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# The State of the Art of Smart Energy Communities: A Systematic Review of Strengths and Limits

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**Abstract:** The Smart Energy Community topic has attracted a lot of interest from policy, research centres, companies and private citizens since 2018, when in Europe the recast of the Renewable Energy Directive, and later in 2019 the Internal Electricity Market Directive, came into force to support the new role of users in energy systems. Following these directives, energy community experimentations, real projects and/or simulations and case studies have been developed and investigated in the literature. In this review paper, an investigation of recent literature about Smart Energy Communities in terms of common characteristics, fundamental scopes, and principal indexes used for their evaluation, has been realized by considering 111 scientific references, 78 of which have been published since 2018. The reference papers have been selected through the "Preferred Reporting Items for Systematic reviews and Meta-Analysis" methodology. In developing the review, significant barriers to Smart Energy Communities' diffusion emerged. The main shortcomings concern citizens' uncertainty about these new projects, due to their poor information and technical skills. These issues often hide energy, economic, environmental, and social benefits of Smart Energy Communities. Therefore, this study wants to be an opportunity for bringing to the attention of citizens Smart Energy Communities' positive outcomes, especially from the social point of view, thus boosting their spreading and overcoming still existing criticalities.

**Keywords:** smart energy communities; REDII; renewable energy community; prosumer; smart energy system

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## 1. Introduction

As part of the Clean Energy for all Europeans Package [1], the recast of the Renewable Energy Directive (REDII) came into force in December 2018 [2], followed by the Internal Electricity Market Directive (IEMD), which was launched in June 2019 [3]. Both directives formulate a strategy for the promotion of energy sharing within distributed energy systems (DESs), the massive spread of renewable energy sources (RESs) and the definition of citizens' new, priority and essential role in the energy transition. These objectives are covered by the concept of the Smart Energy Community (SEC). Such an organization is defined by the REDII as "*a legal entity which, 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, micro, small or medium-sized enterprises or local authorities, including municipalities;*
- *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*" [2].

The sharing approach and the co-ownership of RESs-based plants, which are inherent to SECs, directly involved the prosumer into the energy transition [4]. In fact, the prosumer acts not only as an active-consumer but also as a manager of a SEC, thus being able to influence its effectiveness towards the "ecological-transition" [5]. According to the definition given by the REDII, the energy utilities of a specific area which can be aggregated to define a SEC can be private, public, or even mixed. The multi-users must have in common the purpose to adopt distributed energy conversion systems and to promote the use of RESs [6]. Therefore, SECs are recognized as having a fundamental role in the transition towards a low-carbon society and in the accomplishment of the European (EU) target of about an 80–95% reduction in green-house gases (GHG) emissions by 2050 with respect to 1990 levels [7]. In this context, the buildings sector, which includes the residential and services sectors [8], represents the highest energy consumption sector [9]. This is the reason why, when defining the strategies for the accomplishment of the aforementioned goal, particular attention has been paid to its contribution, which is expected to increase. In 2019, 40% of the global energy consumption pertained to the civil sector, which was responsible for 36% of total GHG emissions [10]. Indeed, the electricity demand of buildings increased at a five-times faster pace than the mitigation of GHG emissions in the power sector [11]. Fortunately, the civil context offers many ways for saving energy. According to the suggestions provided by the International Energy Agency (IEA), in 2040, the average building energy efficiency per floor area, by also considering buildings' envelope and energy conversion devices efficiency, would rise by 39%. In turn, this improvement will result in an energy consumption decrease of up to 1.3% in comparison with current levels [12]. These improvements would mitigate the urban heat island effect caused by metropolitan cities' high housing density. As a result, they may significantly affect the sustainability of the energy system [13].

