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Review

Key Aspects and Challenges in the Implementation of Energy Communities

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Abstract: Energy communities (ECs) are an important tool towards a fair energy transition. Hence, the European Union (EU) has positioned ECs at the centre of its energy strategy and the foreseen transformation of its energy system. This paper aims to give an overview of key aspects and challenges for the implementation of the EC concept. Firstly, the regulatory framework is examined with a focus on the new definitions for ECs introduced by the EU, Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs). Secondly, examples of established ECs and their main objectives are mentioned. Additionally, based on the identified challenges and requirements of establishing ECs, the key technologies that are implemented or have the potential to be deployed in an EC are examined, as well as innovative cross-cutting services that are optimally suited to be integrated in an EC. Moreover, the data management challenges linked to some of these technologies are considered. Finally, an overview of actual or potential financing schemes to support the EC development is given. Overall, the analysis highlighted the regulatory, technical and financial aspects and challenges that ECs are facing and the need to address them so that the EC concept is effective and successful. The main challenges identified for each of these aspects are the regulatory compliance with the legal framework, the data management dimension when innovative technological concepts are adopted and the financing of new projects.

Keywords: energy communities; regulatory barriers; smart grids; technologies; data-driven services; data management; financial barriers

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1. Introduction

The 2022 energy crisis has shattered the myth of the assumed national energy independence of developed countries and highlighted the necessity for a diverse energy mix. Reacting to the crisis, the EU announced the REPowerEU package that sets its revised energy targets [1]. Governments, private companies and the energy sector as a whole are expected to intensify their efforts to cope with the new paradigm [2]. Now more than ever, radical ideas are needed to revolutionise the energy sector. Even though an EC is not a new concept, since there are as many as 3500 ECs across Europe, ECs are recognised by experts as one of these radical ideas [3,4]. More specifically, ECs are considered to be an effective system to fast-track the energy transition by increasing the involvement of citizens [5]. The

EU has recognised the potential of ECs and, via the Clean Energy Package (CEP), officially issued a new general legislative framework for ECs [6].

This paper aims to provide an overview of the main aspects and challenges for the development of ECs. Three dimensions of ECs were identified as key parts for their success: the regulatory, technical and financial aspects. For each of these aspects, the main challenges are analysed. Firstly, for the regulatory dimension of ECs, the new definitions of ECs, introduced by the CEP, are examined. Providing definitions inherent to ECs is intrinsically linked to the regulation and legal framework defined by each country. Thus, the general structure of the legislative frameworks will be presented according to their local particularities. Moreover, to comprehend these definitions, existing examples of ECs, along with their potential benefits, are analysed, not only from a general point of view, but also from a cross-cutting perspective. Secondly, the technical aspect is addressed with the examination of technologies that are implemented or have the potential to be implemented in an EC environment. However, technology integration is empowered through the use of energy services from both operational and financial perspectives. Therefore, such energy services will also be presented, along with their structure in the ecosystem of ECs and the data management challenges that arise by using them. Finally, recognising the importance of the financial sustainability of ECs, an economic analysis is presented that examines possible solutions to potential financial barriers.

EC is a broad topic, and many research reviews have been contacted in the past on different aspects. Ceglia et al. [7] focused on analysing social positive outcomes from ECs to motivate and boost the concept. In addition, Hewitt et al. [8] also explore the social dimension of community energy and identified four operation criteria to recognise social innovation in community energy projects. Moreover, other studies examined the key factors for the emergence of ECs [9], potential business models for ECs [10] and the new actors that can emerge in an EC environment and their interaction with existing ones [11,12]. A couple of studies performed a similar analysis as this paper [12,13]; however, in comparison to those studies, this paper examined the regulatory aspect distinguishing the differences between RECs and CECs. Further, the technological dimension of ECs was investigated in connection to data management challenges and smart grid technologies. Finally, beyond the identification of financial barriers, this paper also examines potential solutions to them.

2. Regulatory Framework for Energy Communities

The energy sector is undergoing a profound transformation at an exponential rate globally, moving from a “top-down vision of energy value chain with centralised production and rigid distribution framework, to a collaborative ecosystem of self-managed prosumers equipped with distributed energy resources and ability to act independently on liberalised energy markets” [14]. This paradigm shift has already had an impact on the value chain of the market, leading to (1) a constant increase in the number of renewable energy sources (RES) in the system; (2) upgraded electrical transmission networks that offer higher intra- and cross-border energy exchange and (3) prosumer-rich distribution networks with high decentralised energy production. ECs are one of the tools that can allow citizens to be an active part of this energy paradigm [3]. As a means to enable and boost the EC idea, the EU introduced two new definitions, which are presented in Table 1. First, Renewable Energy Communities (RECs) were introduced in the Renewable Energy Directive II (REDII) in 2018 [15], and then, Citizen Energy Communities (CECs) were defined in 2019 via the Electricity Market Directive (EMD) [16].

Table 1. RECs and CECs definitions.

Aspect	Renewable Energy Communities (RECs)	Citizen Energy Communities (CECs)
Form	"a legal entity" [RED II, Article 2, para 16]	"a legal entity" [EMD, Article 2, para 11]
Membership Eligibility	"in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity; the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities" [RED II, Article 2, para 16]	"that is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises" [EMD, Article 2, para 11]
Primary Purpose	"the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits" [RED II, Article 2, para 16]	"has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits" [EMD, Article 2, para 11]
Activities	The REDII also states that RECs shall be entitled to produce, consume, store and sell renewable energy, including through renewables power purchase agreements. [RED II, Article 22, para 2(a)]	"and may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders" [EMD, Article 2, para 11]

By analysing the two definitions, as well as the directives in which they were released, key differences can be observed between RECs and CECs. First, concerning the technologies that can be used, no limits are set for CECs, in contrast to RECs, where the REDII is stated that they can only use renewable energy technologies. Second, RECs have limitations regarding their membership eligibility because the members or shareholders have to be located in the proximity of the developed energy projects, in contrast to CECs, where no restrictions apply. Furthermore, an alteration can be observed regarding the ownership and government principles of the EC; concerning the RECs, small- and medium-sized enterprises (SMEs) can take control of a REC if their primary commercial activities are not related to the energy sector, but for CECs, this is restricted to small and micro enterprises. This, in turn, does not mean that there are no legal mechanisms that allow the active participation of large companies in the decision-making bodies of ECs, but that the regulatory basis for decision making must be controlled by social and citizen action in strict compliance with the law. Finally, both definitions mention the allowed activities of each type of EC, with the CECs to be limited only to the electricity sector, in comparison to RECs that can be active in all energy sectors.

With the two definitions, the EU has set the basic regulatory framework for ECs. However, as recognised by the Council of European Energy Regulators (CEER), a host of regulatory aspects are not addressed, and a lot of freedom is given to the member states (MS) to transpose the EU legislative framework into national law [17]. Therefore, key differences between MS are expected that will finetune the framework based on the particularities of each MS. However, there is the danger of misinterpretation of the concept, which can result in the abuse of the concept. In order to properly address this, it is very important to consider existing examples of ECs and implementations that can become the blueprint for new ECs and to adopt novel solutions that can mitigate any potential misuse of the EC idea.

