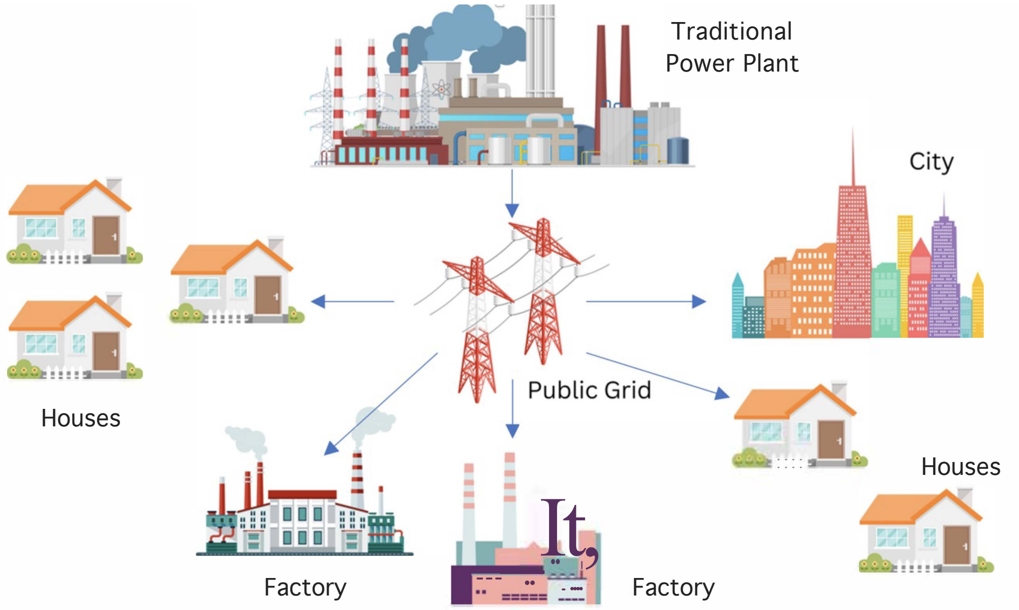

Figure 16. Schematic of centralized energy systems.

Energy trading associated with peer-to-peer (P2P) refers to the direct energy exchange between low-scale producers and consumers, without the need for utilities or energy companies or other intermediates related to this aspect, where the energy is locally exchanged. Through P2P, ECs can become more self-sufficient. The energy surplus of a community member can be traded to another community member that is part of the P2P system, facilitating load balance according to each member's needs. Blockchain technology can be used for secured and transparent transactions between members of the P2P EC. Blockchain allows for the tracking and verification of energy transactions, ensuring that all parties are fairly compensated for the energy they generate and consume [81]. An assessment of various communication technologies among elements of an energy community is conducted in [82], presenting the standards useful for deployment of interoperable smart microgrids.

The VPP represented in Figure 17 describes a decentralized network with medium-scale power generating units (e.g., wind farms, PV plants, combined heat and power (CHP) units), flexible consumers, and storage systems and can be implemented in ECs. Although ECs promote RESs, traditional energy sources are included for stability. VPPs are operated by a central control entity that aggregates the capacity of power resources through dedicated software in order to provide power and grid services like a traditional power plant. A VPP optimally manages the collective energy resources of the community to supply the EC demand or sell power surplus to the grid, thus providing backup power during outages and stability during peak demand periods [83–85]. The community-based VPP concept is proposed and three practical cases from Ireland, Belgium, and the Netherlands are presented, with an overview of various components, participants, and configurations. The performance of organic Rankine cycle (ORC) systems operating in combined heat and power (CHP) mode is investigated in [86]. An organic Rankine cycle (ORC)-based biomass combined heat and power system for community-scale applications is investigated concerning its technical and economic aspects in [87]. The configuration of a ground-source heat pump in parallel with an ORC with the capability for seasonal thermal storage for the ground heat exchanger is investigated for use in cold regions, specifically in Canadian climatic conditions, in [88]. An overview of biomass-fueled organic Rankine cycles, including working fluids, analysis methods, and environmental issues, is conducted in [89].