With respect to the increase in the exploitation of RESs and the mitigation of global warming, significative actions had already been involved in the political agenda of developed countries in less recent years. The Energy Performance of Buildings Directive (2010/31/EU) established the Zero Energy Building goal [14], the 2009/28/EC Directive supported renewable energy generation [15], the Energy Labelling Directive introduced energy labelling into industrial and commercial sectors [16], the Eco-design Directive enhanced the purpose of defining efficiency benchmarks for energy fed devices [17], the European Energy Efficiency Directive set a group of binding measure for supporting European 20% energy efficiency target to be met by 2020 [18]. These measures were fit into the political framework built to counteract the increase in the globally averaged land surface air temperature [19] and to keep it below 2 °C, as stated in the "Paris climate agreement" of 2015 [20,21]. Yet, these actions did not return the expected results with regard to the social acceptability of RES-based plants, especially among the civil sector's users. The SEC configuration is instead recognized as a perfect way to match both consumers' activity and sustainability, by acting also on collective awareness and primality of virtuous citizen [13]. In the past, the increasing number of large-scale RES-based projects intervening the area of life of communities raised public concerns related to their environmental and social impact. Integration of public concerns into such projects should therefore go beyond communication measures through the direct involvement of citizens aiming at stimulating new projects' acceptability. Despite being currently a very topical issue, energy communities based on the exploitation of RESs have a long history. In fact, following EU rural electrification cooperatives already existing by the beginning of the 20th century [22], energy cooperatives later emerged as new tools for people's commitment to the energy transition. In this regard, wind cooperatives have developed in Denmark since the 1970s, contributing towards the rapid diffusion of new renewable-based community projects all around Europe. As a result, 34% of the renewable capacity installed in Germany by 2012 belonged to community groups [23]. Beyond the EU boundaries, Japan can undoubtedly be considered the pioneer country in the development of SECs and of the new consciousness about the social aspects related to energy co-production [24].

Although during last three years many researchers conducted literature reviews about the directives, SECs' real applications and simulations worldwide, some aspects could be further investigated [25–27]. In the literature review conducted by de São et al. [25], many definitions and overlapping acronyms used to refer to SECs were comprehensively discussed. In a study of van Summeren et al. [26], some characteristics of a typical SEC were listed. The focus of this paper was addressed to the use of multiple methods of literature review to define community virtual power plants in energy provision rather than to focus on the sharing of energy plants based on local RES availability and on the social aims of SECs. However, social-oriented analysis had already been performed in several review papers. For instance, in [27], Knox et al. conducted an analytical review on energy justice and the community concept to solve energy problems. This approach, also adopted in [28], included a social analysis focused about citizen ownership and investments supporting northern-Europe adoption of decentralized and sustainable energy technologies. In addition, a review on island communities was carried out to define the acceptability parameters based on local benefits and mechanisms for managing intra-community conflicts [29]. The literature review conducted in [30] focused on the analysis of both the social and economic value arising from the application of peer-to-peer energy trading, community self-consumption and transactive energy models within the SECs. Specifically, the social value depends on peoples' care, while the economic one is quantified as a function of the savings, revenues, and services offered by the implemented model.

The analysis of the results of these studies clearly showed that a standard definition of "energy community" does not exist in the scientific literature. In this proposed study, when referring to energy communities, the authors decided to include the adjective "smart" to highlight the progressive development of intelligent tools for the management of such organizations, useful to reduce the energy costs and to increase energy system's flexibility, safety, and sustainability. In this way, it was also possible to differentiate SECs from energy cooperatives, which represent a not fully developed form of SECs from a regulatory, technical and socio-economic point of view. Moreover, the SEC term allowed to not discriminate the exclusive RES presence according to the IEMD [3]. Nevertheless, to standardize the concept of SEC, it would be also useful to outline the elements and peculiarities which characterize it. Hence, the current literature analysis has been mainly oriented towards a better definition of the features and the objectives of SECs. Since the recast of the REDII was the first EU explicit regulatory reference to SECs, only world-wide real cases, case studies and simulations of SECs successive to 2018 have been selected. In this way, great attention has been paid to the investigation of the stimulus at the base of the transition from experimentations to regulation.