The regulatory framework and the associated challenges of ECs have been a topic of many studies. Many researchers have proposed ways to enable the correct and fast adoption of ECs following the basic regulatory framework set by the EU. For example, Chantrel et al. [18] proposed a participative governance structure that uses blockchain technology, a fair, transparent and secure way to settle and record transactions between multiple parties without the involvement of a third party, which can facilitate the regulatory compliance of ECs. Moreover, Dorahaki et al. [19] introduced an integrated operating model that is based on the definitions of the CEP. In addition, a study provided a collection of business models that can be used in an EC and follow the basic rules of the regulatory framework for ECs [10]. Studies have also examined the regulatory challenges in different MS. Silvestre et al. [20] investigated the regulatory challenges that emerge on an international scale and analysed further the case of Italy. More recently, a similar analysis was conducted by Bashi et al. [11] that highlighted the need for regulatory reform in many MS.

2.1. Energy Communities Examples and Their Objectives

As mentioned before, there are many ECs around the EU [6,21,22]. New ECs need to have access to information about established ECs [23]. In this section, examples of the two types of ECs, RECs and CECs, and their objectives are described. It is important to stress that the majority of the cases presented are not officially regarded as RECs or CECs since most of them preceded the regulatory framework. However, the examples that best fitted the definitions were selected to best represent the concept of each definition.

Regarding the RECs, a notable case is the three-wind turbine project developed by a rural community in Denmark with the aim to finance the modernisation of their local harbour [24,25]. Moreover, a community in Germany established a bioenergy combined heat and power (CHP) plant in order to satisfy the heating demand and to tackle the problem of unreliable fuel deliveries in the area [26]. Additionally, a local cooperative in Edinburgh, Scotland, installed community-owed PV systems on public buildings, and all profits are divided between its members [27,28].

There are numerous examples of CECs, as well. A case worth mentioning is a housing association located in Estonia. An association was formed within the framework of an apartment complex, which managed the rehabilitation of the solvent installations, as well as the installation of a PV site on the complex, with the aim to improve the living environment of the residents by funding retrofitting projects and to produce their electricity [29]. The Svalin co-housing complex is another EC established in Denmark. The EC was formed to produce its electricity collectively and to utilise strategies such as P2P trading [30]. Lastly, in the Netherlands, an island called Amerland established a cooperative that plans and develops many different energy projects, such as a blue hydrogen production facility and a solar farm across the island. The island aims to become 100% energy self-sufficient [31,32].

ECs have been the subject of many European Projects in recent years [3]. In order to give an overview of the general requirements and challenges of real cases of ECs, the pilots of the EU project Next-Generation Integrated Energy Services fOr Citizen Energy CommuNities (NEON) project are presented. Within the NEON project framework, the authors of this paper analysed four CECs from the Mediterranean Area, namely, CEC 1—Berchidda (Italy), CEC 2—Domaine de la Source (France), CEC 3—Polígono industrial las cabezas (Spain) and CEC 4—Stains city (France). These communities are in different establishment and operational stages and are planning to adopt different tools and technologies for achieving their primary goals. Hence, the issues and challenges that they encounter are according to their particularities.

Some of the challenges and issues that communities are facing are presented in Table 2. Specifically, the engagement of existing or potential members of the community and the efforts to convince them to join the EC or to adjust their energy behaviour is considered to be a major issue. Connected to that is the need for effective business models and contracting schemes, and also ways to convince the members of the community that their energy security is ensured.

Table 2. Challenges and requirements for EC establishment and operation.

Challenges	Requirements
- User engagement and behaviour change	Collective self-consumption Joint purchase
- Need for effective business models and contracting schemes	Remuneration and smart contracts for energy saving and shared flexibility Energy Performance Contracting (EPC) and Pay for Performance (P4P) contracting
- Need for improved energy efficiency, energy conservation and reduced energy consumption	Maintenance and control of community assets Analysis of flexibility potential and balancing of exported energy Optimisation of the community energy profile Optimisation of energy production and demand response strategies Building management and consumption optimisation
- Environmental aspects and CO_2 reduction	Prepare decarbonisation scenarios for decreasing the final energy consumption and operation costs

Moreover, there is a need to improve the energy efficiency of the building stock of the community and address environmental aspects related to potential new projects or regulatory compliance. The actors identified in this analysis are also shown in Figure 1. As presented, the new actors, prosumers and aggregators play an important role in achieving the EC's objectives. The prosumer is an electricity consumer that uses electricity produced from his/her power plant [33]. Because of the need for more controllable generation and load on the demand side, demand-side flexibility is urgent and hence the requirements for optimisation of prosumers' energy profiles on a building and EC level. The role of the aggregator is to interface with the Transmission System Operator (TSO), Distribution System Operators (DSOs) and Balance Responsible Parties (BRPs) [34].

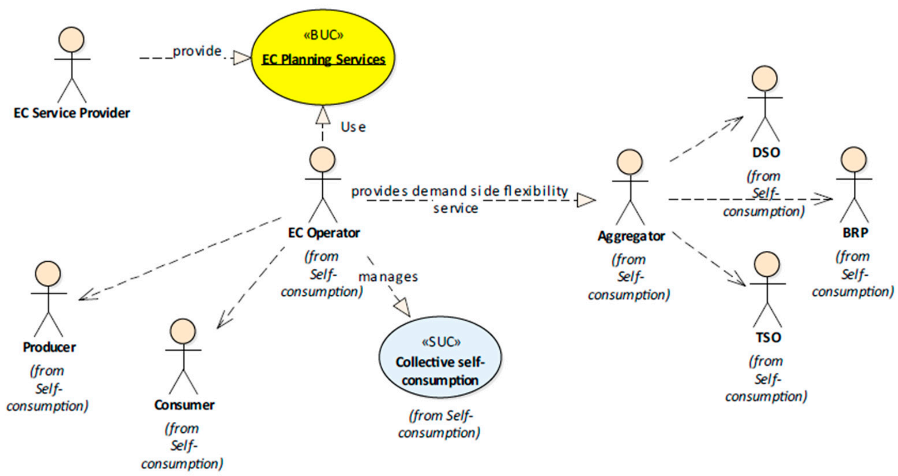

Figure 1. A high-level view of the interactions between the identified actors in an EC context.

All the examples presented have the EC as a common asset, which is governed according to the rules established based on its governance system. This system is a socio-economic management environment, democratically constituted and that must have a legal figure established and contemplated according to the legislation of each country. It can be associations, cooperatives, foundations and even trading companies that, regardless of their legal essence, must contemplate the three pillars of ECs: the social sphere, environmental benefit and economic justice.

