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Review

Technological Elements behind the Renewable Energy Community: Current Status, Existing Gap, Necessity, and Future Perspective—Overview

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Abstract: The Renewable Energy Community (REC) in Europe promotes renewable energy sources (RESs), offering social, economic, and environmental benefits. This new entity could alter consumer energy relationships, requiring self-consumption, energy sharing, and full utilization of RESs. Modernizing energy systems within the REC requires addressing self-consumption, energy sharing, demand response, and energy management system initiatives. The paper discusses the role of decentralized energy systems, the scenarios of the REC concept and key aspects, and activities involving energy generation, energy consumption, energy storage systems, energy sharing, and EV technologies. Moreover, the present work highlights the research gap in the existing literature and the necessity of addressing the technological elements. It also highlights that there is no uniform architecture or model for the REC, like in the case of microgrids. Additionally, the present work emphasizes the role and importance of technological elements in RECs, suggesting future recommendations for EMS, DSM, data monitoring and analytics, communication systems, and the software or tools to ensure reliability, efficiency, economic, and environmental measures. The authors also highlight the crucial role of policymakers and relevant policies, which could help in implementing these technological elements and show the importance of the RECs for a sustainable energy shift and transition.

Keywords: decentralized energy system; renewable energy community; key aspects of REC; technological elements

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1. Introduction

1.1. Background Study

Over the past century, the electricity industry has traditionally been managed by large-scale centralized energy systems where few participants are involved. In centralized systems, energy is transported over long distances from big generation centers to the final consumers through various points—power generation, power transmission, power distribution, and supply centers—associated with the path, and the energy must arrive at the final consumer, as presented in Figure 1. The centralized system mainly generates electricity from fossil fuels, resulting in an increase in environmental and economic issues and challenges in terms of interconnected power system operation efficiency [1,2]. The system necessitates a transformation in the energy archetype, transitioning from a centralized to a decentralized system and replacing pollutant energy sources with RESs. These RESs are cost-effective, sustainable, cleaner, and reliable [3,4], resulting in the promotion of SDGs and the reduction of negative environmental impacts in the future. A decentralized system or distributed generation (DG), in contrast to the traditional power system, helps reduce transmission losses and associated costs due to long distances. DG refers to energy produced by end-users utilizing small-scale energy resources like solar PV, wind, biogas, and small hydroelectric plants [5,6] and can be integrated with the local grid. The deployment of DG systems using RESs reduces their dependence on the utility grid due to their own generation for their energy demand. However, the traditional central utility grid could be supplied and integrated with RES local power-producing plants [7], like at the substation (with a large capacity) or at the building level (with a small capacity) in the power system [8]. Figure 1 shows a pictorial view of the electrical power system network [9] with the addition of distributed RESs at different points, like the PV system.

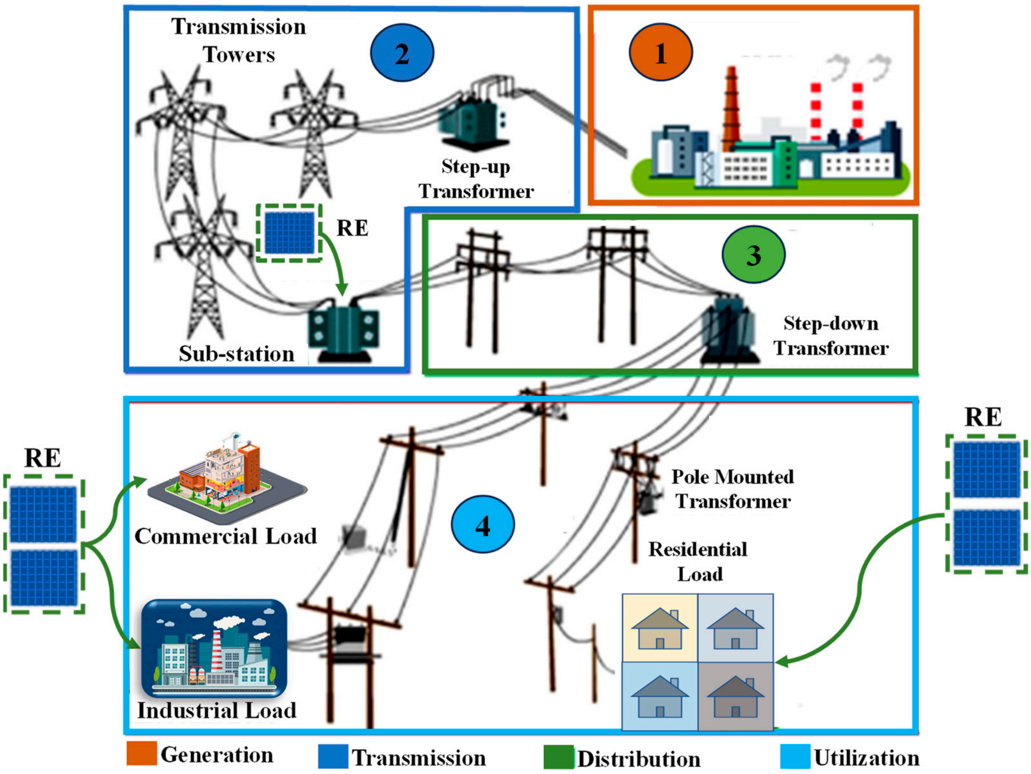

Figure 1. Representation of electric power system with distributed renewable energy sources.

DG systems provide local control for energy production and distribution, aiming to meet local energy demand by using available distributed renewable energy systems (DRESs) [10]. These systems support local resilience, encourage energy independence, and reduce complexity, cost, and inefficiency. Decentralized systems can promote creative ideas through efficient use of RESs, community involvement, and authority for their participants [11,12]. Collaborative approaches like energy sharing are emerging to enable RE sharing in decentralized energy systems, reduce energy use, and encourage flexibility in energy use [13]. Integrating local DRESs and involving local ECs is an effective way to handle changes in the local energy landscape [14,15]. ECs play a crucial role in improving energy poverty, security, and autonomy in developed and developing countries. Several EC benefits have been discussed; these encompass distinct categories from the literature highlighted in [16] and are mentioned in Figure 2.

Due to its many advantages, the EC has come a long way and is now positioned to play a key role in building a more flexible and decentralized energy system in which citizens have a greater influence. Different countries have adopted the EC model by utilizing the RESs to take advantage of social, environmental, and economic benefits. The European Union has also come forward to be involved in EC initiatives by focusing on environmental concerns. To combat climate change, the European Union (EU) aims to become carbon neutral by 2050 [17]. The European Union's Clean Energy Package underscored that, by 2030, 32% of the energy mix should be from the RESs and that the energy market should be reformed to take flexibility into account, acknowledging the critical role played by the energy sector given the climate issue [18]. Two types of ECs, named RECs and CECs, were introduced and established after their inclusion in the Clean Energy Package. Notably, the REC concept was introduced by the 2018/2001 RED II directive, which focuses on the use of RESs, while the CEC concept was introduced by the 2019/944 ED directive, which focuses on electricity. They both have the primary focus of delivering economic, social, and environmental benefits to their participants [19,20]. The members of RECs generate RE for their own use and have the option to store, sell, and share the self-produced RE with other members of the same EC or with the electricity market. RECs have gained popularity in Europe recently since many stakeholders are eager to engage in this topic. These stakeholders could be energy planners, mayors, and other local individuals, as well as scholars. Moreover, many researchers are involved and work on REC for different countries on different topics like public opinion and acceptance in communities [21], modeling considering the impacts [22], designing focusing on social acceptance [23], techniques to increase self-consumption [24] and many other topics focusing on the benefits and profitability like saving costs and reducing environmental issues.

Figure 2. Energy community benefits [16].

1.2. Research Problem and Scope of the Work

Despite the numerous benefits of RECs, there could be several issues that could hinder progress, including policy, regulatory framework, financial incentives, environmental assessment, and public acceptance. Furthermore, there is also a lack of awareness and knowledge about energy generation, consumption, prosumer roles, energy storage, and sharing, which are crucial for addressing these challenges. This requires proper technological elements like smart systems, EMS, DSM, proper monitoring systems, and communication systems among the meters, resulting in the exact measurement and examination of the data to check the gains and incentives after sharing the energy within the REC and proper management. Moreover, software tools are also discussed, which could be beneficial for the planning, design, simulation, and optimization of the various elements of REC. These technological innovations significantly and positively impact the effectiveness of RECs. An investigation is also carried out to find the review articles discussing the key technological elements of REC. The list of review articles was found and added to Table 1, which shows the list of REC review articles from the last four years, highlighting the limited progress of discussion on the REC's technological elements.

Table 1. Status of Research Review Articles Published on EC and their Focus (2021–2024).

S No.	Reference	EC and REC Paper Titles
1	G. Kallis et al. [25]	The challenges of engaging island communities: Lessons on renewable energy from a review of 17 case studies
2	M.H. Bashi et al. [26]	A review and mapping exercise of energy community regulatory challenges in European member states based on a survey of collective energy actors
3	H. Kazmi et al. [27]	Toward data-driven energy communities: A review of open-source datasets, models, and tools
4	M. Kubli et al. [28]	A typology of business models for energy communities: Current and emerging design options
5	M.A. Heldeweg et al. [29]	Renewable energy communities as 'socio-legal institutions': A normative frame for energy decentralization?
6	A. Tatti et al. [30]	The Emerging Trends of Renewable Energy Communities' Development in Italy
7	C. Inês et al. [31]	Regulatory challenges and opportunities for collective renewable energy prosumers in the EU
8	V.Z. Gjorgievski et al. [32]	Social arrangements, technical designs and impacts of energy communities: A review
9	M.L. Lode et al. [33]	A transition perspective on Energy Communities: A systematic literature review and research agenda
10	C.E. Hoicka et al. [34]	Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities
11	I.F.G. Reis et al. [35]	Business models for energy communities: A review of key issues and trends
12	F. Hanke et al. [36]	Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases
13	R.J. Hewitt et al. [37]	Social innovation in community energy in Europe: A review of the evidence
14	J.J. Cuenca et al. [38]	State of the Art in Energy Communities and Sharing Economy Concepts in the Electricity Sector
15	Y. Zhou et al. [39]	Peer-to-peer energy sharing and trading of renewable energy in smart communities—trading pricing models, decision-making and agent-based collaboration

There are no papers discussing all the technological elements and tools used for the REC. In this context, this work addresses the above research area and covers a comprehensive overview of key aspects of the REC and the required technological elements, including the software tools that make up RECs, thus serving as a valuable resource from a research point of view. This research topic has great scope, as it will result in increased reliability and high efficiency by following the optimum solutions and increased economic benefits. Moreover, this work serves as a novel idea for community-driven, sustainable energy systems, consolidating existing literature and research findings. It also provides insights into the current progress and scenario of REC technologies and covers discussions on the important directions for future research followed by literature, as technological advancements are crucial for a sustainable, decentralized energy system.

1.3. Original Contribution of the Work and Paper Organization

The work focuses on the decentralized system and the REC, with their key considerations and aspects of technological activities and elements having the capability of improving energy resilience, reliability, and sustainability. Covering the latest developments in REC components helps to identify emerging trends, innovative solutions, and cutting-edge research areas. Also, the motivation behind writing this review paper is to provide a comprehensive overview and analysis of the state-of-the-art in REC technology. Reviewing this emerging field, like technological elements, facilitates understanding the necessary developing sections of RECs, which include both RES generation and ESS, energy consumption, and energy sharing as well. The technological elements discussed in this research work are EMS, DSM, data monitoring and analytics, communication systems, and software tools. The novelty of this work lies in exploring all these technological elements that enhance the performance, efficiency, and resilience of REC, and the main objectives are to synthesize existing literature, identify gaps in knowledge, and propose future research directions. Moreover, it also stems from the need to disseminate critical information to researchers, policymakers, industry professionals, and other stakeholders interested in REC development and deployment. Through this, the review paper contributes to the academic and practical understanding of REC technology by consolidating knowledge from diverse sources and facilitating informed decision-making and technology adoption. To summarize, the persistence of writing this article on the key aspects and technological elements of RECs is to clarify their significance, investigate new advancements, explain why they are important, and provide valuable input to the decentralized energy systems research community, industry professionals, and policymakers.