A cataloguing of SECs' characteristics and aims has been conducted identifying inclusive categories and approaches. Differently from previous literature review studies, this method has been adopted according to the main findings of the REDII [2]. As a result, the discussion focused on the definition of the limits and the barriers of SECs that hinder their pervasion arising from the reviewed case studies. In addition, this study wanted to bring up the failures of SECs' experimentations and to define innovative evaluation criteria in order to support the energy policies regarding SECs. This second element of novelty reflected in the attention paid to SECs' social aspects, since in the literature, to the best of the authors' knowledge, there was no attempt to identify innovative indexes useful to increase the valorisation and rewards of SECs also from the social standpoint. The results of the analysis brought to light conclusions about SECs' criticalities which, together with their causes and effects, are worth an adequate space of reflection.

In Section 2.1. the method adopted for carrying out the literature review will be introduced. SECs' common characteristics and aims will be detailed in the subsections of Section 2.2. Specifically, Section 2.2.1 will investigate the sharing approach adopted within RESs-based distributed energy systems to meet multi-users' electric and thermal energy demand, Section 2.2.2 will be about the adoption of energy storage systems (ESSs), Section 2.2.3 will detail the application of the Internet of Things (IoT) and demand-side management (DSM) in the programs adopted for managing SECs. A brief discussion of all the previously listed topics will be conducted in Section 2.2.4. Acknowledged

SECs' most important objectives will be defined in Section 2.3, by distinguishing them in energy, environmental and technical (Section 2.3.1), economic (Section 2.3.2) and social (Section 2.3.3) aims. Therefore, Section 2.4 will be about the discussion of the principal indexes encountered during the literature analysis and used for the evaluation of SECs. In Section 3, the results of the review carried out will be collected and discussed. Specifically, Section 3.1 will deal with the current criticalities of SECs, while Section 3.2 will detail their future challenges and perspectives. Finally, in Section 4, the conclusions will be drawn. The structure of this study is outlined in Figure 1.