2.2. Potential Benefits of Energy Communities

As set by the definitions, the primary goal of an EC is to provide benefits to its members. In this section, some important EC benefits are examined to understand not only the potential effect that ECs can have on the energy transition, but also on their members. Following the categorisation, set by the framework of RECs and CECs and as described in the preceding section, the benefits are organised into financial, environmental and social categories.

A significant social benefit is the participation of citizens in renewable energy projects, which will increase the support for green technologies [35]. With the participation of the public, a culture that is based on sustainability and clean energy will be cultivated and reflected in future government strategies that will enhance the efforts towards energy transition [6]. Furthermore, getting the public involved can affect their behaviour as consumers, making them more conscious of the impact of their decisions [36].

Financial benefits are strongly linked with social benefits because they can drive social innovation [37]. On a community level, economic benefits might be profits from energy production, energy savings and possible employment opportunities connected to local energy projects [38]. These benefits can have a greater effect on rural communities [38]. On a wider scope, ECs can support the decentralisation of the electricity grid with locally produced electricity that can reduce transmission losses and help avoid expensive upgrades connected with a centralised grid [36]. Furthermore, the development of advanced green technologies will boost the integration of RES into the energy mix and drive the cost of energy down [39].

Lastly, ECs can also generate environmental benefits, which are closely connected to the financial and social benefits, though they are difficult to quantify since they usually have an indirect connection. For instance, a conscious user will reduce the amount of energy they consume. As a result, the collective avoidance of carbon emissions will be a significant environmental benefit [40]. Moreover, beyond the financial benefits, a decentralised system will also result in the reduction of carbon emissions associated with electricity production [41].

3. Technological Aspects of Energy Communities

The selection of the right technologies is a fundamental part of the successful implementation of ECs. Being aware of the available technologies and their potential impact can unlock great possibilities for new and existing ECs. In this section, important technological aspects are analysed, along with key challenges that can surface.

3.1. Energy Communities and Smart Grids

Smarts grids (SGs) are intelligent electrical grids that deploy information and communication technologies (ICTs) and are able to adjust to unexpected fluctuations in load and production, while sustaining the equilibrium of demand and production and the quality of the electricity supply [42,43]. The upsurge of financial resources invested in digital technologies for electricity networks reflects the importance of SGs [44]. Usually, ECs are linked to initiatives that are based on communities, and their core objectives are associated with energy generation, efficiency and economic benefits for the community. Nevertheless, communities are gradually assuming control of their energy systems with the implementation of SG technologies [45]. To achieve the new objectives of an EC, specific technical and organisational developments are needed. Therefore, SGs are viewed as a key aspect of ECs.

3.2. Architectural Views

Having established the importance of SG technologies to EC, it is crucial to mention that the incorporation of such technologies makes the design process of an EC more complex, and the need for an architecture model is important. Taking also into consideration that an EC has to be integrated into a larger power system, generic architecture models are discussed, and their applicability to the ECs context is assessed. In this vision, one EC can expose their services to the global community via data space-compliant connectors [46,47].

3.2.1. SGAM Architecture

One of the most prevalent architectures for SGs and potentially very useful for ECs is the Smart Grid Architecture Model (SGAM). In 2012, the CEN-CENELEC-ETSI Smart Grid Coordination Group published the SGAM as a product of the standardisation of SG in order to fulfil the tasks laid down in the EU Mandate M/490 [48]. It especially considers interoperability and aggregate interoperability categories, resulting in five interoperability layers, as shown in Figure 2. The SGAM structure can be used to describe the entire operating environment of an EC, as it considers all the interoperability layers [49]. The most basic one, called the component layer, encompasses all the energy assets that can be integrated into an EC. Then, the communication layer manages the interaction between the assets of the component layer and the different services integrated into the EC ecosystem. These services, as well as the models and metadata necessary for their operation, are included in the information layer [50].

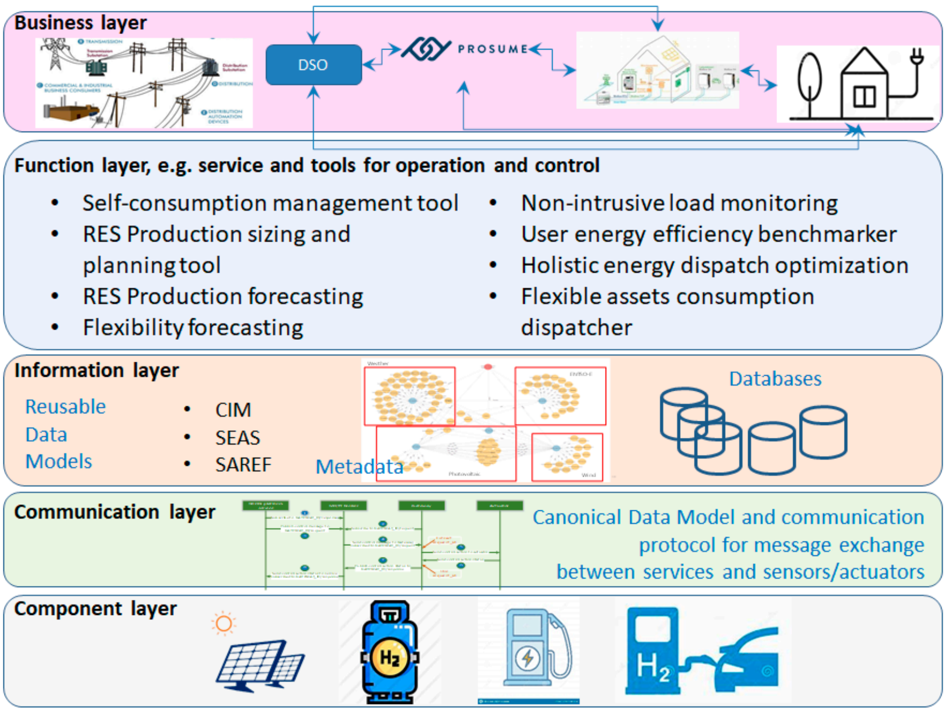

Figure 2. NEON SGAM-compliant architecture.

Next, the functional layer, based on the systems and subsystems defined in the previous layers, establishes the bases for the operation and control of the energy system of the EC. The functioning layer can be utilised and exploited through its integration into energy efficiency schemes and within the framework of the basic constituent pillars of the ECs. Such exploitation, together with blockchain transaction models and the participation in the national electricity market, comprise the last layer, the business model layer.

Before deployment of the operation and control platform in a real environment, to analyse the integration between the EC and the electricity grid, the Digital Twin (DT) concept is used. A DT platform is a virtual testing environment for a specific EC [47].