Keeping up with this, the contribution of the research work carried out in our article is organized in different sections. The first section covers the introduction, highlighting the background work, like decentralized energy systems and energy communities' concept and characteristics, covering the lack of discussion on the REC's technological elements, and highlighting the research scope and contributions of the work. Section 2 focuses on the key aspects of the REC, the key activities as energy technologies like RES generation, Energy consumption from consumer and prosumer perspective, Energy storage system (ESS), Energy sharing, and Electric vehicle (EV) technologies. Section 3 presents the role and importance of the REC's technological components and research work progress and discusses the key components associated with the RECs, like EMS and DSM, data monitoring and analytical systems, communication systems, and software tools. Section 4 discusses the overall work, suggests the future perspectives to be considered for REC technologies, and suggests the importance of policy and the policymakers who play the main role in establishing REC technologies. Finally, Section 5 summarizes the overall work, contribution, and significance. Apart from this, this work is depicted in Figure 3 with different sections and subsections in a sketch that clearly illustrates the work carried out and the contributions.

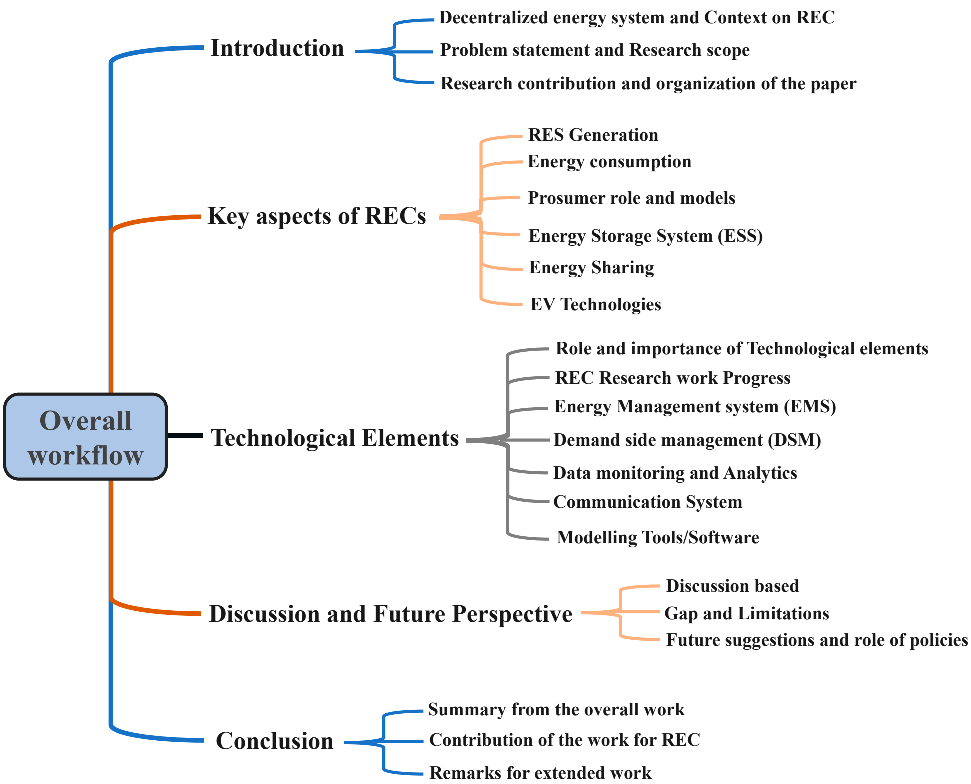

Figure 3. Overall workflow.

2. Key Aspects of RECs

A collection of energy utilities operating in a specific geographic area, whether privately, publicly, or jointly owned, is referred to as an energy community. In this arrangement, end users—citizens, businesses, and public administrations—join forces to jointly meet their energy needs. The Clean Energy for All Europeans Package (CEP) contains acts and directives that address these novel ideas. As a result, it is possible to distinguish between two distinct kinds of ECs [40,41]: RECs and CECs. The establishment of both CECs and RECs can be essential to actively and successfully assist in the accomplishment of energy and climate goals. Achieving benefits in terms of sustainability, safety, and cost-effectiveness is the ultimate objective [42]. The characteristics and differences between the two EU directives are discussed in Table 2 by focusing on the definitions, participants, goals, and possible areas of activity for the two categories [19,20,43].

Table 2. Characteristics and comparison of energy communities (RECs and CECs).

	Energy Communities	
	Renewable Energy Communities (RECs) /RE Cover	**Citizen Energy Communities (CECs) /Electricity Cover**
Directive	Directive 2018/2001	Directive 2019/944
Purpose	Generating social and environmental benefits instead of focusing on financial profits.	
Members/ Participants	Restricted Membership, Open and voluntary by natural persons, local authorities (including municipalities), micro, small, and medium enterprises (MSMEs), but their involvement or membership is not their main economic part.	No restrictions, any actor can participate, Nevertheless, decision-making is not possible for those engaging in large-scale commercial activity where energy is the main economic activity.
Technological Activities	Aggregation, Energy generation and consumption, Distribution, Energy storage, Energy sharing, Energy supply, and Energy related service provision	
Ownership and Control	Both ECs place a strong focus on involvement and effective control by citizens, smaller businesses, and local authorities having no key economic interest in the energy sector.	
Generation Plants	PV systems are included, but also any type of RES can include wind, hydroelectric, solid biomass, biogas, etc.	Operate in the electricity sector and are technology-neutral (fossil fuel source or RE)

The public acceptability of RE projects and the advancement of clean energy change in local ECs are significantly supported by collective and citizen-driven energy measures that prioritize the citizens. This new socio-energy DG from the RESs-based system is emerging as local ECs increasingly participate in the management, ownership, and administration of energy production plants [44,45]. These programs simultaneously improve energy efficiency, lower electricity costs, and generate employment opportunities in the community for the benefit of the public [46]. A key element in inspiring the broader use of on-site RESs is the recognition of RECs, which typically consist of several key technological activities that work together to facilitate the production, distribution, consumption, storing, selling, and sharing of energy, as mentioned in Figure 4. These activities are discussed individually in different sub-sections and together synergistically; they create a sustainable and locally driven energy ecosystem, enabling ECs to participate actively in the energy transition and promote RE adoption at a grassroots level.

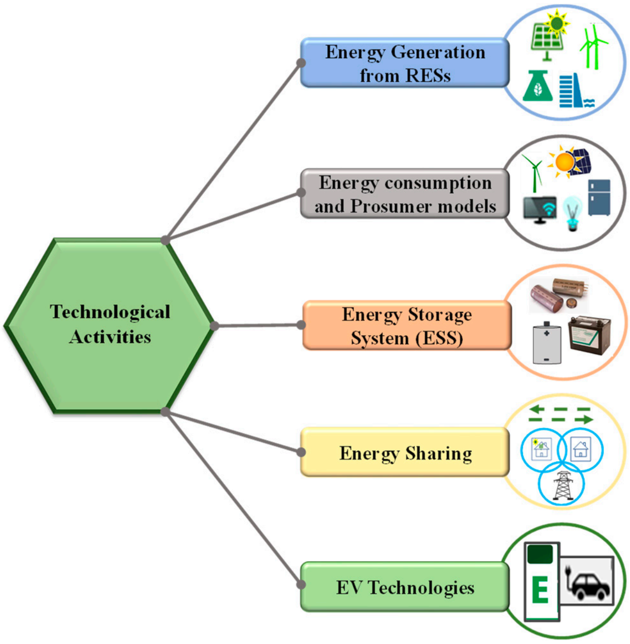

Figure 4. Renewable Energy Community technological activities.

2.1. Energy Generation from RESs

At the local level, like in the case of RECs, distributed energy systems represent a promising opportunity to enhance the utilization of RESs. Distributed generation from RES has positive societal advantages and can improve distribution network performance [47,48]. RESs on the distribution side incorporate a variety of technologies such as wind energy [49], solar energy [50], biomass, small hydropower plants [51], fuel cells, and more [52,53]. As for the production units, all RE-powered plants are eligible to be included in a REC. This consists of any kind of RE system, such as PV, hydroelectric, wind, biogas, solid biomass, etc., depending on the availability and requirements of the different countries in different regions. Notably, substantial advancements have been made in solar PV technology [54,55]; however, achieving the ambitious climate and energy objectives necessitates continued high rates of installation. However, there are considerable opportunities associated with the installation of solar PV, involving favorable compensation schemes (particularly in the EU) [56]. Moreover, the cost of RESs like solar and wind has decreased in recent years, resulting in more integration into RECs, and this will also stabilize the costs of energy for the EC members over the long term.

As discussed, the RESs produce clean energy locally, reducing reliance on traditional fossil fuel-based energy sources, and the principal motivating element behind the growing inclination toward technologies such as RES-based plants is the environmental benefits [57]. These RESs in ECs also increase reliability and resilience by reducing the dependency on centralized energy systems and transmission infrastructure. Moreover, these also increase job opportunities for the residents of the REC, resulting in economic development. These jobs could include the installation, maintenance, and operation of RESs, as well as administration and management. Along with the above benefits, there are also some required improvements for utilizing the RESs in ECs, like the need for improved grid integration technologies for placing RESs while sustaining the stability and reliability of the grid, ESS integration with the RES which can help in the intermittent behavior ensuring a consistent and reliable energy supply, and easy policies and regulatory supports and standards that support the deployment and development of RESs. Moreover, the adequate and satisfactory infrastructure of transmission and distribution networks is also required, which can support and operate easily with the integration and expansion of RESs. Lastly, awareness about the advantages of RESs for the community can help boost the utilization of RESs.

2.2. Different Energy Consumption Scenarios and Prosumers Models

Energy consumption could be from the consumer side, the prosumer side (self-consumption), collective self-consumption, or grid consumption, as mentioned in Figure 5. The consumer side consists of those consumers who either consume energy from the grid or from the community. Self-consumption is considered by the actors who generate and utilize the electricity generated on-site within a building or community. Collective self-consumption could come from both prosumers and consumers. Nowadays, the REC is encouraging people to become prosumers because of several advantages, such as energy independence and cost savings. Community members are encouraged to become active participants in energy generation by installing RES on their properties and contributing to the overall energy production of the community [58]. The cornerstones of RE that ensure a successful energy transition are the co-ownership of the consumer and ECs. Ownership of RECs enables consumers to become prosumers, producing, using, and sharing their own energy [59,60]. ECs surrogate the "prosumers" concept, which focuses on individuals who both can consume and generate energy. Figure 5 also presents an overview of the strategic position of energy prosumers and the role of consumers and energy producers as per supply and demand, based on the literature assessment [61]. Additionally, their roles as prosumers, producers and consumers are depicted in the Figure.

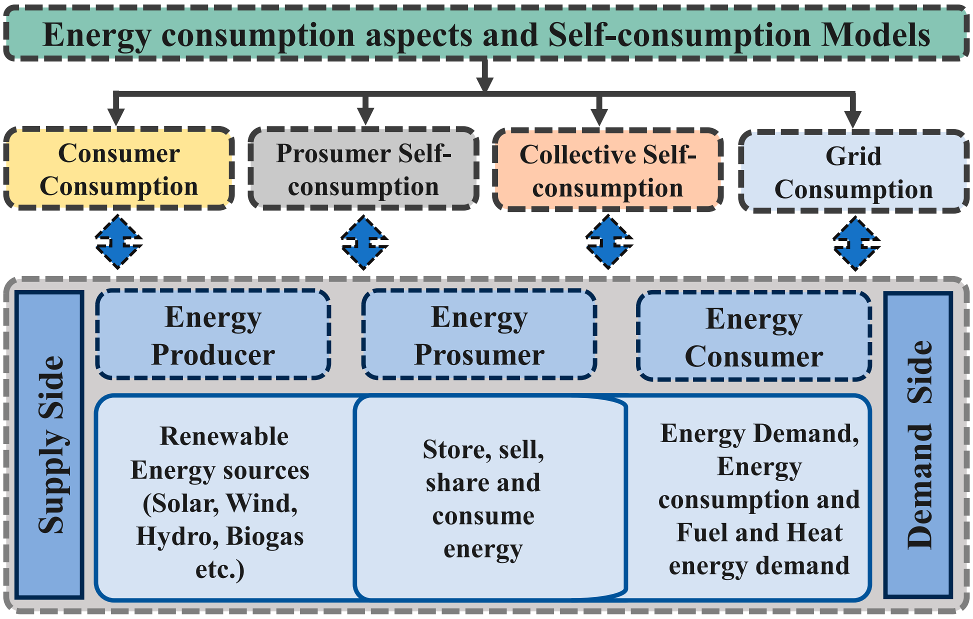

Figure 5. Types of Consumption, prosumer, and producer differences.