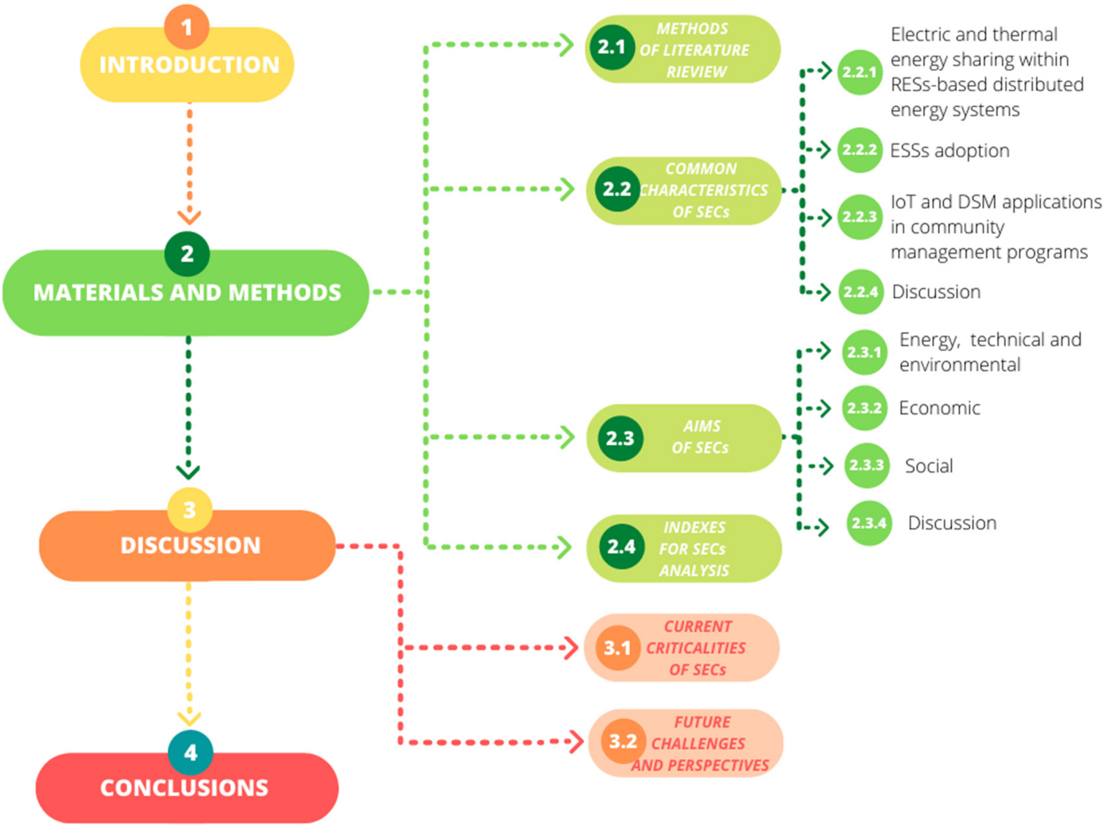


**Figure 1.** Paper's structure.

## 2. Materials and Methods

In this section, the methods of literature review and the materials used will be described.

### 2.1. Methods of Literature Review

In order to analyse the concept and all interpretations of SECs, a literature review was conducted by defining the main research trends, the current applications, the directives and the prospects. The Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) methodology was used following a four-phase flow diagram, since systematic review methods help the researchers to keep up to date [31]. The four steps followed are listed in the following bulleted list and further explored in Figure 2:

- Identification;
- Screening;
- Eligibility;
- Inclusion.