3.2.2. The 1 + 5 Architectural Views Model

The architectural views model 1 + 5, shown in Figure 3, has been proposed for designing integration solutions of collaborating software systems [8]. The model enforces a high-level breakdown of the software system into Integrated processes, Use cases or Scenarios, Logical, Contracts, Integrated services and Deployment. Applying the model to the EC context, the integrated processes view refers to the management of the EC, while the use cases view explains the system functions that are important to its users, e.g., Figure 1 points to the EC Planning Services as a Business Use Case (BUC) and Self-Consumption as a System Use Case (SUC). Based on the logical elaboration of the functions, the integrated services view is dedicated to modelling the data exchange flows between system components or parties in the EC ecosystem d [51]. The integration of the monitoring and control platform with devices (energy charging station, energy storage system and the PV plant) used in the EU project NEON is given as an example in Figure 4.

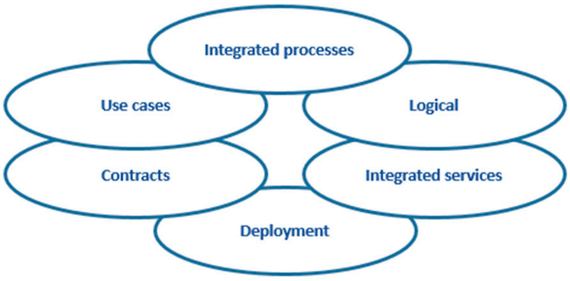

Figure 3. The 1 + 5 Architectural Views Model (from business processes to deployment).

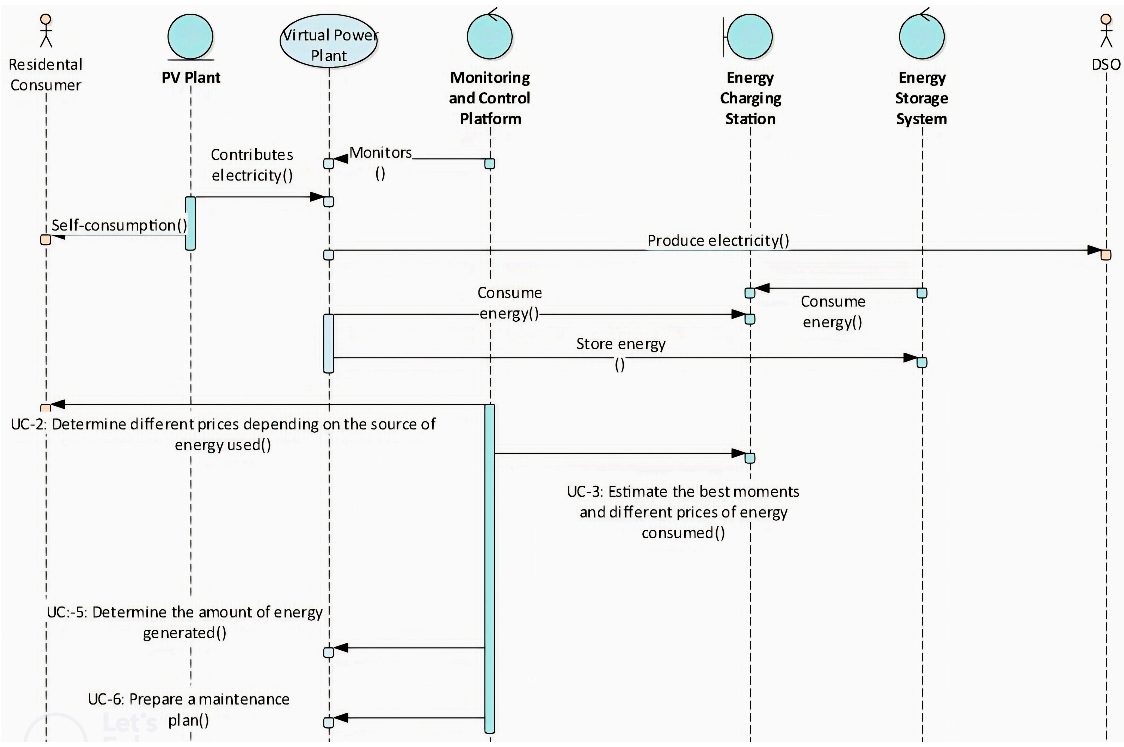

Figure 4. The 1 + 5 Architectural Views Model (integrated services view).

In order to understand the most relevant aspects of the SGAM structure and the 1 + 5 architectural view projected on the EC, the different assets and agents of this structure will be analysed. Figure 5 illustrates the structure of the different components that are examined in Sections 3.3 and 3.4.

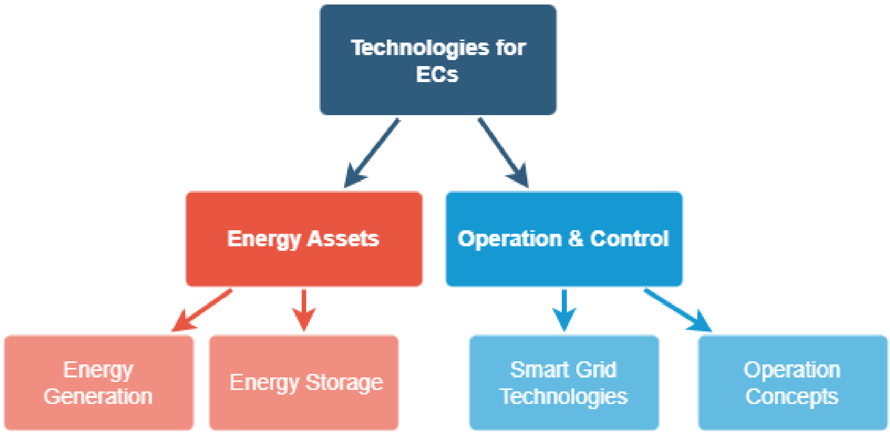

Figure 5. Structure of the different technological components analysed.

3.3. Energy Assets

3.3.1. Energy Generation

Energy generation assets that can be used in an EC can be divided into two general categories: thermal and electricity generation. Thermal generation can be very beneficial to an EC since it can ensure comfortable living conditions for the local community by providing heating, cooling and domestic hot water. An example of this was provided by Kumar et al., who proposed a poly-generation system that can provide cooling, power, heating and desalinated water for rural communities in India [52]. Common technologies for thermal generation are boilers [53], heat pumps [53], absorption chillers [54] and CHP plants [55,56]. In addition, electricity generation is a fundamental element of the EC concept, since it allows the ECs to be self-sufficient by utilising RES and to create economic opportunities for its members. A variety of RES have the potential to be used in ECs. The most common and cost-effective are PV systems [57]. PV systems are easy to install, and they can realise almost any power requirements since they come in many different capacities, making them ideal for an EC [54,57,58]. In addition, small wind farms can also be used, but due to the high space requirements, they are not common for ECs [54,59,60]. However, this is expected to change because the capacities of wind turbines are increasing, and as a result, fewer of them will be needed [56]. Finally, a technology that has great potential and currently has a lot of momentum for decentralised electricity generation is fuel cells [61]. Fuel cells can exploit hydrogen to produce electricity through an electrochemical process, with water as the only byproduct [62,63]. Currently, there are limited applications of fuel cells due to their low efficiency and high cost [64]. Moreover, the profitability of a hydrogen project can become a challenge for an EC. Raimondi and Spazzafumo [65] explore the implementation of a power-to-power hydrogen system for RECs in Italy. The study found that despite the current financial support for RECs in Italy, the system is not financially sustainable.