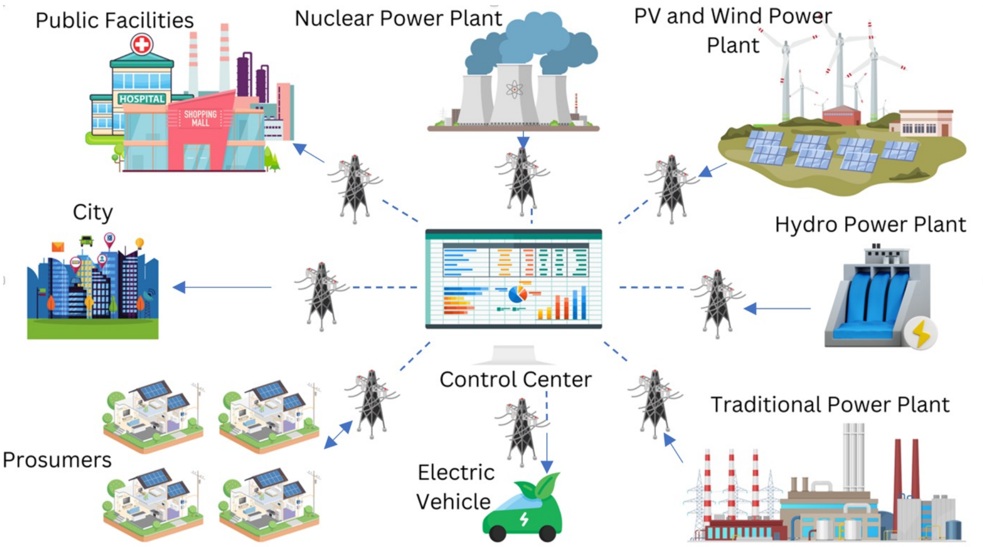

Figure 17. Schematic of virtual power plant.

ECs can improve reliability by diversifying their energy sources and creating redundant systems that can continue to operate even if one energy source or system fails. In ECs, RESs can be combined with energy storage systems (ESSs) to create more reliable and resilient energy systems. Another way to improve the reliability of ECs is through the use of microgrids. Microgrids are small, self-contained energy systems that are designed to be capable of operating independently from the main grid. Microgrids can supply consumers from a specific geographic area or community. By creating microgrids with RESs and ESSs, ECs can increase their energy reliability and resilience. Microgrids are improving energy access for low-income households or marginalized communities that have difficulties in accessing energy services, and moreover reducing transmission and distribution costs. The energy surplus can also be sold back to the main grid or another neighboring microgrid. ECs are already implemented in different countries around the world, Table 1 shows some of the countries that have already put ECs into practice. EC implementation differs depending on the functions of the different technologies to be implemented (Figure 11); the area of installation and its needs are dependent on regulations and the involvement from ECs.

Table 1. ECs implemented in different countries in Europe and generation sources used.

Country	City	Community Characteristics	Grid Specifications	Key Outcomes	Ref.
Germany	Hessen	82 properties, each with 5 kWp of PV. Each house must have the capability of storing energy.	Entega is a municipally owned utility offering electricity, gas, water, district heating, and energy services with about 570,000 energy customers; community energy storage with a gross capacity of 115 kWh and a charging capacity of 250 kW; residential units and community storage connected to the public grid.	Increase self-consumption to lower costs and increase independence; ecological and economic advantages in using PV and energy storage.	[90]
Germany	Cologne	9 apartment buildings, 74 residential units; 225 kWp shared PV.	Community energy storage of gross capacity of 96 kWh and a charging capacity of 18 kW. Internal microgrid and community storage not connected to the public grid.	Economic savings; clean energy.	[90]
UK	Brighton	7 MWp of solar rooftop; more than 700 members.	Local grid; electricity sold directly to the market.	Clean energy; economic advantages; solar energy to educational facilities.	[91–93]
UK	Nottingham	1150 homes; 5 MW solar farm.	Low-voltage local grid.	Sustainable operation; counter fuel poverty increase in low-income areas; economic benefits; increased energy efficiency.	[91–93]
Netherlands		484 communities are active at national level; these energy cooperatives involve 70,000 Dutch citizens. Solar capacity 74.5 MWp.	Local grid.	Energy efficiency; renewable energy supply; economic viability.	[94]
Spain	Valencia	100 kWp PV system. Battery energy storage, 100–300 kWh. Battery ownership: individual or communal.	Grid connected; local grid; surplus sold to the main grid.	Energy efficiency; economic profit; sustainable development.	[95–97]