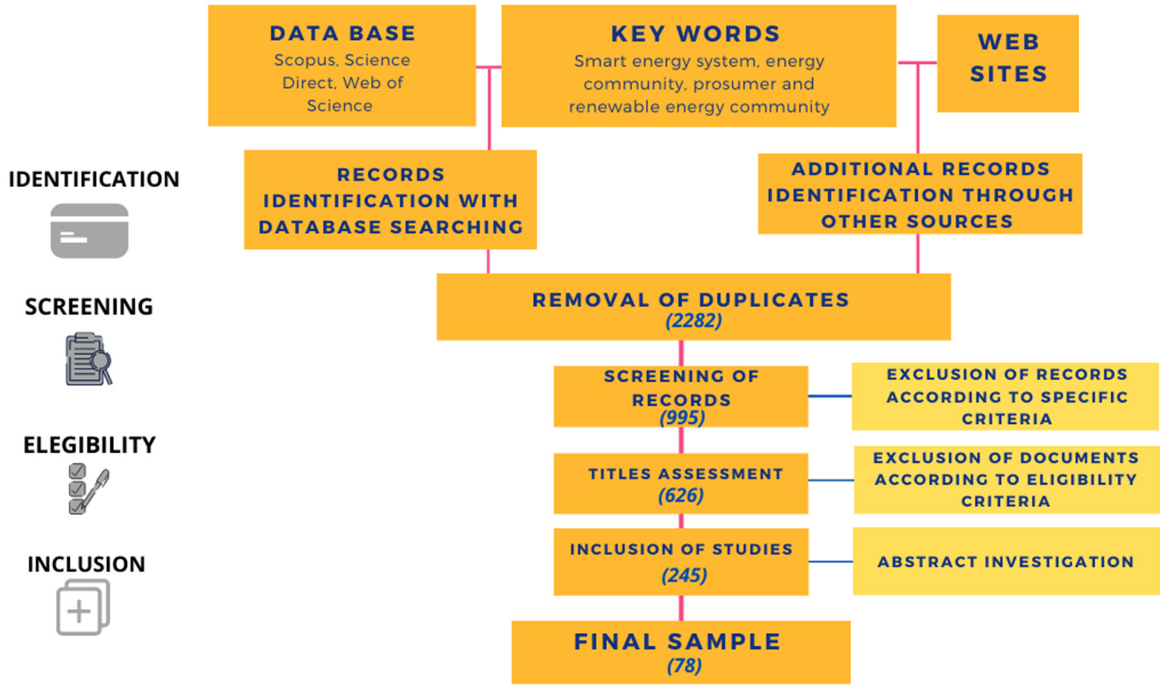


**Figure 2.** Flow-chart of the adopted review method.

The identification of investigated studies started by defining the databases, the keywords and the websites used for the sources search. Specifically, Scopus™, Science Direct™ and Web of Science™ were used as databases. The most used keywords were *smart energy system*, *energy community*, *prosumer* and *renewable energy community*. In the second phase, the identified records were screened, and all duplicates were deleted. Furthermore, the sources that appeared not focused on the topic were excluded after having analysed their title and abstract. In this mix of documents, specific criteria were adopted to define the eligibility of sources. The inclusion criteria are listed in the following bulleted list:

- Full access to the source;
- Article or conference paper;
- Source belonging to the energy subject area;
- Source intended to evaluate the energy, or the economic, or the environmental benefits arising from energy sharing;
- Source dealing with the exploitation of at least one RES;
- Source describing the results of a simulation or a case study;
- Source developed by at least one energy expert;
- Source referring to countries where the REDII directive has already been transposed into national law or with interest in energy sharing.

Instead, the exclusion criteria were:

- Grey research;
- Duplicate source;
- Non-indexed source;
- Non-English source;
- Source antecedent to 2018 (year of publication of the EU REDII);
- Source focused on sharing but without energy scopes;
- Source containing not relevant keywords, such as those related to non-energy communities (e.g., microbial communities);
- Conference paper not focused on the exploitation of RESs;
- Journals with fewer than ten publications about the topic published after 2018.

The research carried out by assuming *smart energy system* as keywords produced 52,753, 162,104, and 61,181 results in Scopus™, Science Direct™ and Web of Science™, respectively. Next, the results were filtered to keep only references successive to 2018 and to focus on *energy* topic. Since this approach was not applicable in Web of Science™ database, it was excluded. To avoid the presence of duplicates and to ensure the access to the sources for all authors, only Scopus™ was used as database. The references coming from the websites were excluded as well, since they responded to the exclusion criteria. After the application of the inclusion and exclusion criteria, the title of 626 remaining documents had been evaluated by the authors. Subsequently, in order to avoid bias, the abstract of the remaining 245 documents had been analysed. The final set of references included 78 papers.

In Table 1, the screenings for the number of documents published from 2018 to 2022, found in Scopus™ and Science Direct™ databases and belonging to the *energy subject area*, are reported. In the last column of each row, the total number of papers published from 2018 to 2022 and referred to each keyword and database is specified. In the last row, the total number of papers found in each database using the Boolean function {"smart energy system" OR "energy community" OR "prosumer" AND "renewable energy community"} AND {"limit to the energy subject area"} AND {"year of publication"} as query is shown for each analysed year (from 2018 to 2022). The result is that in Scopus™ database, the *prosumer* term realized the best increase in the number of citations. Moreover, with respect to 2018, it is possible to detect an increase between 17% and 36% of the number of papers about *energy community* and *renewable energy community* published in 2019 and 2020, thus following the publication of the REDII and the IEMD.

**Table 1.** Identified papers belonging to the *energy subject area*.

| Keywords | Database | 2018 | 2019 | 2020 | 2021 | 2022 | 2018–2022 |
|---|---|---|---|---|---|---|---|
| Smart energy system | Scopus™ | 2590 | 2770 | 2397 | 2482 | 682 | **10,921** |
| | Science Direct™ | 3408 | 3862 | 4227 | 5605 | 3416 | **20,518** |
| Energy community | Scopus™ | 1131 | 1377 | 1473 | 1777 | 609 | **6367** |
| | Science Direct™ | 5075 | 5459 | 6302 | 7961 | 4426 | **29,223** |
| Prosumer | Scopus™ | 143 | 254 | 273 | 336 | 103 | **1109** |
| | Science Direct™ | 46 | 25 | 44 | 46 | 44 | **205** |
| Renewable energy community | Scopus™ | 376 | 485 | 508 | 657 | 245 | **2271** |
| | Science Direct™ | 2885 | 2977 | 3526 | 4613 | 2696 | **16,697** |
| **Smart energy system, energy community, prosumer, renewable energy community** | **Scopus™** | **376** | **485** | **507** | **661** | **253** | **2282** |
| | **Science Direct™** | **2885** | **2977** | **3526** | **4611** | **2767** | **16,766** |