Energy generation is a fundamental aspect of ECs, and it has been the subject of many scientific articles. The selection of energy generation assets and the optimal sizing of them has been identified as a major activity for an EC. To address this, Karunathilake et al. [66] proposed a multi-criteria selection method that, based on the life cycle of each generation technology, can help ECs decide which RES best fits their requirements. Similar studies utilised multi-objective optimisation to determine the optimal energy mix for net-zero ECs [67] and the optimal sizing of RES for ECs [68,69]. Finally, the variety of energy generation technologies that can be implemented can give a multi-carrier dimension to ECs, and the synergies between the different carriers can maximise their impact. Jin et al. [70] proposed an energy planning methodology for a university campus that considers multiple technologies for different energy carriers. Moreover, Pastore et al. [56] investigate the coupling strategies for Power-to-Heat and Power-to-Gas for RECs to increase the self-consumption of the communities. Both studies highlight the importance of investigating the synergies between energy carriers in ECs.

3.3.2. Energy Storage

Energy storage technology is a fundamental pillar of the future energy structure, as it can be part of the solution to the stochastic nature of RES and the fluctuations in energy output [71]. Inevitably, energy storage technologies are also very important for ECs since they face the same problems, but on a smaller scale. Different types of energy storage that are easy to implement are electrochemical batteries [72], supercapacitors [73] and electric thermal storage [74]. A more complex energy storage system is the compressed air energy storage (CAES) [75] and the pumped-hydro power plant (PHPP) [76]. These storage systems are considered reliable, since they have no power output variations, but have a high initial cost [76]. Lastly, similar to the use of fuel cells for the production of electricity with hydrogen, a power-to-X storage strategy is to use excess electricity to produce hydrogen and store it. The fact that hydrogen has a minimum environmental impact when produced from RES has given hydrogen political and business momentum [61]. The process used for producing hydrogen from water and electricity is called electrolysis and is performed with an electrolyser [63,77]. There are three types of electrolysers: Alkaline Electrolyser [78], Proton exchange membranes (PEM) electrolyser [61] and Anion exchange membrane (AEM) electrolyser [79]. PEM electrolysers are considered the optimal option when the electricity comes from RES since they operate better in partial load conditions [77,80]. For storage, hydrogen can take liquid or gas form and be stored in geological storage or storage tanks [61].

The importance of energy storage for ECs is highlighted by the fact that it has been a topic of research for many years. In fact, ECs can be considered case studies of energy storage technologies before applying them on a wider scale. A study by Jin et al. [81] analysed the operation of two different storage technologies, a battery and hydrogen energy storage, coupled with small hydropower plants for an off-grid EC in Italy to determine the most suitable solution. In addition, similarly to energy generation, the sizing and selection of different energy storage technologies for ECs are identified as important, with many recent papers on the topics [71,82–85]. Moreover, recent studies are also focused on the operation, control and management of ECs that own energy storage systems [86–90]. A notable example is the study by Gu et al. [88] that developed a two-stage, stochastic energy-sharing methodology in communities with prosumers and community-owed energy storage. Finally, in an EC environment, storage systems can increase the self-sufficiency of a community, but on a wider scale, enhance the flexibility and operation of the local grid [91–93].

3.4. Operation and Control

3.4.1. Smart Grid Technologies

- Advanced Metering Infrastructure

All the technologies used in an electrical grid to facilitate bidirectional communication between the components of the network are collectively referred to as an advanced metering infrastructure (AMI) [94]. Smart meters are the core components of an AMI, and they can provide information about real-time consumption and RES production [95]. By collecting these data, the capability of real-time system operation and management control is made possible. An example of this control is the implementation of demand response (DR) strategies [96]. For ECs, the development of such infrastructure can enable the use of technologies and concepts that can help them maximise their potential. However, even though an AMI can generate opportunities and increase the capabilities of electrical networks and ECs, the main challenges rely on sustaining the security of the network from physical and cyber-attacks [96,97].

- Demand-Side Management

As previously mentioned, the collection of data through the AMI enables the implementation of Demand-Side Management (DSM) strategies. DSM is an essential constituent of a SG, and it can be a great asset for an EC that allows its members to monitor and manage their load consumption patterns [98]. Through the application of DSM techniques, it is possible to regulate the required demand to match it with the available energy production [99]. DSM is based on two main strategies [100]: Energy Efficiency Services (EES) and Demand Response (DR) programs.

EES can be defined as services that aim to improve the energy efficiency of the users by implementing technological measures designed to conserve or increase the efficient use of primary energy [101]. However, for ECs, the implementation of such measures can become challenging due to the lack of technical know-how. Therefore, EES are typically conducted by energy service companies (ESCOs) that an EC can employ, which use various tools and techniques, such as benchmarking, energy modelling and data analysis, to identify areas of energy waste and develop customised solutions [102]. EES can be a tool to improve the energy efficiency of a community [103]. Several studies have assessed the impact of EES on energy consumption, cost savings and environmental sustainability. For instance, a study evaluated the impact of energy efficiency measures on energy consumption in the UK commercial sector [104]. The study found that EES can reduce energy consumption by up to 30% and lead to significant cost savings. Alshehri et al. [105] assessed the impact of EE measures on energy consumption and CO_2 emissions in the Saudi Arabian residential sector. The study found that EES can reduce energy consumption by up to 40% and CO_2 emissions by up to 50%.

EES encompass a range of technologies and services, such as building automation systems (BAS), LED lighting, HVAC systems, renewable energy and energy management software. For example, BAS can optimise energy use by controlling and monitoring a building's HVAC systems, lighting and other building systems. Jin et al. [106] assessed the impact of BAS on energy consumption in a commercial building and found that BAS can reduce energy consumption by up to 24%. LED lighting is another key technology for reducing energy consumption in commercial and residential buildings since it can lead to significant cost savings of up to 60% [107]. Moreover, the use of data analytics has become increasingly important in EES, as it can help identify energy waste and optimise energy efficiency measures. For example, a study by Zhou [108] used data analytics to identify energy efficiency measures for a university campus, leading to a 16.3% reduction in energy consumption. Moreover, Ceglia et al. [103] state the relationship between the energy efficiency of buildings and ECs in which technologies, based on the improvement and optimisation of energy efficiency, can be adapted and thus unify the state of the art in energy efficiency with specific models adapted to ECs.