In [62], the authors emphasized the production and consumption of energy for households or entities. By doing this, they are able to lower their energy costs while simultaneously generating additional revenue from the sale of their excess production [63]. With these profits and benefits, prosumership has become attractive for the ECs that expect to be embedded gradually, leading to a wide range of participants and actors [64,65]. Different prosumer models are discussed in the literature, which has mixed the concepts of individual self-consumption, collective self-consumption, and the role of self-consumption in ECs. In [66], different schematic diagrams for the prosumers are properly differentiated and understood, like the prosumer household, collective prosumers in a building, prosumers for public institutes, and the EC schematic diagram, as presented in Figure 6. In Figure 6a, a single-family home with PV panels mounted on the roof or balcony, perhaps in conjunction with an ESS to boost self-consumption, is shown. In Figure 6b, an apartment building's PV plant is owned by the owners' association. An owners' association is established by the unit owners, who can make an investment and have the option to directly use the power produced by that plant, depending on the rules that are in place. In Figure 6c, a schematic diagram of a public building with a PV system mounted on its roof, like a school or government office, is shown. This property could be owned by an SME on its office building roof or free space. Figure 6d shows that the energy sector makes an investment in a particular kind of RES, such as district heating, huge batteries, PV systems, or wind turbines, in all scenarios, indicating that there are two primary forms of ECs: the one in which the members contribute to the organization and the other in which the shareholders own and manage the organization.

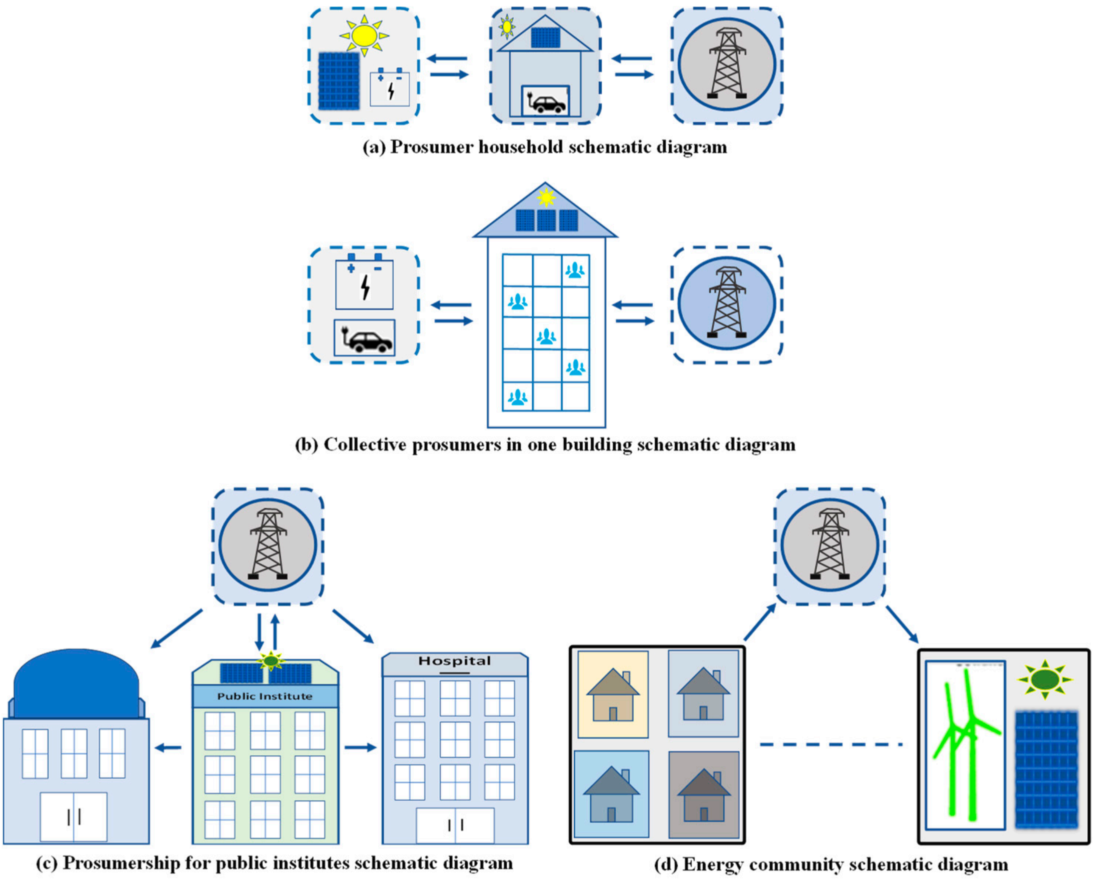

Figure 6. Different schematic diagrams for the prosumers.

Different work is carried out on the self-consumption concept in various aspects; however, this focuses on the role of self-consumption in ECs. The study [67] does a regional analysis of the best self-consumption systems in accordance with the newly established Spanish regulatory framework. The best installation size, both with and without compensation for excess energy, results in cost reductions for self-consumers throughout the entire region, according to the findings. N. Franzoi et al. [68] evaluated the advantages of the EC using models of typical Italian buildings with a range of dimensions, energy efficiency levels, solar PV and heat pump-driven heating systems, and locations in climates with a predominance of heating. At the building and community levels, the EC alone can improve self-consumption by up to 5% while reducing net energy consumption by up to 10%. Nonetheless, self-consumption can also be increased by 15% when the EC is paired with other maximizing techniques like rule-based control and DSM. The study [69] corresponds to the framework of collective self-consumption in ECs, where people can trade and swap energy within a specific area. When comparing the worldwide community bill to a case where the members are not structured as an EC, the numerical findings acquired on an actual test case in France reveal an 11.7% savings for the EC. Additionally, the study suggested that allocation procedures enable uniformizing savings in accordance with the distinctive bill reduction, which may persuade end users to become part of an EC even more.

Overall, self-consumption is an attractive and better option due to many benefits like independence of energy, resilience, cost-effectiveness, environmental sustainability, and community engagement. By generating their own energy and utilizing it, the ECs could reduce dependency on the centralized grid, and in the event of grid outages, the ECs could supply their load from their own generation. Utilizing their own generation, particularly RESs, they could save money by not connecting with the grid, and in case of excess, they could sell and share it with other members or the grid.

2.3. Energy Storage System (ESS)

ECs are considered an invaluable structure for advancing the use of RESs and increasing the efficiency and self-sufficiency of different consumers. Because of its ability to arbitrage energy and effectively manage RES, ESS may be particularly advantageous in these kinds of paradigms [70]. An energy storage system (ESS) is a device that acts as a buffer between energy production and consumption, converting electrical energy into a storable form and transforming it back to electricity as needed [71]. ESSs are essential components of energy conservation systems and are expected to positively impact the energy shift while assisting citizens' and local residents' needs and opportunities. They enable effective storage of extra energy produced during peak output, which can be used during high demand or when renewable energy sources are not actively generating electricity [72]. ESS technologies can be categorized into mechanical energy storage (MES), mechanical energy storage (TES), chemical energy storage (CES), electro-chemical energy storage (ECES), electrical energy storage (EES), and hybrid ESS [73,74]. The further subclassification of ESS technologies is given in Figure 7 [73,75,76].

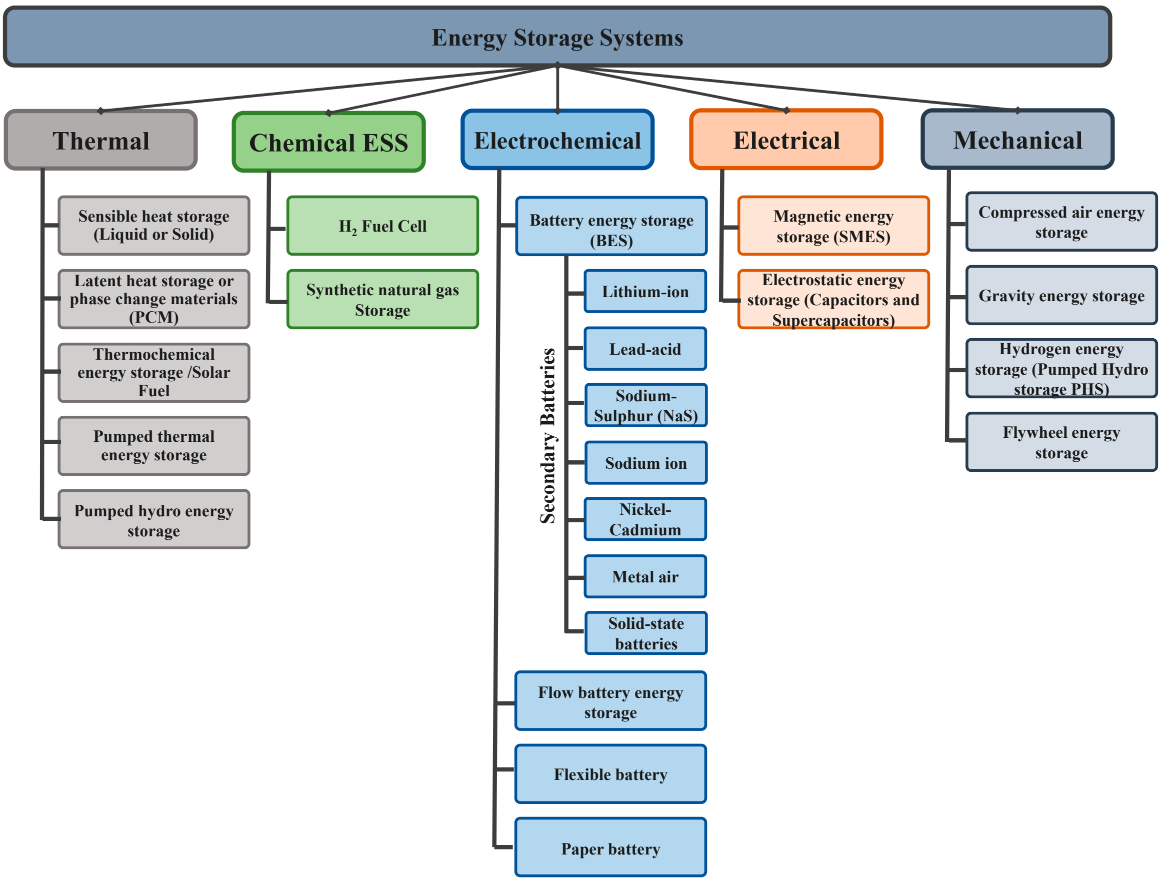

Figure 7. ESS classification.

EES is one of the most promising options, while batteries are a more affordable choice in the current economic climate [77,78]. G. Talluri et al. [79] suggest a plan for BESS scheduling in RECs. Contrasted to the non-optimized BESS use, a prosumer alone could see an average revenue increase of 10%; this revenue boost is achieved by decreasing the BESS utilization by around 30% compared to the unmanaged baseline case. Bartolini et al. [80] focused on the ESS in local communities. By utilizing the synergies between various energy networks in a real residential district with a high PV penetration rate, they explore the possible role that storage systems and poly generation may play in RE self-consumption. Other than the "baseline", two scenarios were modeled: one evaluating the best possible selection of energy conversion and ESS technologies and the other attaining the same objective with batteries alone. W. Guedes et al. [81] presented the optimization model, taking into account the addition of the BESS to the EC market idea. In addition to accounting for BESS degradation and assessing various BESS arrangements in EC markets, the primary aim of this approach is to increase community income.

Based on the above description from the literature, ESSs have a great impact on ECs and play an important role in enhancing the impact and resilience in several ways, like balancing loads, stability in the grid, backup power options in case of deficits or outages, increased self-consumption in cases of good capacity of ESS, peak shaving, and enabling better RES integration with the ESS. Moreover, there is the sharing of energy in case of excess power from ESS technologies and receiving incentives for it. This eventually results in the growth of ESS integration in the REC as compared to where there is no sharing.

With the benefits, there are also improvements required like a reduction in cost for ESS technologies, which is a major problem for not integrating them into REC, performance to increase the capacity and reliability of ESS, proper integration, and control of ESS in ECs, resulting in the optimum operation, increased efficiency, and proper coordination with RESs and grid. Overall, the innovations for ESSs, the reduction in costs, the updated policies and regulatory frameworks, and easy incentives and standards are important for realizing the full potential and deployment of ESS, resulting in the enhancement of reliability, resilience, and sustainability.