In carrying out the literature analysis, several topics were found to be able to summarize SECs' common characteristics. They are listed in the following bulleted list:

- Electric load sharing;
- Thermal load sharing;
- Photovoltaic (PV) systems adoption;
- Exploitation of RESs different from solar;
- High efficiency cogeneration (CHP) systems usage;
- ESSs presence;
- DSM programs;
- Information and Communication Technologies (ICT) implementation.

It results that none of the 2019 reviewed papers considers SECs which implement thermal load sharing, while the electric load sharing topic tends to be quite equally distributed within the analysed years. As a matter of fact, the former was discussed for 70.9% in 2018 papers, for 17.7% in 2020 papers and for 11.4% in 2021 papers. The latter was discussed for 24.8% in 2018 papers, for 38.8% in 2019 papers, for 14.0% in 2020 papers and for 22.4% in 2021 papers. This outcome is indicative of the great attention paid by the

REDII to the sharing of electric energy, which is easier to apply than the thermal energy sharing since electric grids are public and already extended and branched. The topic about the exploitation of RESs other than solar was argued only by papers of 2020 and 2021 for 61.0 and 39.0%, respectively. On the contrary, the topic about the adoption of PV systems appears to be quite equally distributed within the analysed papers, since it was discussed for 26.8% in 2018 papers, for 18.6% in 2019 papers, for 26.8% in 2020 papers and for 27.7% in 2021 papers. These outcomes reflect the continued attempt of the literature to find profitable ways to boost the exploitation of RESs. Nowadays, PV systems are affordable and easy to install, thus representing an optimum tool for the promotion of renewable electricity generation also at the community level. However, the exploitation of other types of RESs is gaining more interest, thanks to the opportunity to improve SECs' energy self-sufficiency (SS) and to counteract RESs' uncertainty. For this to happen, it is also useful to design SECs equipped with ESSs and/or CHP units. This assumption explains the quite equal distribution of these topics among analysed papers. The former has been analysed for 33.9% by 2018 papers, for 23.5% by 2019 papers, for 15.1% by 2020 papers and for 27.5% by 2021 papers. The latter has been analysed for 7.1% in 2018 papers, for 44.4% in 2019 papers, for 44.4% in 2020 papers and for 4.0% in 2021 papers.

A similar analysis has been carried out about SECs' principal purposes, which, alongside with better local RESs exploitation and improvement in users' SS and self-consumption (SC), turn out to be as follows:

- Primary energy saving;
- Operating energy costs reduction;
- GHG emissions saving;
- Electric peak shaving;
- Power quality supply adjustment;
- Social outcomes (local economy improvement, energy democratization, gaps in energy access resolution).

The most equal distributions in terms of year coverage are found for the topics regarding the reduction in operating energy costs and GHG emissions. In fact, each publication year covers this topic between 20.2% and 35.0%, as evidence that both goals have been recognized to be essential key drivers of energy transition and, according to the REDII, the creation of SECs is expected to enhance their achievement. In the case of the other aims, the variability of the percentages is much more pronounced. For example, in relation to power quality enhancement, the year coverage varies between 1.4% and 41.0%. In relation to social outcomes, the year coverage varies between 2.7% and 66.8%, and in relation to energy consumption reduction, the year coverage varies between 3.1% and 77.5%. In the stacked graph of Figure 3, the percentage distribution of each topic among the analysed years is reported to assess the shift in the interest in the literature. It results that the social outcomes expected by SECs have progressively gained importance after 2018, as they cover 6.7% of analysed papers from 2018, 33.3% of 2019 papers and 58.3% of 2020 papers. This trend can in part be attributed to the publication of the REDII, and specifically to the role given to SECs about ensuring social and environmental benefits rather than financial profits. As further evidence of this, from the values obtained, it results that the environmental aims had always been recognized essential goals of SECs. In fact, the reduction in GHG emissions results to be quite equally distributed among the analysed papers in all the years considered, since the percentage values vary between 8 and 27%. The same values are found for the reduction in the operating energy costs, while the variability is much more pronounced for the other goals. However, this outcome could be attributed to the specific field of engineering which the selected papers belong to.