DR is the other strategy that can be used for DSM, and it refers to the deviations in load consumption by end-users from their standard usage patterns, based on the maximum utilisation of local RES or in response to incentive payments [109]. DR schemes can be classified according to their control scheme into two categories: centralised control scheme and distributed control scheme [110]. In a centralised control scheme, a utility company is the main load-monitoring entity and central authority. The users communicate their available flexibility to the aggregator, and the central authority manages the power dispatch schedule. In distributed control concepts, the consumers schedule their consumption after receiving requests from the aggregator, and they can adapt their consumption after coordinating between them. In this case, the control strategy is more complex, but there is no limitation for privacy violation [111,112].

The use of Internet of Things (IoT) tools and Machine Learning algorithms allows the development of DR programs based on new EES, such as Non-Intrusive Load Monitoring (NILM), which is a promising approach to monitor energy consumption with a minimum invasion of privacy and to disaggregate the electrical load of individual appliances from the load of the entire house [113]. Therefore, NILM techniques can be applied to residential buildings within an EC to make predictions of daily load profiles and to optimise energy consumption by detecting the load profile of the main home appliances and suggesting their optimal usage during the day or for the day ahead [114]. Moreover, these techniques can be used to evaluate the energy consumption and behaviour of the members of the EC, to fairly share the community's revenues among the participants [115].

3.4.2. Operation Concepts

In this section three operation concepts that have the potential to be used in an EC and become part of their business model are described. These concepts can help determine how the community manages, distributes and utilises its energy assets.

- Peer-2-Peer

The volume of data used from a variety of components and actors in an advanced energy network created the need for a dynamic, efficient and flexible communication system [80]. A promising concept, due to the decentralised way it works and the ability to retrieve and store data, is the Peer-2-Peer (P2P) scheme [116]. The operation of P2P systems is based on three core properties: bidirectional sharing of physical and logical resources, self-organisation and decentralised operation [117]. Based on the arrangement of its peers, P2P networks can be categorised into structured P2P [116], unstructured P2P [118] and hybrid [119]. In the environment of an EC, P2P trading can be used as an innovative energy managing strategy that, without the overview of a central entity, enables the participants to trade electricity [120]. Moreover, a P2P network can maintain its continuous operation even if a peer is added or removed [121]. This makes it ideal for ECs since it is in line with the regulations that state that a member of an EC is free to leave the community at any time [16]. There are two main parts of a P2P application to an EC, namely, the physical and virtual parts. Each part is composed of different elements necessary for the operation of the P2P system [121].

A vital element of the virtual part is the pricing mechanism used to regulate the trading price of electricity [121,122]. A transparent pricing strategy is crucial in order to establish a trustworthy trading strategy. In addition, the information system is another essential part responsible for ensuring the equal participation of all members of the community in the trading following the restrictions defined by the operation strategy of the market [122]. Blockchain is an information system compatible with the decentralised nature of P2P trading and is considered a vital option for an EC application [123]. Moreover, the information system also supports the market operation of P2P trading in defining the payment rules and bidding format [122]. Lastly, each P2P network has an energy management system (EMS) that can access information about the demand and excess electricity and can secure P2P trading transactions among peers [124]. Usually, P2P trading is performed on a DSO-owned grid to avoid any unnecessary grid extensions [17]. Hence, the AMI and the part of the electrical grid that is being used to connect all peers are elements of the physical part of a P2P network [122].

In a P2P energy application, a smart contract is used to specify the set of rules for the exchange of energy or flexibility and the price setting for the trading. Smart contracts operate as autonomous and self-deployed programs that can monitor and modify the record of trades according to the set rules. Usually, they are stored inside a blockchain [125]. Blockchain is a decentralised technology that provides a secure and immutable ledger, a data book of transactions and processes that is used to keep track of records of digital transactions. The blockchain is used to implement the P2P network protocol; this implies that all nodes/members of the EC have an updated copy of the blockchain at any time. For new information and transactions to be added to the chain, every node of the network has to verify the validity of the transaction [126]. For an EC application, the blockchain is a valuable option for ensuring trust between the members [127,128]. Blockchain also represents a smart solution for an EC to improve the energy performance of its buildings.

This can be achieved by transmitting behavioural data among community users, in an encrypted manner, encouraging users to change or improve their behaviour [129].

While P2P trading is very promising, its application to electricity grids and ECs can be a challenge due to technical restrictions of the grid [130]. For an EC, these constraints can potentially limit the ability of a peer to trade, and as a result, the principle of fairness is questioned. Further, for ECs in particular, a potential expansion of the community can make the extension of P2P trading to new members very challenging [17,121]. This can affect the open participation of the community. On a wider scope, it is also debatable if the efforts to increase the integration of P2P trading for ECs are negatively affecting the grid due to the many new requirements and regulatory restrictions connected to them [17]. To ensure that this is not happening, innovative ideas need to be applied when P2P systems are implemented in ECs. A solution that is being proposed by many researchers is that the pricing mechanism used within the EC trading considers the stability and the state of the grid [131–133].

- Electric Vehicles Management Systems

Electric Vehicles (EVs) are an important part of the evolution of the transportation sector [134]. Therefore, EVs need to be considered when designing an EC [135]. A study from Piazza et al. that examined the impact of EVs on collective self-consumption initiatives, such as ECs, suggested that EVs can increase the installed capacity of RES in such initiatives by 15% to 25% [136]. Thus, the utilisation of EV management systems is very important to create opportunities for an EC. There are currently two main concepts: Vehicle-2-Grid (V2G) and Vehicle-2-Home (V2H). Regarding the V2G scheme, the battery of the EV is exploited by the EC operator to obtain ancillary services [137]. For a V2H arrangement, the battery of the vehicle is utilised on a building level as electricity storage for the electricity produced from RES, usually from a PV system, to store excess power and increase the self-sufficiency of the building [138]. However, it is important to mention that according to recent research results, V2G and V2H can affect the vehicle's battery lifetime and reduce its capacity by up to 9% [139]. Consequently, EV owners' participation in this kind of scheme is not easy. Yet, it can be the solution when grid outage events occur within a community [140].

- Virtual Power Plants

Virtual Power Plants (VPPs) can be described as a cluster of dispersed electricity generation sources, flexible loads and electricity storage systems that can be coordinated collectively and aggregated, with the aim to have a greater technical or commercial effect [141]. VPPs are considered the coupling of community energy and SGs that can facilitate the participation of ECs in the distribution and trading of energy [45]. Based on the business activities they participate in, VPPs are divided into commercial VPPs (CVPPs) and technical VPPs (TVPPs) [141]. When VPPs offer ancillary services to DSOs and TSOs, they are considered TVPPs, and when a VPP sells flexibility to the electricity market, it belongs to the CVPPs [141,142]. The VPP is a concept that ECs can use to increase their financial benefits and also to increase the flexibility of the grid [45,143]. Yet, in an EC, the majority of the electricity production is from RES, making a potential VPP unpredictable and a threat to the resilience of the grid [144]. Additionally, VPPs consist of many components, and their management is already considered a challenge. In an EC context, where the different components are likely to increase with the expansion of the community, it becomes even more challenging [145].