2.4. Energy Sharing

Recently created legal entities known as RECs enable European residents, municipal governments, and small and medium-sized enterprises to collaborate in the production, distribution, and sharing of electrical energy derived from an RES. Sharing excess energy with others is a good and promising notion for EC members, especially with the proliferation of RESs and ESSs [82]. The sharing of energy in RECs involves the collaborative distribution and utilization of locally generated DREs. The generated energy is divided among the participants in cases of excess, fostering a decentralized and sustainable approach [83]. Enhancing energy resilience, encouraging self-sufficiency in sustainable energy practices, encouraging community engagement, and optimizing the use of RESs are the goals of energy sharing. Numerous scholars are engaged in this complex and emerging topic and have suggested exchanging models and ideas [84,85]. The authors [86] suggested a novel approach to power sharing that allows for the sharing of energy services and power. With the benefits of scalability to a bigger system and simple ESS integration, this concept of a novel approach may be applied to both newly constructed and multi-tenant structures as well as clusters of several buildings. The authors [87] suggested the PSM power-sharing concept, which is intended for the ECs to exchange energy and other services appropriate for bigger towns and building levels. B. Fina et al. [88] investigated the optimal installation capacities and economic viability of the ECs related to the specific buildings, making it more profitable to install the PV system at the optimum scale relative to the buildings. In reference [89], the authors offer a novel power-sharing scheme that is simple to apply in newly constructed and pre-existing multi-unit buildings. It enables end users to unite in a democratic EC and reap both financial and environmental rewards. The authors [90] seek to address home involvement in DR programs and RES sharing on an individual and community level while taking appliance operating schedule limits into account. In order to do that, a genetic algorithm that minimizes energy costs is suggested, put into practice, and verified. It considers distributed generation, dynamic pricing, and home and community energy sharing.

Despite the benefits, there are still challenges that must be addressed and discussed, such as incentive mechanisms for sharing energy and the fair distribution of incentives among REC members like prosumers, consumers, managers who manage REC, or other stakeholders. This will also help people understand the concept of sharing in the REC and the associated benefits, which results in awareness among the community and the acceptance of local people to participate in the REC.

2.5. Electric Vehicle (EV) Technologies and Charging Infrastructure

The popularity of electric vehicles as an alternative to traditional internal combustion engine vehicles has been boosted by the energy crisis and environmental concerns. Electric vehicles now play a more sophisticated function in the electricity grid, thanks to the recent development of the smart grid idea [91,92]. There are many applications of EVs in Microgrids (MGs) and smart grids [93,94]. The authors [95] offer a model designed to investigate how smart charging of EVs and V2G technology can boost the self-consumption of PV power. The various EV integration options available for community microgrids are presented by [96]. They also covered the difficulties and unknowns associated with EV adoption. In the literature considering EVs in RECs, there are no articles discussing the role of EVs and their applications. However, researchers must address the growing need for EV charging stations, considering the growing popularity of EVs. Additionally, in regard to the RECs, there must be charging infrastructures for EVs, and the energy absorbed for EV charging, through optimization techniques, need to be considered for calculating the shared energy within the REC. This would have a positive impact on the RECs and the participants by shifting toward a sustainable energy transition.

3. Technological Elements

3.1. Role and Importance of Technological Elements

A novel idea called "energy communities" arranges RESs that are owned and operated by the community and decentralized. The current goal of energy autonomy has accelerated their deployment, even though customer savings have been minimal thus far. The definition of ECs by the EU places a strong emphasis on non-financial gains, such as reducing energy poverty, decentralizing, and decarbonizing the energy sector, promoting inclusive sustainable development, and achieving other social goals. Simultaneously, several strategies are needed to achieve significant energy savings and a quick transition to RESs. To realize the full potential of this idea, a variety of technologies and their integration are also essential. Many technological activities, like energy generation from RESs, ESSs, EV technologies, and energy sharing, are discussed above. However, to facilitate this integration with existing infrastructure, a sharing mechanism is critical to the effective deployment and operation of RECs. At the community level, these elements are crucial to achieving the benefits of RESs in terms of the environment, economy, and society. Additionally, ECs have the chance to enhance knowledge and explore a variety of domains, including technology, for further improvements to make the system proper and efficient [97,98].

Regarding the technological aspect, the report [99] emphasized the obstacles the nation faces in putting REC legislation into practice. These obstacles include those related to smart meter operation and data collection, grid connection obstacles, the potential for REC for all distribution networks, labor-intensive tasks, administrative concerns, social and economic issues, regulatory and legal concerns, and others. Similarly, the literature currently in publication does not appear to adequately address the relationship that RECs have with the electrical system, or there is a lack of literature relevant to technology and components. The deployment of ECs is still restricted, even in England, because of organizational problems, legislative issues, and technology deficiencies [100]. In reference [101], various action drivers and barriers were confirmed or highlighted during the community energy supply discussion and thematic breakout session. Among the challenges are technological issues and a lack of software tools and IT infrastructure for sharing energy. M. Caliano et al. [102] highlight the role of enabling technologies in their project, which is named the eNeuron H2020 project at the community level in Europe, which is available locally and accompanying technical standards. The authors further discussed that the implementation and success of an energy community depend heavily on enabling technologies, which are primarily associated with those that make it easier to integrate ICT, ESS, sector coupling, and RESs. Some of the enabling ICT technologies discussed are control and management (EMS, BEMS, SCADA, etc.), technologies for analytics, communication technologies, IoT, and computing technologies. A. Tuerk et al. [103] focused on the technologies for EC in the H2020 EXCESS project, which serves as the basis for a discussion of several approaches to materialize Plus Energy Buildings (PEBs) and (PEDs) as ECs. The ICT framework is essential to provide the aforementioned actors with the tools they need to achieve novel use cases under ECs. Thus, the Data management platform, Data analytics platform, Model predictive control component, Data visualization framework, and blockchain infrastructure and apps are all part of the EXCESS ICT platform. They also pointed out that the EU Member States' implementation of the Clean Energy Package is inadequate and constrained without these technologies. In [104], the presentation and necessity of the technologies used in EC were discussed for proper management; some of them include EMS and BEMS for the demand-side flexibility category. In [105], the researchers propose a two-level hierarchical optimization strategy for MG community EMS in their case study analysis. Effectiveness was demonstrated by the results, and the outcomes showed how successful the strategy was. Two out of the four examined scenarios have been found to be cost-effective and are advised for use with communities. L. Wang et al. [106] worked on the DSM by proposing a price-based incentive-based DR uncertainty model and explaining how the incentive price and the DR coefficient are related. The findings demonstrate that, in contrast to the conventional approach, this strategy successfully lowers system-operating costs and enhances the load profile, resulting in a situation where consumers and energy corporations benefit equally.

Concluding from the above discussion, it could be concluded that technologies contribute to the effective operation and management of RECs, so without the necessary technologies, RESs and other energy sources cannot be fully integrated into the electrical grid, including those in EMS, DSM, data monitoring and analytics and the role of digital technologies include information and computing technologies. As a result, it may be said that to create a REC, certain technological conditions must also be met, facilitating the production, distribution, consumption, and sharing of energy with proper design, installation, operation, and monitoring using modeling tools and other techniques for successful outputs and projects. All these components together synergistically create a sustainable and locally driven energy ecosystem, enabling ECs to actively participate in the energy transition and promote RE adoption at a grassroots level. The key technological components of REC are depicted in Figure 8. These are EMS, DSM, data for energy monitoring and analytics, the communication system, and the modeling tools for different purposes from the planning and design to the operation stage, which result in an enhancement in the performance, efficiency, and resilience of REC. Moreover, a literature review is carried out to see the progress made on the following key elements, highlighting the importance of this research work.

3.2. REC Research Work Progress

3.2.1. Technological Elements Concern

The EC offers many attractive benefits, such as the potential to lower energy costs through energy sharing, lower economic costs for services and infrastructure, and support efforts to mitigate climate change by using RES technologies [107]. As discussed, all the components, including DREs, ESSs, and others, cannot be fully integrated into the electricity network without the appropriate technological elements. Moreover, taking and monitoring data for energy production, energy consumption, self-consumption, and energy sharing require proper elements to check, measure, and monitor the data. Based on the parameters checked and monitored the consumption profile can be improved for maximum benefit. Many researchers have worked on many parts of REC, including the REC's technological activities like RESs, ESSs, sharing models, policy requirements, business models and many other topics. A list of articles published relevant to the RECs' technological activities and elements from 2021–2024 is added in Table 3, highlighting the literature work showing the different activities performed by the researchers. This would provide insight for the readers and researchers to check the status of research work being carried out and to further enhance their work in the relevant area.

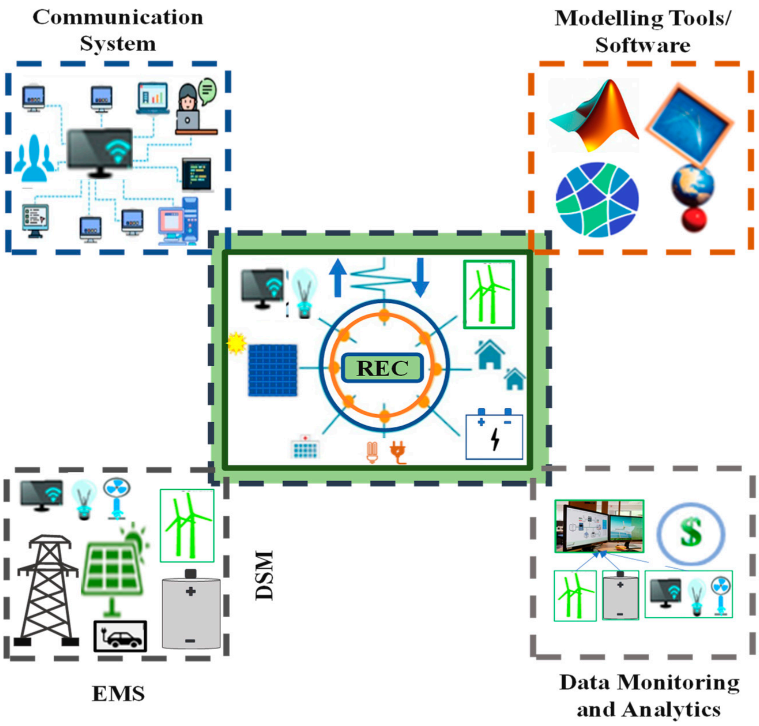

Figure 8. Key elements of renewable energy community.

From the literature, it can be observed that very few research papers are discussing the RECs as per the RED II Directive and European legislation, thus showing the low progress in the development and implementation of RECs. Considering the technological activities, most of the work is carried out on solar PV; few work on ESS and some work on other RESs like wind. Moreover, EV technologies are not discussed or are partially discussed in the literature for the RECs following the above table. Considering the technological elements like ESM and DSM for facilitating RES generation, ESS and EV integration, energy consumption, and energy sharing are no less discussed and lack this gap. Furthermore, the energy monitoring system and data analytics with the proper communication system among the meters is also the key element, which is also lacking in the literature specifically for the RECs, because without proper monitoring and analytics, it is complicated to analyze the energy self-consumption, sharing of energy and the incentives associated with it, and controlling the consumption profile of consumers and prosumers considering the benefits of it. So, checks and balances are necessary for the RECs' operation and control. Additionally, in the literature, it is also seen that software/tools for the RECs are not discussed or partially discussed, covering all the parts from the design stage to the operation stage.

Table 3. REC Research work Progress and their research focus (2021–2024).