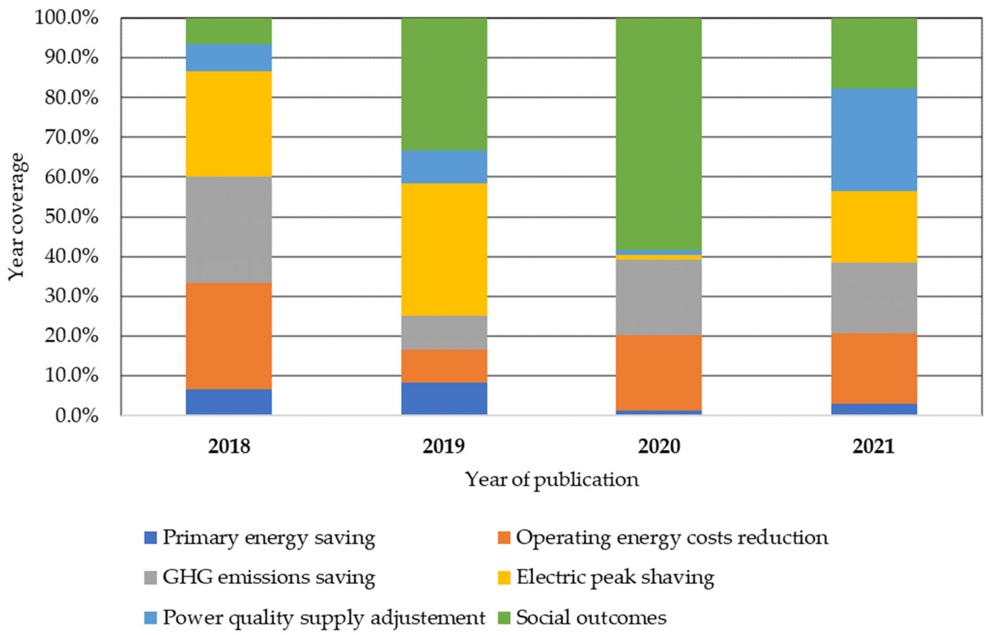


**Figure 3.** Percentage distribution of the goals of SECs among the years of publication of the reviewed papers.

The most diffused topic among all reviewed years is the adoption of PV systems, which has been discussed by a total of 18 papers, followed by the presence of ESSs, included in 15 papers. Thereby, it is further evident that the practical possibility of sharing electric energy among different users regulated and incentivised in Europe by the REDII, together with the affordability and the easiness to install of solar panels, boosted the focus of the literature about the exploitation of solar energy and the adoption of electric ESSs. Indeed, the exploitation of RESs other than solar emerges to be the less diffused topic, with only 2 references dealing with it dating to 2020 and 2021, respectively. The interest paid by the RED II to the renewable electricity supply is also reflected in the objectives of SECs. In fact, as already stated, both the reduction of GHG emissions and of operating energy costs expected by SECs recur frequently within the literature, and both are described in 12 papers among the analysed ones. Yet, social outcomes result to be the most popular aims of SECs, included in a total of 13 papers. These outcomes furtherly account for the main benefits expected from SECs' according to the REDII and demonstrate the potential to simultaneously reap the benefits from the energy, environmental, social, and economic point of view through their implementation. Therefore, it may be concluded that after the launch of the REDII in 2018, the interest of the literature has been shifted towards issues more in line with the regulatory framework.