4. Data Management Challenges in Energy Communities

It is widely recognised that the energy transition goes hand in hand with digitalisation [146]. However, the digitalisation of energy networks entails large exchanges of data that need to be efficiently and securely managed. While trying to scale up the EC concept, the availability and accessibility of data will inevitably become very important, and there is a need for effective data management [66,147,148]. Firstly, to understand the challenges of data management for ECs, the Communication and Information layer of the SGAM architecture will be discussed.

4.1. Data Management in General Context

4.1.1. SGAM Communication Layer

The communication layer enables the communication between the different layers and components of the system, such as smart meters, distribution automation systems, demand response systems and energy management systems, ensuring that all the data are exchanged reliably and securely. Moreover, the communication layer comprises communication interfaces, communication protocols and infrastructure.

- Communication interfaces enable a standard way for different devices and systems to communicate, and they can include physical, transport and application layer interfaces, such as Ethernet, Transmission Control Protocol/Internet Protocol (TCP/IP) and HyperText Transfer Protocol (HTTP).
- Communication protocols define standards and rules for data exchange between the devices and systems, intending to ensure interoperability and compatibility between them.
- Communication infrastructure includes the hardware and software modules that enable efficient communication. The communication should be performed securely and privately, which requires the implementation of different security measures, such as authentication, authorisation and encryption, to prevent unauthorised access and ensure the integrity and confidentiality of the data and information.

4.1.2. SGAM Information Layer

The information layer describes the exchanged information between the different components of the system. Such an information model is an integration of a model of each component with the data and documents related to it [149]. To fully achieve the benefits of SG, software applications and components need to interpret business semantics in a common way. Therefore, to guarantee interoperability in the next generation of energy services, semantic-based integration and semantic representation of data sources/processes have been introduced. For example, the CIM (CIM | DMTF, Available online: https://www.dmtf.org/standards/cim/cim_schema_v2530 (accessed on 2 May 2022)), see CIM V2.53.0 Schema (MOF, PDF and UML) is an open standard that introduces a common set of objects and relationships between concepts and is widely used in the energy sector. Although CIM provides an extensive set of Unified Modelling Language (UML) class diagrams for building the semantic layer in energy management solutions, additional models are also needed, including [150] Smart Appliances REFerence ontology (SAREF) and the extension of SAREF to fully support demand response use cases in the energy domain (SAREF4EE); The International Data Space (IDS) Information Model; Smart Energy Aware Systems (SEAS).

4.2. Data Management in EC Context

4.2.1. Operation Aligned with GDPR Principles

The challenges of data management in ECs rely on the variety of actors involved and the requirement to be in line with national privacy laws and the General Data Protection Regulation (GDPR). While the implementation of data integration and data exchange solutions is still a challenge for EC operation and control, the EC participants shall establish principles (define consent) on how their data will be processed by EC services [151]. As compliance with the obligations of the GDPR is mandatory, the following GDPR principles must be properly addressed by operation systems for ECs: the data minimisation principle, which states that data acquisition must be limited to the extent necessary for the purposes; the storage limitation principle, which entails that data must be stored only for as long as necessary; and the integrity and confidentiality principle, which demands the application of appropriate security measures.

4.2.2. Edge-Based vs. Cloud-Based Analytics

With the increasing integration of RES, EVs and flexible loads to the electric grid, the demand for reliable and efficient data edge-based processing and analysis at the edge of the grid is more important than ever. By processing data at the edge, EC operators can make faster and more informed decisions about grid operations, leading to greater efficiency, reliability and resilience. Hence, the EC operation and control requires additional hardware (e.g., Phasor Measurement Units) and software functionalities (e.g., for grid and power injection observability monitoring). Data at the edge not only contains information about the grid, but is also heavily influenced by nearby connected assets. This opens the opportunity to develop specialised tools that can give advantages at the local level, at the community level (where a cloud-based or central computer is used for optimisation and flexibility dispatch) or at the DSO level. By integrating data with lower resolution on a central computer, better observability of the electric power system is achieved. Services such as production and demand forecasting, flexibility forecasting, energy dispatch optimisation and predictive maintenance are running on a cloud computer.

5. Financial Aspects of Energy Communities

Despite the non-profit nature of ECs, the financial aspect is crucial for the sustainability and, therefore, the existence of ECs. The economic benefits to the members of an EC can be divided into three main categories, based on where they derive from self-consumption benefits, excess energy benefits and benefits from incentives. The first two benefits are typically in favour of the members of the EC that are prosumers, i.e., those users who generate energy from RES, while the benefits deriving from the incentives are typically in favour of all the participants in the EC and can be divided according to different schemes [47,152]. To determine the allocation of the economic benefits, a business model needs to be decided. The business model of an EC can be managed by the members or by a third party, e.g., an ESCO. The involvement of an ESCO minimises financial barriers by allowing individual users to partially own the renewable generation system and avoid large upfront capital investments [102]. Therefore, to promote and encourage private capital investment in energy efficiency (EE) measures for ECs, the application of EE contracts and the use of innovative financing mechanisms, such as Energy Performance Contracting (EPC) and Pay for Performance (P4P), are suggested [153].

There is a diverse spectrum of programs that fall into the P4P category, but essentially, these programs track and reward energy savings and emission reductions, or demand response actions as they occur. More specifically, these mechanisms remunerate end-users, aggregators and ECs for providing or achieving better energy performances, based on metered and verified data, against a baseline scenario and focus not only on the implementation of new equipment or systems, but also on their performance [154]. Regarding EPC, the European Directive 2012/27/EU defines it as a "contractual arrangement between the beneficiary and the provider of an energy efficiency improvement measure, verified and monitored during the whole term of the contract, where investments (work, supply or service) in that measure are paid for in relation to a contractually agreed level of energy efficiency improvement or other agreed energy performance criterion, such as financial savings" [155].

P4P and EPC programs can aid in assessing savings and motivating persistence in savings from complex, multi-measure efficiency projects, including those with behavioural or operational changes, such as an EC, where it is difficult to deem savings in advance [156]. The EPC and P4P market is still under development, and therefore, there is not a strict and predefined structure of contracts, but there are different contractual models that can suit the individual client. These models differ from each other in how roles are assigned, risks are shared and cost savings are allocated among the participants [157].

Possible Solutions to Overcome Economic and Financial Barriers

Along with novel contractual and financing schemes, structuring an EC requires tailored investments to overcome several economic and financial barriers [158]. The sustainable finance community is increasingly interested in innovative investment opportunities, such as ECs, capable of offering positive environmental and social outcomes, ensuring profitability. Nonetheless, energy-related investments are often characterised by relevant barriers. First of all, since a project within an EC is usually small and not sufficiently aggregated, this can result in high transaction costs. This can impact investors negatively; for example, investments related to EEM, such as retrofits of buildings, usually have relatively long payback periods, and investors are wary that the savings achieved will not justify the cost of the intervention [159]. The same goes for investments in ECs ancillary services, e.g., congestion control or peak shaving through DR. A further barrier to financing these projects is a certain degree of difficulty in assessing the investment risk that private investors may face. However, there is increasing data that suggest that the risks linked with EE projects are lower than what markets assumed; investors have to be reassured that EE projects are mostly safe business cases [160]. There is also an acute need for standardisation at all technical and regulatory steps of the investment process to increase the confidence of financial institutions. Currently, the lack of standardisation of projects blocks the securitisation of EE assets, and as a result, financial institutions are not able to refinance their debt [161].