Reference	Technology				Cons:/Self-Consumption	Optimization					Sensitivity Analysis	Simulation	EMS/DSM	Modelling/Operation	Energy Sharing	Economic Concern	Environmental Concern
	Solar	Wind	Other	ESS		Sizing	Allocation	Management	Investment Options	Other							
J. Sousa et al. [108]	√	√							√		√				√	√	
F.R. Bianchi et al. [109]				√				√						√		√	
E. Cutore et al. [110]						√		√								√	√
G. Raimondi et al. [111]	√	√		√												√	
F Lazzari et al. [112]	√						√			√						√	√
H Gribiss et al. [113]				√	√									√		√	√
A. Ahmadifar et al. [114]										√	√		√				
G. Spazzafumo et al. [115]			√													√	
S. Aittahar et al. [116]										√						√	
J. Faraji et al. [117]								√		√					√		
M. Pasqui et al. [118]				√	√				√							√	
F. Ceglia et al. [119]					√								√		√	√	√
L.M. Pastore et al. [120]			√	√	√											√	√
V. Casalicchio et al. [121]									√	√						√	√
M.A. Ancona et al. [122]	√				√										√	√	√
R. Sudhoff et al. [123]														√	√	√	
F. Conte et al. [124]	√							√		√						√	
A. Felice et al. [125]										√						√	
F.D. Minuto et al. [126]												√			√	√	
B. Fina et al. [127]												√				√	
A. Cosic et al. [128]			√							√						√	√
A. Cielo et al. [129]	√			√		√		√		√						√	√

3.2.2. REC Architecture Concern

Furthermore, our research work also focused on the architectures and models used for the RECs as per the European directive because it also keeps a vital role for the ECs, members, stakeholders, and researchers to easily understand the concept of the REC with different components integrated into it. For this, a thorough understanding of the many possible technologies is also required to finalize and implement the architecture for the REC. Overall, the development and technology aspects of RECs have received little attention in the literature for their architectures. Similarly, it appears that the literature currently in the publication does not adequately address the relationship that RECs have with the electrical grid in terms of LV and MV voltage levels, consumer and prosumer roles, energy sharing mechanisms, and RECs with different RESs, ESSs, and EVs considering the power constraint of 1 MW. This is a crucial topic since the introduction of RECs and relevant architectures has created new technical hurdles for the energy system and its administration. So, the main point that must be highlighted here is the architecture of REC. There is no uniform design and architecture that must be followed and implemented, like in microgrids, where there are AC MG, DC MG, and hybrid AC DC MG with different components connected with them [130]. Many models were used in the research articles, and some types or examples are presented in Figure 9 with different components [108,119,131,132]. Type-01 shows the simplified architecture of the EC. Supporting the energy change, the EC under consideration seeks to meet load demand through RE. Consequently, as illustrated in type 2, when also displaying the models, an EC made up of many homes and DERs (solar panels and batteries) is taken into consideration. Type-03 shows the connection with RE generation, different buildings (mall, church, and hotel), and the grid. In type-4, three members of REC (REC-1, REC-2, and REC-3) are linked to the power grid (MV). REC-1, which is the investing member, can finance RE production (PV and wind) for self-consumption, with the additional being sold to the grid at market rate. Moreover, the comparison of these different types of architectures from Figure 9 based on their key characteristics, components, and functionalities is also represented in Table 4 for clear understanding and analysis.

Table 4. Different REC Architectures.

Different Types of Architecture for EC			
Reference	**Characteristics**	**Components**	**Functions/Activities**
Type-01 [131]	RES Utilization, ESS as a positive role in REC, social, economic, and environmental factors	Transformers and Grid, RES generation (PV and wind or other), Participants (Prosumer and Consumer), MV-LV substation	REC concept highlighting the RES and ESS integration and associated energy sharing with the incentives.
Type-02 [132]	RES, ESS, Grid-connected operation mode, electricity consumption, sizing of DRESs, economic analysis, Energy transition	EC with several households and DRESs (solar PV and ESS), Grid	The EC considered in this architecture aims to meet the load demand by using RESs, which contribute to the energy transition.
Type-03 [119]	Only RES power plants, MT/LT Network, no possibility of direct private connection from plant to final users, the shareholders or participants or members must near the facilities of RES plant, energy exchanges	RES Plants, Grid, Load for Hotel, church, and mall	Production; sale; sharing; energy exchange within the EC is virtual; access to all electricity markets, directly or via aggregation; supply of energy; aggregation and other commercial energy services.
Type-04 [108]	REC, investment in RES plants, optimal investment decision, self-consumption motivation, selling excess energy, economic benefits	REC Members, MV Grid, RES generation (Wind and PV)	The architecture illustrated as per the study of the three REC members (REC 1, 2, and 3) connected to the grid. From them, REC-1 (the investing member) can invest in RES generation for self-consumption (for both individual and collective), and the surplus would be sold to the grid.

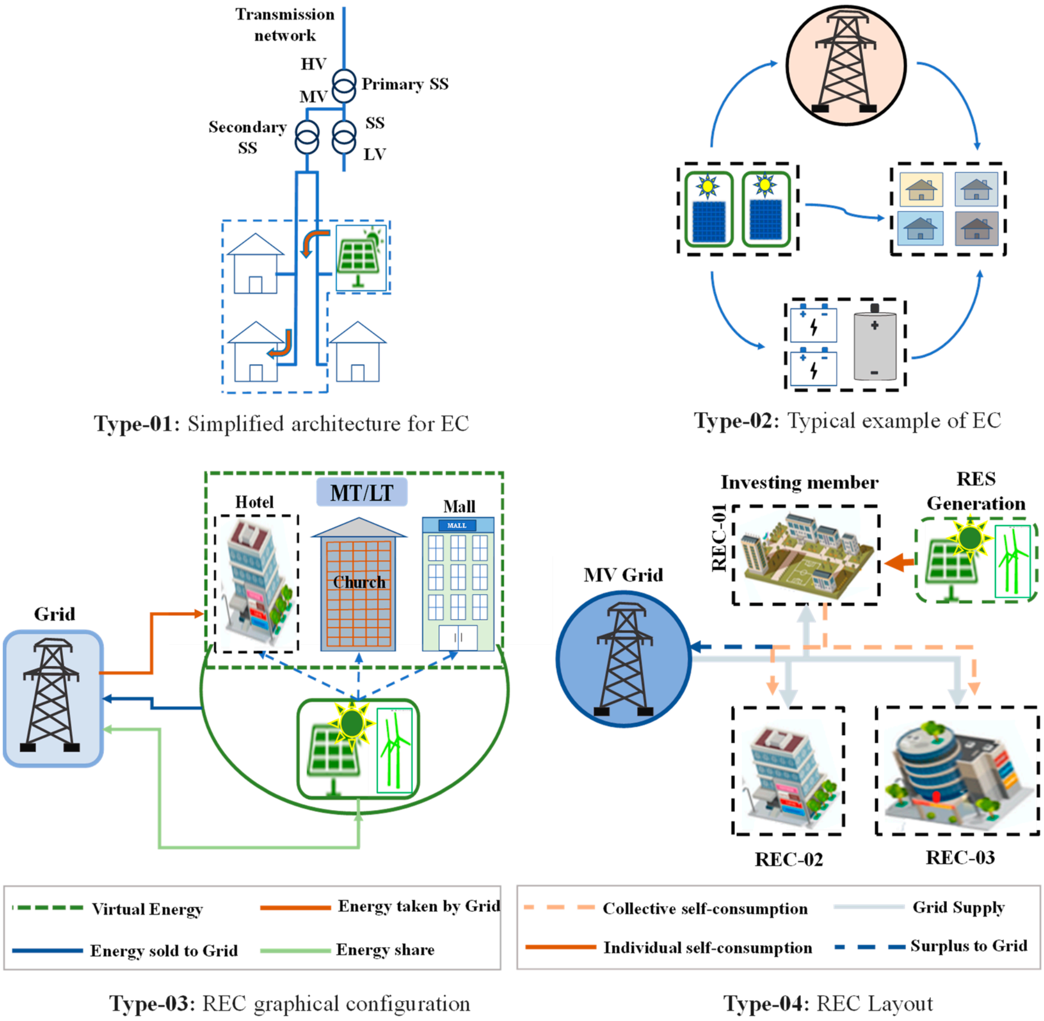

Figure 9. Energy community architectures or layouts.

Although the concept could be the same for all, it is important that there be uniform architectures so that the analysis from various perspectives (like types of energy sources and technologies, grid connections, and constraints, integration of with main grid, DC or AC system, Hybrid system, ESS integration with one plant and different collective RES plants, ESS system for different prosumers or prosumers, participants like prosumer, consumer and producer role, RES plant with one investor or different investors, RES plant for different prosumers, one plant for different prosumers, types of loads like commercial, industrial and residential, EV technologies integration and charging infrastructure, etc.) can be carried out.

Considering a unique, easy, and uniform REC architecture with specified components as per the different requirements of the different participants would be helpful for all for the easy understanding of RECs, and eventually, this will enhance the willingness of the public to get involved in developing the RECs. Stakeholders, policymakers, researchers, and industrialists must address the specific requirements and peculiarities of each community while promoting uniformity, efficiency, and sustainability by incorporating the ideas into architectural designs for RECs. Architects, planners, engineers, legislators, and community members can work together to ensure that planning processes are collaborative and that architectural designs accurately represent the goals and common vision of the RE.

Reflecting the gaps in the literature, like technological elements, the next part discusses EMS, DSM, data monitoring and analytics, communication systems and software/tools pertinent to RECs.

3.3. Energy Management System (EMS)

Recent advancements in smart grid technology have heightened the adoption of advanced energy management and control techniques [133]. EMS is used to monitor and optimize energy production, consumption, and storage within the microgrid and community [134,135]. This empowers consumers to generate, buy, and sell electricity with greater flexibility. Consequently, it is imperative to develop an EMS that can efficiently support ECs in their efforts to monitor, maximize individual and collective self-consumption, trade peer-to-peer, and control other parameters like voltage [136,137]. This will ultimately lead to high satisfaction levels and adherence to standard specifications. In essence, it is an algorithm that uses real-time sensor data to manipulate system parameters in order to attain a predefined target state [138]. As per the IEC standard application program for power systems, IEC-61970 [139] outlines an EMS as a "computer system that includes a software platform offering essential support, along with a suite of applications that deliver the necessary functionality for the efficient operation of electrical power generation and transmission services, ensuring a secure energy supply at the lowest possible expense." [140,141]. The EMS takes on a sort of function, such as data analysis, predictive modeling, optimization, HMI, and network reconfiguration, to facilitate real-time communication within the EMS [142]. These systems enable efficient use of DREs, load balancing, and demand-response capabilities [143]. Y. Li et al. [144] have created an integrated demand response system to boost the use of RESs. They tested this system in a real-world scenario and found that their approach, called the DRO model, effectively balances economic efficiency and resilience when compared to traditional stochastic programming and robust optimization methods. T. Huy et al. [145] propose a multi-objective mixed-integer linear programming framework for a comprehensive HEMS. This system optimizes energy costs, peak-to-average ratio (PAR), and discomfort index (DI) while utilizing vehicle-to-home and home-to-grid capabilities. Numerous researchers have dedicated their efforts to developing EMS for microgrids [146–148]. Y.K. Chen et al. [149] presented the development of an EMS utilizing fuzzy control for a DC MG system. It includes the modeling, analysis, and control of distributed power sources and energy storage units using MATLAB/Simulink, and the EMS is realized through integrated monitoring with LabVIEW. Other researchers have introduced the MG Platform (MP), an advanced EMS aimed at enhancing MG efficiency. The MP was meticulously designed to encompass all essential microgrid EMS functions (optimization, forecasting, human-machine interface, and data analysis) while also addressing key engineering challenges such as extensibility, interoperability, and flexibility. Also, a prototype system has been created and implemented in two smart grid testbeds [150]. When extending the application of these systems to ECs and incorporating the established rules as constraints, it becomes possible to efficiently manage all accessible resources with minimal oversight. Given that an EC encompasses multiple consumers and prosumers, the primary goal of an EMS is to align supply and demand within the EC, while also distributing advantages to enhance societal well-being [38]. A platform is also presented in Figure 10 showing the EMS for the prosumer for REC, which could be an example or prototype to be followed for ease.

Different RESs like wind and solar, ESS, and EV technologies, including the grid system, are highlighted in the figure. The EMS system should be adequate and reliable so that energy flows from various sources to loads can be optimally operated, and excess power should also be shared and monitored efficiently using optimization techniques and algorithms. Moreover, there must be a cloud-based EMS system with an intelligent system, which gives access, monitors, and controls the data remotely in different aspects like energy generation, energy consumption, energy storage, EV charging, and energy sharing.