Table 1. *Cont.*

Country	City	Community Characteristics	Grid Specifications	Key Outcomes	Ref.
Spain	Zaragoza	50 dwellings; 255 Wp PV generation; 30 kW wind turbine.	Grid-connected system; economic optimization; optimal configuration of grid-connected polygeneration system.	Economic benefits; energy security benefits; advantages of thermal and electric integration.	[95–97]
Spain	Getafe	95 kWp installed PV power; 100 houses.	Local grid; the energy deficit is taken from the upstream grid.	Energy-cost savings; social benefits; clean energy impact.	[95–97]
France	Les Ailes de Taillard	164 communities. Wind farm ownership, 200 MW; >100 MWp photovoltaic generation. Biomass installed capacity 10 MW. Hydroelectric capacity 942 kW. Methanation installed 489 kW.	Local grid.	Social participation; citizen involvement; clean energy; energy efficiency; energy savings.	[98]
Philippines	Rural area electrification	>20 kW of photovoltaics, wind energy, and battery systems.	Local grid.	Techno-economic benefits; social benefits.	[99]
Norway	Oslo	>3000 residents; 17 MWp of PV power.	Local grid.	Zero-emission neighborhoods; social benefits; inclusive cooperation.	[100,101]
Norway	Trondheim	PV production from 15 different locations; 53 households.	Local grid.	Energy savings; economic benefits; renewable energy, clean energy.	[100,101]

4. Conclusions

Energy communities are a collaborative energy form, centered on a local exchange system, to promote joint management, sustainable development, and reduce energy dependence. Energy communities not only aim to satisfy energy needs, but also encourage the creation of new socioeconomic models characterized by circularity. In an energy community, the subjects are involved in the various phases of production, consumption, and exchange of energy, according to the principles of environmental, social, and economic responsibility and active participation in all energy processes. Energy communities are equipped with energy production systems that can be shared, as in the case of a photovoltaic or wind power plant available to the community, or individual: the installation of a photovoltaic system on the roof allows the concept of energy communities to be applied to condominiums, homes, companies, or public buildings. In this way, passive consumers (consumers) are transformed into prosumers, as they are equipped with their own system for generating electricity for self-consumption, giving the excess energy to other subjects connected to the smart grid and sometimes even with advanced storage systems for accumulating electricity not immediately used.

Through digitalization, it will be possible to control and optimize each phase of use of electricity, from production to exchange, allowing energy efficiency, with real-time control. In fact, through sensors, IoT devices, and the cloud, it will be possible to promote energy and monetary exchanges within the ECs, in a transparent, safe, and reliable way thanks to blockchain technology. Smart metering remains fundamental to this sharing and participation, to ensure real-time sharing of information on energy production, self-consumption, sale, etc.

Energy communities are helpful to the energy transition and inclusive innovation. As decentralized and renewable energy-based projects, energy communities can promote sustainable energy production and consumption. Through consumer awareness and community-based initiatives, energy communities can play an important role in social innovation as they reflect a fundamental change in consumer behavior. The traditional passive consumer becomes an energy consumer, co-owner of renewable energy installations, and community energy participant.

The paper deals with the overview of energy communities, the regulations and technical development that led to their realization, as well as different topologies and configurations that exist in order to increase benefits, and their deployment as key elements of smart cities.

A literature review was conducted to investigate the characteristics of energy communities and the benefits brought to the participants, in particular the shared use of local renewable energy sources and the economic benefits from consumption flexibility programs, as well as the deployed configurations and benefits to local cities towards their transformation into smart cities.

The new way of conceiving distributed generation has transformed energy communities, based on renewable sources, to achieve the sustainability objectives as foreseen by the 2030 Agenda, or Sustainable Development Goals (SDGs). Some fundamental steps are needed, which research can support, which we can translate into the "Rule of the 3 Cs": the competence that must be spread with maximum co-sharing to finally make everyone conscious of the importance that each of us has, with every behavior, on the path towards sustainability and the energy transition.

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