From a consumer point of view, the cost of these investments is likely to be recouped solely through energy savings, but as it is becoming increasingly apparent, there is growing evidence of the key role of non-energy benefits in investment decisions, as well. Especially in the case of an EC, these include the rise of the building's value and lower tenant turnover or vacancy rates, as well as better comfort and indoor health parameters [162]. A crucial risk-mitigating factor and driver for funding is represented by the increase in collateral value, implying an enhanced loan-to-value (LTV) ratio. This results in a lower probability of default (PD) in mortgages, estimated at around -20%, since a higher equity stake in the loan minimises the incentive to default [160]. At the same time, a lower LTV ratio implies a loss reduction given default (LGD), due to the increase in the collateral value that the bank can use if the borrower defaults [163]. Thus, there are tangible financial incentives to convince financial institutions to finance energy projects more in ECs.

The implementation of energy-related projects, such as an EC, can be supported both through private and public funds. Private funds include financial instruments from commercial banks, investment funds and crowdfunding platforms (equity capital and investment funds, leasing, loans, Energy Efficient Mortgages (EEMs), green bond and sustainability-linked bonds and microfinance instruments). Public sources include European institution funds, national and regional funds, and National and International Development Banks (e.g., European Energy Efficiency Fund (EEEF), Private Finance for Energy Efficiency (PF4EE) and Green Economy Financing Facility (GEFF)). Both types of funding bodies are interested, for different reasons, in supporting the energy transition process, with the aim on the public side to reach carbon neutrality objectives set at the EU level for 2050, and on the private side, to meet mandatory and voluntary targets for sustainable investments and minimum financial performances to generate revenues for investors.

To fully understand the possible solutions to overcome economic and financial barriers for an EC, it is important that a qualitative analysis is performed on an energy service level. Table 3 includes an analysis that was conducted within the NEON project for different energy services to be implemented by the NEON pilots [163,164]. The analysis involved the identification of financial channels to fund each service, drivers that can act as reasons for choosing to deploy the service and barriers that can affect the decision of adopting the service. All the findings were then used to determine the payback period of the service. The results showed that the optimisation and control of the heating, ventilation and air conditioning (HVAC) system, along with the EV charging from RES, are the most cost-effective, with a short-to-medium payback period. Next, the collective self-consumption service followed, with a payback period from a medium–long-term period, and finally, the analysis concluded that the service that involved the use of hydrogen to cover the electricity demand when there is no production from PVs has a medium-to-long-term payback period. Performing this type of analysis can help inform the members or potential members of the community about the economic environment around ECs and the potential performance of their investment.

Table 3. Analysis and estimation of the payback period, financial instruments and barriers to financing different services in an EC environment.

Energy Service	Payback Period	Financial Channels	Drivers	Barriers
Collective self- consumption	Mid–long-term	Credit institutions, retail energy companies, financial investors of the energy sector, grants and subsidies, and own financing (private capital)	- Facilities' prices reduction - Network connection rates reduction - Public grants and incentives - Electricity price rise - Reduction of maintenance costs	- High capital costs - Price of PV modules - Cost of batteries - Financing difficulties - Investment rate of return - Initial investment - Low cost effectiveness - Uncertain returns in the short term
Electricity compensation with hydrogen storage during the off-PV production period	Long-term	Banking disintermediation through the financing of the retail energy company, cost savings in equipment, in addition to financing provided by public subsidies	- Flexible contracts for consumers - Reduction of pollutants in the environment (clean energy and long lifetime) - Revenue generation - Utility-scale storage	- Legislative and administrative barriers at the national level - High price - Techno-environmental barriers (such as natural topography, land use, vegetation clearing) - Cost overruns - Resettlement issues
HVAC system optimisation and control	Short–mid-term	Banking loans, crowdfunding, owner financing, EPC	- Innovation, R&D - High impact on final energy consumption - Supporting automatic DR mechanisms - Public incentives	- Digital divide - Contractors' trustworthiness and expertise - Market reliant on public subsidies - HVAC possible lack of experience/interest in EE - Awareness and education of building owners
EV charging from RES	Short–mid-term	Public subsidies or private energy companies	- Profit of public charging infrastructures - Charging demand - Charging price - Electricity price in comparison to fuel price	- Installation costs can reduce profitability - Unit subsidy for construction and operation - Ground rental cost - Maintenance cost - Number of charging units to provide

6. Conclusions

The EC idea has the potential to be a driving force for energy transition and the efforts to reduce carbon emissions. However, for the concept to be successful, key aspects and challenges need to be considered.

From a legal perspective, the regulatory framework issued by the EU will help avoid any exploitation of the concept and also to expand the development of ECs in EU countries where the EC concept has no presence, though the EC concept is not new and the regulatory compliance of existing developments can be challenging. Already established ECs will need to act between the new regulations to be legally considered a REC or a CEC to continue their operations and to utilise the new possibilities that the new framework offers. Moreover, the EU framework gives a lot of freedom to the MS on how to translate the framework into national law. That can be a threat to the EC concept and its primary goals.

From a technical perspective, EC can give a lot of solutions to the challenges that the energy sector is facing. The need to increase the integration of RES creates challenges to the traditional way the electricity network operates. In order to safeguard the resilience of the network, there is the need to increase the monitoring and control level of the electricity system. Hence, ECs with the use of SG technologies can enhance the flexibility of the network, help avoid costly upgrades and, by becoming technology test beds, boost the application of SG on bigger energy networks. Nevertheless, the use of SG technologies can also be challenging since data privacy and data management will become core activities that the EC will need to consider. Therefore, a structured approach to develop the environment of these technologies is needed, such as the SGAM and the 1 + 5 Architectural Views Model.

From a financial perspective, over the past years, the commitment of governments, companies and financial institutions to sustainability raised the attention of the financial communities to sustainable energy-related projects, such as ECs. This comes with opportunities to exploit and barriers to overcome. Reducing high transaction costs, mainstreaming risk assessment and, therefore, minimising business risks, supporting technical and legal standardisation, and becoming aware of non-energy benefits are just some of the key drivers to maximise the involvement of public and private investors in funding ECs initiatives. Several financial instruments are available, each of them capable of overcoming specific barriers related to the type of investment.

ECs have a pivotal position in the new policies of the EU. It is now evident that there is a shift from policymakers towards social innovation and citizen participation, aiming for a faster, sustainable and fairer energy transition. However, the right legal, technical and financial environment must be formed for the EC concept to achieve the expected goals.

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