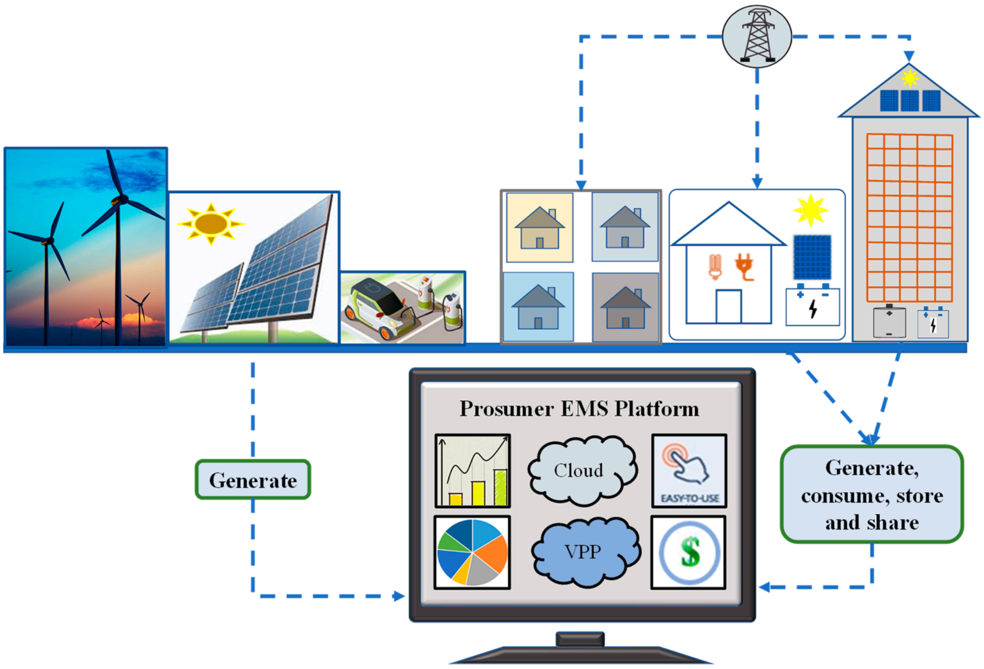

Figure 10. EMS Platform of Prosumer.

Concluding this topic, researchers must focus on the EMS for the RECs, which function efficiently, optimally, and with resilience. This will contribute to the development of a sustainable energy ecosystem that benefits the environment and the community by integrating RESs, optimizing energy efficiency, and enabling DSM. However, there could be challenges for the EMS in RECs, such as the integration of diverse energy sources (RESs, ESS, and EVs) issues, size and scalability issues in cases of increasing capacities of RECs, cyber-security issues that result in system blackouts and disturbances in operations, gathering and managing real-time data issues relevant to various energy sources (consumers, prosumers, and grid perspective), and interoperability issues having a negative impact such as a disturbance in continuous integration. However, solutions for these challenges could exist such as an implementation of modular and proper EMS architectures that have capabilities of integrating different energy sources with increased sizes and flexible scalability, an adherence to proper communication protocols and standards to integrate easily and simply, advanced cyber-security measures like firewalls, encryption and regular security check and audit ensuring the mitigation of risks, and lastly, the use of advanced technologies like ML and AI for data processing resulting in efficient solutions and increased decision-making. For all the solutions discussed, the support from the stakeholders like policymakers and government plays a vital role in implementing these solutions.

3.4. Demand Side Management (DSM)

Optimizing the energy system, one of the most intricate and significant technological innovations, is the goal of EMS. Although energy generation and distribution optimization are well-trod areas, industries and researchers are focusing more on the demand side. Demand side management is a collection of measures, that aim to enhance the energy system on the consumption side [151]. DSM is an emerging innovation in smart grid technology that facilitates communication between energy providers and consumers and signifies an innovative planning approach for electric utilities. In essence, it expands the planning perspective to align the customer's needs and preferences with the utility's objectives [152]. The phrase "demand-side management" was initially introduced by Clark Gellings in 1984. This concept was historically referred to as "load management" [153]. Many researchers highlighted the concept of DSM as strategies that reduce energy demand or consumption during peak periods [154], incorporate or omit energy efficiency strategies [155], incorporate consumer responses to price variations, and shift the loads to non-peak hours for cost benefit [156]. P. Palensky et al. [151] discussed DSM as a range of actions aimed at enhancing energy consumption, including boosting efficiency through improved materials, introducing intelligent energy pricing models with incentives for specific usage patterns, and implementing advanced real-time control of distributed energy resources. Referring to the literature, different approaches and categories have been represented in Figure 11 [157–160] focusing on the demand response, energy efficiency and distributed energy resources. All these terms have significant characteristics for the demand side management having the objective of utilizing RESs efficiently and economically. In different articles DSM is categorized with different options. Three types of DSM activities are increasing in popularity as DR, DER, and EE Figure 11a. In some papers, it is mentioned that DSM has two approaches, including energy efficiency (EE) and demand response (DR) as shown in Figure 11b. P. Warren et al. [157] discussed the three branches of DSM as depicted in Figure 11c. The first is discussed as a category, and the primary types of DSM are classified into three overarching classifications: EE, DS response, and on-site backup. The second is highlighted as the main implementers of DSM programs, which include the government, aggregators, customers, DNOs, and utilities. The third branch is relevant to policy and includes regulatory, market-based, voluntary, and financial.

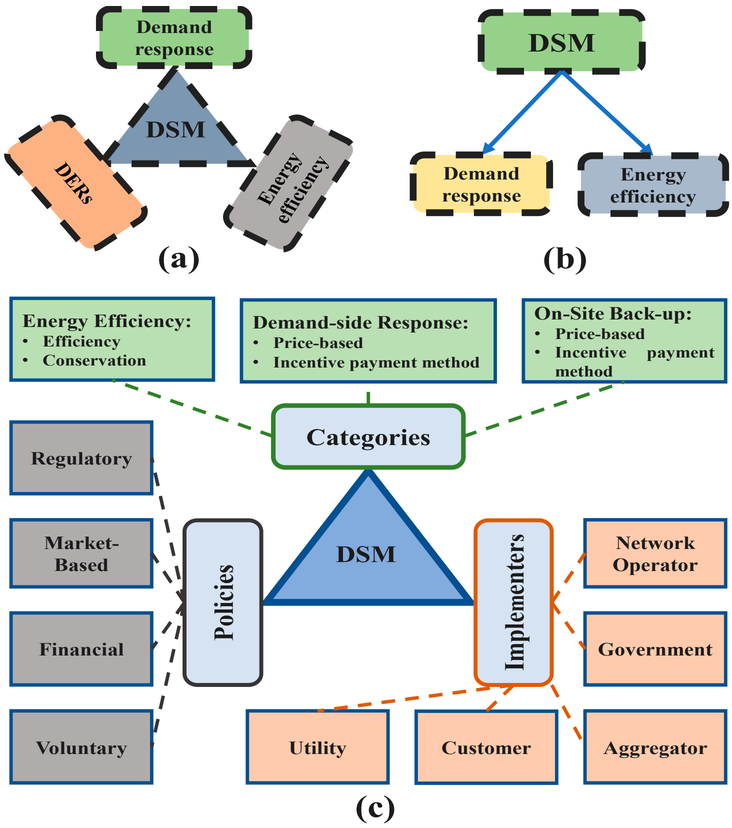

Figure 11. (**a**,**b**) DSM categories (**c**) Different DSM approaches and categories.

Continuing with this, F. Boshell et al. [161] discussed DSM initiatives in Europe, Japan, and the USA, outlining their design, implementation, results, and conclusions. The analysis indicates that DSM programs are most successful when they integrate EE, EC, and DR concepts. The incorporation of DSM, along with the integration of DREs and ESS, is progressively viewed as vital for realizing the smart grid concept and effectively balancing the substantial energy output from RES [162].

After the development of RES and ESS technologies in MGs and ECs, DSM is fundamental for managing the unpredictability of RE generation and load. This growing penetration of RES with the ESS complements DR measures, benefiting both utilities and consumers, whose primary goal is to reduce peak demand, lower electricity costs, and decrease emission rates [163]. Research in optimizing RE MGs and DSM has gained momentum [164], resulting in a variety of approaches, including hierarchical frameworks [165], dynamic programming [166], and evolutionary algorithms [167]. M. Afzal et al. [168] introduce a distributed DSM system for multiple homes within a community microgrid. It leverages IoT smart meters and incorporates RESs. This work outlines an energy consumption game aimed at reducing the electricity costs for individual homes and the overall energy consumption costs for the entire community. G.H. Philipo et al. [169] suggest a DSM strategy involving load shifting and peak clipping implemented in MATLAB/Simulink and fine-tuned through ANN optimization. Simulations were conducted to evaluate the model's performance in a stand-alone PV-battery MG located in East Africa. E. Dal Cin et al. [170] explore three EC setups with local prosumers generating renewable electric and thermal energy. It assesses two DSM strategies: post-design optimization price-based demand response and pre-design optimization DSM based on local RESs. The results show an improved balance between generation and demand, reducing grid stress.

Mostly, research is carried out on MGs for the DSM; however, attention must be paid to this topic from the researchers, especially in the case of RECs. In RECs reliant on RESs, DSM is essential because it makes it easier to use RES efficiently, improves grid stability, decreases dependency on fossil fuels, and encourages economical energy-use habits. RECs may optimize the benefits of RESs while guaranteeing a dependable and sustainable energy source for the future by proactively regulating energy consumption. Challenges for the DSM for the RECs may occur as well like community participants' engagement issues due to lack of awareness and knowledge to engage in DSM programs, data privacy, and insecurity concerns for knowing consumption scenario from the participants, Policy and regulatory barriers for not supporting financially in DSM initiatives and high cost and payback issues on utilizing money for DSM programs and not getting return on time. Following the challenges highlighted, there must be solutions and options for the RECs such as training and awareness for the REC participants, an elaboration of the knowledge and benefits of DSM system, a focus and implementation of strict compliance on data privacy in order to ensure the participants to be in safe zone, easy and supportive policies, and a regulatory framework facilitating with the funds and loans for implementing the DSM system, using the economic analysis techniques to check the feasibility and profitability for short and long term duration and also the technological advancements that support the DSM infrastructure.

3.5. Data Monitoring and Analytics

The monitoring system regulates every piece of equipment to make sure it is stable and safe while also monitoring each piece of equipment in real time. It is crucial to make sure the monitoring system is constantly updated. ECs monitor energy production, consumption trends, and overall system performance using data monitoring and analytics technologies [97]. The data-driven methodology pertaining to monitoring and analytics facilitates the identification of optimization opportunities, informed decision-making, and the maintenance of the energy community's smooth operation. In [171], authors presented the energy community data platform (ECDP), a middleware platform designed especially for collecting and evaluating large amounts of data on energy use in local ECs, with the main objective being to encourage users to use energy more wisely and with more awareness.

Online sources are essential for educating people and bringing attention to the advantages of ECs. To assess public awareness and the media's importance on this topic, researchers look at online news data. They also use a novel metric known as the Semantic Brand Score (SBS), which blends text mining and social network analysis methods [172]. The authors [24] suggested data analytics modules to help community members optimize their creation and utilization of resources in order to lower their electricity expenditures. Additionally, they provide a day-ahead wind power forecasting algorithm that makes use of state-of-the-art machine learning methods. M. Sănduleac et al. [173] urge the integration of information gathered at wildly different reporting intervals. Because the distribution power grids experience partial observability problems, mostly due to poor metering infrastructure, especially in areas downstream from medium-voltage substations, it is necessary to increase system situational awareness and monitoring accuracy. In [174], their suggested method, which uses a Raspberry Pi and the Flask framework to present solar energy consumption in real time, is discussed. This intelligent monitoring application helps users analyze their energy usage and its effect on the utilization of RESs and electricity worries by providing daily insights into renewable energy consumption. Hernandez-Matheus et al. [175] outline the development of a local EC concept, drawing from an analysis of 25 EC projects, and it involves a comprehensive literature review categorizing ML algorithms for various local EC applications, including forecasting, storage optimization, energy management, power stability, security, and energy transactions. C. Goncalves et al. [176] emphasized the need for extensive data in testing innovative energy models. They tackled the issue of costly and time-consuming on-site load data collection by creating a dataset for a residential community. This dataset includes sample consumption and PV production profiles and provides a detailed breakdown of household power consumption into individual appliance usage. A.J. Albarakati et al. [177] highlighted the monitoring systems for MGs classified as monitoring systems using IoT, monitoring systems using SCADA, and monitoring systems using cloud computing. Figure 12a shows the monitoring system using monitoring through the cloud, in which the measurement unit sends the measured data straight to the cloud, and Figure 12b shows the monitoring system using the SCADA system [178].

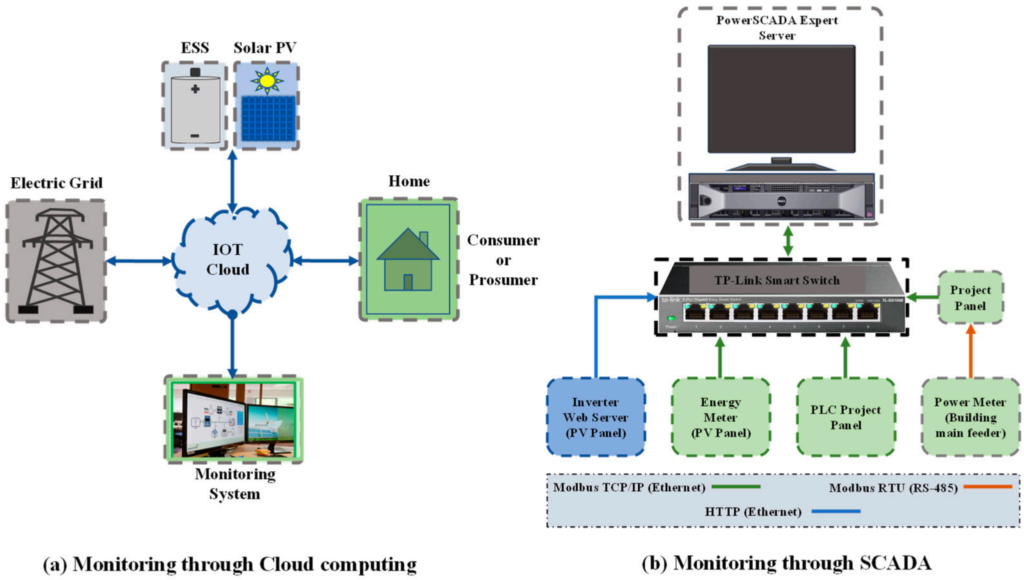

Figure 12. Different Monitoring Systems.

The above architectures have different characteristics with different pros and cons, like installation, cost, operations, and easy or friendly use. Considering the architectures above, there is a possibility of making a proper and efficient monitoring system for the RECs by following the legislation and standards. Again, most of the work is carried out on monitoring and data analytics for the MGs and ECs, which are not as per EU directives or in different countries except Europe. So, the researchers must focus on this important topic specifically for the RECs because the data must be obtained on an hourly basis (like in the case of Italy) or as per the different EU countries' times (the specified time (1 h, ¼ h or ½ h)) as the energy shared incentive is time dependent depending on the country's requirements. In the case of Italy, the energy consumption data is in minutes and is based on viewings of every 15-min consumption profile. For this reason, energy consumption data should be on an hourly basis. Moreover, in the case of energy generation for the prosumer, data taken for the solar PV system with or without storage through the inverter company portal should also be on an hourly basis to check the energy production and consumption profile and share energy accordingly. So, for this reason, proper monitoring with different optimization techniques is required concurrently for both generation and consumption profiles, following the constraints set as per legislation.

It could be highlighted here that every system has benefits as well as challenges. However, the challenges for monitoring systems and analytics could be relevant and require data like time dependency, the accuracy of data for effective outcomes, overloading of data, interoperability, a skilled system having the ability to understand the system monitoring, and high initial costs in the case of RECs. There exist solutions for the challenges highlighted, such as setting parameters in the system to take data as per required time, proper calibration of the equipment associated with monitoring purposes, and maintenance to ensure data accuracy. They use advanced technologies and tools for the management of data. They include AI and big data analytics or others for managing large data and protecting against overloading, following open and proper standards and interoperable systems, thus facilitating integration, proper training, workshops, education, awareness for enhancing skills to understand and control the data, and a cost-effective system starting from a small prototype then growing to a significant level after successful and required outcomes with support of governments and stakeholders.

3.6. Communication System

Reliable and timely information is now essential for the electric utility's profitability, customer satisfaction, and reliable and proper distribution of power to end users in today's competitive market. Electric utilities need a proper data communication network with high performance and efficiency that can serve both current and future operational needs to meet their operational and commercial objectives [179]. Effective management of complex power systems depends on information flowing across different network components, which requires proper communication [180]. The generating station and the end customer were not communicating in the past. After the development of communication technology, energy may now be managed efficiently between the generating station and the load side through bidirectional communication. Communication technologies can be used to transmit data to the server or cloud. The equipment's performance is examined using the data that have been gathered [179]. A system like EC or MG needs a dependable, strong, and affordable communication system with the right amount of latency, security, and coverage in order to function properly [181]. The key motivations and benefits of the communication infrastructures, as shown in Figure 13, are related to the environment, system, and operation sides [182].

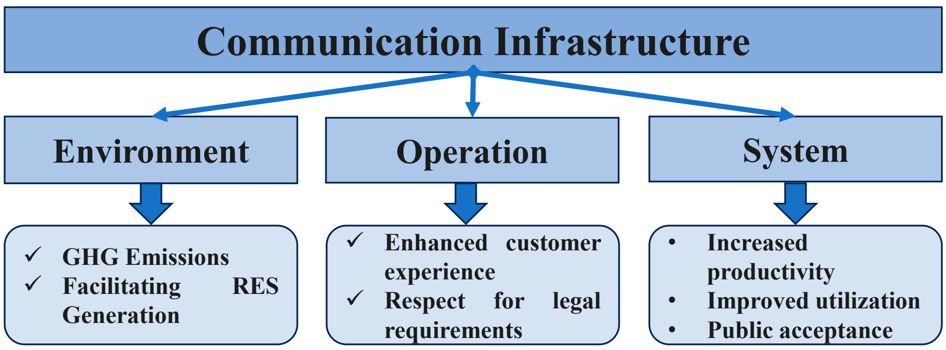

Figure 13. Communication technologies and applications [182].

There are multiple standards for the communication network because they offer specific instructions and methods that are generally applicable [183,184]. Globally, governments and businesses have acknowledged the significance of standards in the energy sector. Standards promote communication and aid in ensuring quality and safety [185]. It is challenging for manufacturers to develop or install a system that can be used anywhere in the world in the absence of different standards for communication. There are two types of communications, namely, wired and wireless, with different characteristics [186]. Several wireless technologies are present [187]. Wireless communication technologies are currently surpassing wired-based alternatives due to their many benefits, including affordability, ease of installation, mobility, and convenience. In Figure 14, each of these technologies is named PAN, LAN, MAN, and WAN based on the distance and applications [185].

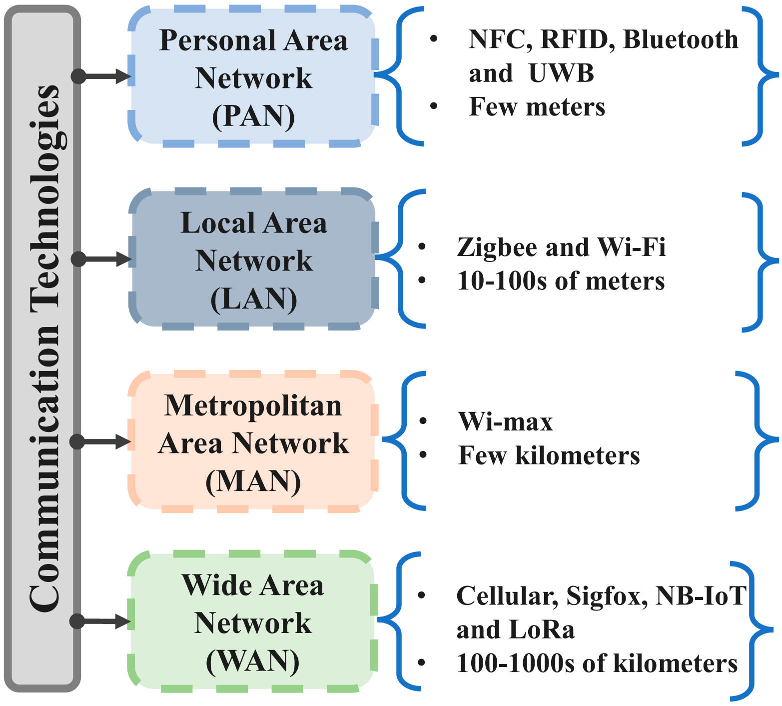

Figure 14. Communication technologies and applications.

As per [188], the communication system architectures for the smart power system, for instance, a smart MG, can be broadly categorized into three levels depending on the corresponding function and location: HAN, FAN, and WAN. It is crucial for smart meters, intelligent household appliances, and in-home displays to communicate with one another. Smart meters that can be integrated with the ZigBee protocol are preferred by many AMI vendors, including Landis Gyr, Elster, and Itron [189]. Moreover, the technologies used for measuring are smart meters (an electronic box with a communication link) and advanced metering infrastructure (AMI) with integration with WAN, HAN, and MDMS for the smart grid [190]. The communication system for REC should consist of a network of sensors, controllers, and communication protocols that allow for easy coordination, control, and monitoring of the system's energy generation, energy storage, and energy consumption. Among the essential elements of such a communication system could be smart meters, actuators, sensors, DCS, SCADA, data communication networks, and others [191].

So, overall, the communications system for the RECs is very important and beneficial due to many reasons such as proper coordination and control, energy flow optimization, detection of fault and management, DR and management of load, integrating RESs, and increased reliability and resilience. Ultimately, the goal is to contribute to the energy needs of the RECs effectively and sustainably.

3.7. Modeling Tools/Software

The development of modeling and simulation tools for energy systems has received a lot of attention from researchers, industrialists, and other stakeholders because it is a key component that powers the modern economy [192]. The inadequate sizing and design of RECs and components like RES components, ESS components, EV technologies, and other associated elements can lead to economic losses due to oversized, undersized, or poorly planned systems. RESs require technical and economic analyses to streamline designs and maximize utilization for harnessing efficiently. With the complexity of the multiple generation sources and systems, the software and simulation tools and models are important for proper design, optimization, analysis, and economic planning. In the case of an REC, from the initial phase, including planning and design to implementation, software and tools are necessary at each point, giving positive outcomes like a proper and efficient REC system. Sunanda Sinha et al. [193] presented 19 software applications, outlining their primary features and current statuses. They also conducted a review of research involving hybrid systems across various global locations using these software tools, whose primary aim was to offer an up-to-date overview of these software options, assisting researchers in identifying and selecting appropriate tools for their R&D endeavors in the field of hybrid systems. Hans-Kristian Ringkjøb et al. [194] provided an extensive review of 75 modeling tools utilized for analyzing energy and electricity systems. The assessment covers a wide range of modeling tools, spanning from small-scale power system analyzers to global long-term energy models. Tu A. Nguyen and Raymond H. Byrne offer an overview of software tools used in assessing and designing ESS. The primary objective of these tools is to simplify technical challenges for stakeholders, thereby lowering the obstacles to the widespread adoption of ESSs. Some examples of such tools are Storage Value Estimation Tool (StorageVET), QuESt—Energy Storage Application Suite, MASCORE—microgrid asset sizing tool, and RE Integration and Optimization (REopt) [195]. F. Vecchi et al. [196] review the around twelve energy modeling tools for the REC having the potential and evaluation for it. As per their findings, none of the existing tools satisfy the co-existence of various criteria because most of them only analyze a small number of areas of interest while only partially taking other factors into account. Leveraging insights from academic literature and industry expertise, various stakeholders, including national laboratories, utilities, and system integrators, are actively working on the development of software tools for RESs, ESSs, economic and environmental assessment, and other areas for RECs. Moreover, the list of software and tools used for energy systems, electrical power systems, and RES, and non-RES, with different purposes and applications is listed in Table 5.

All software and tools have access to technical energy-related evaluations and RES assessments, and they frequently contain the economic aspect as well. Energy evaluation, which typically complements the RES assessment, is the central component of modeling tools. From the list, some software and tools are simulation-based, and some are calculation-based. Recurrent system optimization usually requires matching energy and economic criteria to determine the ideal system size depending on the optimization's goals. The groups of tools have not developed environmental analysis as much, and DER-CAM and iHOGA can simulate CO_2 minimization. Financial mono-objective and multi-objective optimizations, in which economics are matched with other variables, are performed by iHOGA. URBANopt minimizes life cycle costs, whereas CitySIM and SimStadt are characterized by energy-driven studies. MATLAB is used to design the REC system, and simulations are run to analyze the operation. Python could help in numerical calculation, focusing on the technical and economic aspects of optimization techniques. Each software has its own characteristics. No single tool or software could be used to cover all the parts of RECs. However, different software and tools could be used for the successful operation of RECs, focusing on economic, technical, and environmental analysis from the initial to the final stage. The above table contains a list of tools that can help the researchers work on the RECs efficiently and optimally.

Table 5. List of software/tools used for energy, electrical power systems, and renewable energy system applications.

Software	Developed By	MG	RES/DRES/RET	ESS	Economic/ Financial/Cost	Environmental	Grid System	EPS/Other	Purpose/Applications
HOMER [193,197]	NREL USA	√							• reliable hybrid MG and grid-connected systems.
INSEL [198]	University of Oldenburg, Germany		√						• for researchers, students, and teachers, engineering offices, planners, and operators of RESs.
RETScreen [199]	Ministry of Natural Resources, Canada			√	√	√			• to evaluate both financial and environmental costs and benefits of RET
PVsys [200]	-		√					√	• researchers, engineers, and architects are the target audience for PVsyst. • provides a user-friendly approach with a project development guide and helps with the techniques and models utilized
EnergyPLAN [201,202]	Aalborg University, Denmark							√	• for the electricity, heating, cooling, industry, and transport sectors
SUNtool [203]	-							√	• a decision-making tool at an early stage for sustainable urban design developed by an EC-funded research project
Hybrid2 [204]	University of Massachusetts Amherst		√	√	√			√	• performing the long-term performance in detail and economic analysis on a wide range of hybrid power systems
iHOGA/MHOGA [205]	researchers of the University of Zaragoza (Spain)		√					√	• two versions of the HOGA software for the simulation and optimization of Electric Power Generation Systems based on RE
DER-CAM [206]	Lawrence Berkeley National Laboratory (Berkeley Lab)		√					√	• finding the optimum portfolio, placement, sizing, and dispatch of DERs at a wide range
OpenDSS [207,208]	developed in 1997		√				√		• a DSS simulator designed to support DER grid integration and modernization

Table 5. *Cont.*

Software	Developed By	MG	RES/DRES/RET	ESS	Economic/ Financial/Cost	Environmental	Grid System	EPS/Other	Purpose/Applications
GridLab-D [209,210]	Power distribution system simulation and analysis tool							√	• to provide valuable info to users who are designing and operating the distribution systems.
TRNSYS [211]	University of Wisconsin System and University of Colorado					√		√	• used for simulating the behavior of transient systems focused on assessing the performance of thermal and EES.
BSET [212]	PNNL			√			√		• a modeling and analysis tool that enables users to evaluate and size a BESS
VBAT [212]	PNNL			√				√	• provides assessment of VB potential from residential loads with thermostatically controlled building at different geographic levels
MDT [213]	Sandia National Laboratories (SNL)	√			√			√	• decision support tool for MG designers for using and searching the algorithms to identify as well as characterize the alternative MG design considering cost, performance, and reliability
REopt [214]	NREL				√			√	• techno-economic decision support platform for optimizing energy systems (ECs, buildings, MGs, and campuses).
MATLAB [215]	-	√	√	√	√	√	√	√	• have many applications like MG, ECs, and others
Python [216]	-	√	√	√	√	√	√	√	• many applications like web and internet development, scientific and numeric, education and software development, etc.
SAM [217]	NREL	√	√	√	√			√	• Providing the financial and energy optimization and techno-economic analysis of energy technologies, as per different market models
H2RES [218]	-		√					√	• Minimizing the operation and system costs on a yearly basis

Table 5. *Cont.*

Software	Developed By	MG	RES/DRES/RET	ESS	Economic/ Financial/Cost	Environmental	Grid System	EPS/Other	Purpose/Applications
URBANopt [219]	NREL		√				√	√	• Optimizing the energy systems for district thermal networks, building retrofits, local RES, and electric distribution system
CEA [220]	-		√					√	• Optimizing the urban energy systems for designing building retrofits, district thermal networks, local RES, and changes in urban form
SimStadt [221]			√					√	• Simulation of energy transition scenarios and comparing them
CitySIM [222]			√					√	• Estimating the RES potential and sustainability in the urban community

Summarizing the above discussion, modeling tools, and software are crucial for RECs and the effective operation and integration of RESs. The general dependability of RECs all depends on a proper infrastructure that makes it possible to monitor, manage, and optimize energy resources in real time, which helps create an energy infrastructure that is more resilient and sustainable.

4. Discussion and Future Perspective

This article offers a systematic review and detailed analysis of the REC, as well as key aspects, technological aspects, and key technological elements in the REC. Although the technological activities like RES generation, energy consumption, ESSs, energy sharing and EVs discussed in Section 2 are linked with the technological elements discussed in Section 3, both works together to create an integrated energy system; they each serve specific functions and address different aspects of energy generation, distribution, management, and optimization within RECs. In the literature, researchers mainly discussed the activities, but they lacked other parts like technological elements, which are necessary because there are opportunities to create better operation, control, and planning strategies. In-depth research could be conducted and followed in these areas, such as EMS, DSM, monitoring and data analytics, communication systems, and the software or tools used for them to enhance the creation, management, and operation of RECs properly and efficiently. The following are the comments to be addressed based on the above discussion:

- Technological components like EMS, DSM, energy monitoring, analytics, and communication systems are crucial for RECs. Moreover, precise system modeling is essential for effective planning and management. They enable operators and participants to analyze parameters, enhance systems, and plan effectively. Researchers and stakeholders should focus on these tools for planning, design, operation, and maintenance.
- Improving infrastructure adaptability and grid flexibility, governments and energy regulators can amend laws and regulations to allow for the community-level integration of RESs. This entails enabling DR programs, putting smart grid technologies in place and permitting bidirectional energy flow. The advantages connected with energy generation, sharing, and consumption should be the main points of emphasis, along with a thorough grasp of the process for doing so. In a very significant way, the IoT and SCADA facilitate the formation and connectivity of decentralized and transactional energy markets for real-time platforms to monitor the data. Although two-way energy exchanges between producers and consumers will probably be the most challenging in the future, based on their earlier studies, new technology should nevertheless be able to address this issue.
- To improve flexibility, utilities can also invest in changes to the grid infrastructure such as the installation of ESSs, the deployment of sophisticated metering equipment, and the use of distribution automation technologies.
- For more growth and advancement in the discussed technological elements for RECs, there must be the integration of new emerging technologies like AI, machine learning, IoT, and blockchain in energy systems like RECs to make the system reliable, efficient, cost-effective, sustainable, and user-friendly. These additional technologies will enable and foster more positive outcomes like gathering real-time data and monitoring, fault detection and analysis and its diagnostics, forecasting and analysis based on it, smart systems and automated control, optimum energy use and flow, and improving energy efficiencies.
- It is shown that there is not any common or unique REC architecture, model, or example following the literature, which confuses readers working on it. It is possible to create a new, improved, or uniform model or architecture that would lower planning and operating costs by considering the stochastic nature of integrated distributed generation in RECs, ESSs, EVs, or other components and following the constraints. This could be possible with the support of researchers, stakeholders, and policymakers.

- Community-based RE targets are examples of supportive policies and regulations that governments can introduce to encourage the development of RECs. Although the addition of the above-recommended technological elements, including software and tools, has a high cost, it is challenging for investors and community members to cover it. However, in this case, great support is required from the government, policymakers, researchers, and practitioners to foster the development and adoption of RECs.
- Policymakers play an important role by giving supportive policies through financial support (by giving loans or subsidies), regulatory frameworks, easy and fast processing, less documentary work and barriers, flexible permission procedures, and supportive legislation and standards, promoting the REC and the awareness of its benefits in public. Moreover, the researchers could also be the main part of the RECs, who contribute by giving innovative ideas and technological solutions in optimizing the energy flows and efficient operation using algorithms, carrying data and their analysis, forecasting, research collaboration to develop and enhance the current work, proper modeling, design, and simulation. All these are considered as the key pillars for reliable, efficient, economical, and sustainable options for the RECs. By considering both the policy and research as a priority, we see that they result in the fast adoption and development of RECs making resilient, efficient, reliable, and sustainable energy transition options.

From the above points, it is summarized that governments, stakeholders, policymakers, researchers, practitioners, and communities may collaborate to support and accelerate the growth of RECs by putting the above ideas into practice, which will result in a more decentralized, equitable, intelligent, effective and sustainable energy system.

5. Conclusions

The work emphasized the decentralized system by focusing on the RECs, which have several advantages in the social, economic, and environmental areas. The REC topic has gained value recently because it supports local economic growth, improves energy security and resilience, lessens GHG emissions, builds social solidarity, reduces poverty, and empowers communities. Despite the many benefits and concentration on this topic, there is still limited progress in REC development and a lack of discussion on technological elements. Many articles discussed only technological activities like RES generation, ESSs, energy consumption, and energy sharing concepts. However, there are also gaps in the widespread implementation of comprehensive data monitoring and analytics systems within RECs. Challenges include the need for standardized data protocols, cost-effective deployment of advanced metering infrastructure, and ensuring data security and privacy. Moreover, there is a need for cloud-based EMS platforms that offer remote monitoring and control, providing users with detailed insights into energy generation, consumption, and storage. Despite the advancements in EMS technology, there are still challenges to be addressed. These include the need for more robust and resilient systems, better integration with existing infrastructure, and enhanced capabilities for managing distributed energy resources. Considering the above scenario, this article completes this gap by focusing on and discussing the technological elements, which include proper EMS, DSM, data monitoring and analytics, proper communication systems, and the software/tools used for REC. The review also highlights the necessity for a standardized REC architecture to streamline implementation and enhance understanding among stakeholders. Uniform models can facilitate better planning and operational strategies, ultimately leading to more effective and efficient REC systems. By adhering to and putting them into practice, there are good opportunities to create better planning strategies, operations, control, and management, resulting in the development and growth of RECs. Furthermore, it also highlights the role of governments, stakeholders, and supportive policies from policymakers, who could be a main pillar to support, like funding, research, and others, for addressing and implementing these technological elements to make the system more convenient and efficient.

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Nomenclature

Acronyms

ANN	Artificial neural network
ANSI	American National Standards Institute
BSET	Battery Energy Storage Evaluation
BESS	Battery energy storage system
CEA	City Energy Analyst
CitySIM	City simulation
CEC	Citizen Energy Community
DSO	Distribution system operator
DCS	Distributed Control Systems
DER-CAM	Distributed Energy Resources Customer Adoption Model
DSM	Demand side management
DR	Demand Response
DREs	Distributed Renewable Energy resources
DSS	distribution system simulator
DGs	Distributed Generators
ESS	Energy Storage System
EES	Electrical energy system
EC	Energy Community
EMS	Energy Management System
EE	Energy efficiency
EU	European Union
GHG	Greenhouse gases
HAN	Home area network
HOGA	Hybrid Optimization by Genetic Algorithms
HMI	human-machine interaction
HESET	Hydrogen Energy Storage Evaluation Tool
HOMER	Hybrid Optimization of Multiple Energy Resources
HMI	human-machine interaction
H2RES	Hydrogen to Renewable Energy System
ISO	International Organization for Standardization
IEC	International Electrotechnical commission
IEEE	Institute of Electrical and Electronics Engineers

ITU	International Telecommunication Union
MDT	Microgrid Design Toolkit
MASCORE	Microgrid Asset Sizing considering Cost and Resilience
PV	Photovoltaic
PCM	phase change materials
PSHET	Pumped-Storage Hydropower Evaluation
PHS	Pumped Hydro storage
P2P	peer-to-peer
RE/RES/RESs	Renewable Energy/Renewable energy source/Renewable energy sources
REC	Renewable Energy Community
RED II	Renewable Energy Directive
REopt	Renewable Energy Integration and Optimization
RET	Renewable energy technology
SAM	System advisory model
SCADA	Supervisory Control and Data Acquisition
SMES	Superconducting magnetic energy storage
TIA	Telecommunications Industry Association
ToU	Time of Use
URBANopt	Urban Renewable Building and Neighborhood Optimization
VBAT	Virtual Battery Assessment Tool
WAN	Wide area network

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