The selected papers for this research involve many researchers from different countries. In Figure 4, the thematic map about the number of papers considered for each country is reported. These values are furtherly detailed in Table 2. Each value has been calculated by assigning to each paper the country of its corresponding author. In the case of papers with more than one corresponding author coming from different countries, the score of each involved country has been evaluated accordingly as a fraction of one. It results that the countries counting more than five papers are Austria, Italy, Portugal and the United Kingdom.

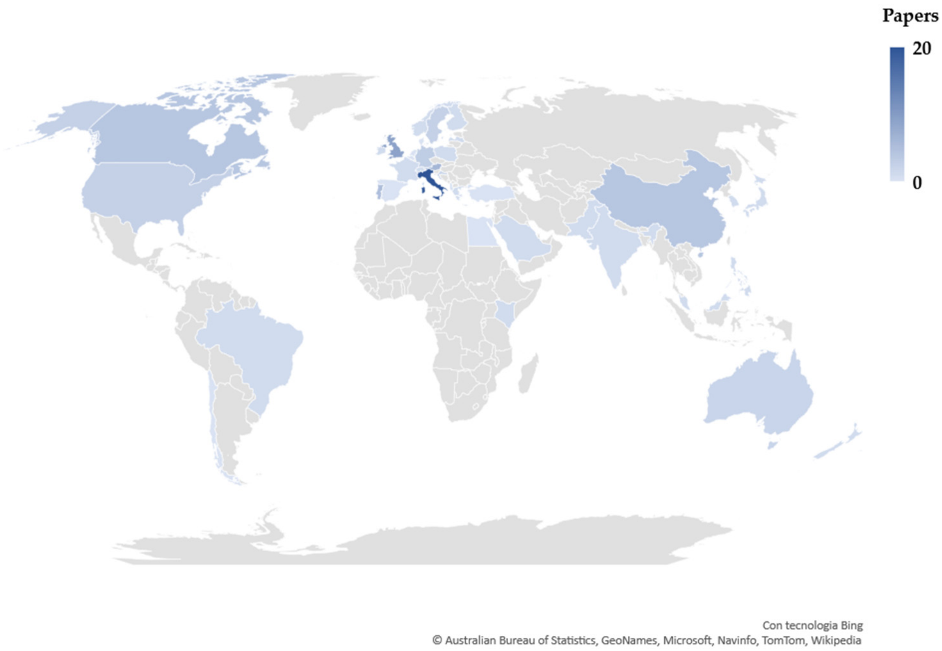


**Figure 4.** Thematic map about the number of papers reviewed for each country.

**Table 2.** Number of papers reviewed for each country.

| Country | Number of Papers |
|---|---|
| Australia | 2 |
| Austria | 6 |
| Brazil | 1 |
| Canada | 4 |
| China | 4 |
| Croatia | 2 |
| Finland | 1 |
| France | 1 |
| Germany | 3 |
| Greece | 1 |
| India | 1 |
| Ireland | 1 |
| Italy | 20 |
| Japan | 1 |
| Kenya | 1 |
| Latvia | 1 |
| Malaysia | 1 |
| New Zeeland | 1 |
| Norway | 1 |
| Pakistan | 1 |
| Philippines | 1 |
| Poland | 1 |
| Portugal | 5 |
| Republic of Korea | 1 |
| Saudi Arabia | 1 |
| Sweden | 2.5 |
| Switzerland | 1 |
| United Kingdom | 9 |
| United States of America | 2.5 |
| **Total** | **78** |

### 2.2. Common Characteristics of Smart Energy Communities

In this section an overview of the common characteristics of SECs will be defined. The categories of analysis identified are shown in Figure 5. Specifically, Section 2.2.1 will investigate the electric and thermal energy sharing within RESs-based distributed energy systems, Section 2.2.2 will investigate the adoption of energy storage systems and Section 2.2.3 will investigate the applications of IoT and DSM in community management programs. At the end, in Section 2.2.4, the acknowledged common characteristics of SECs will be briefly discussed.

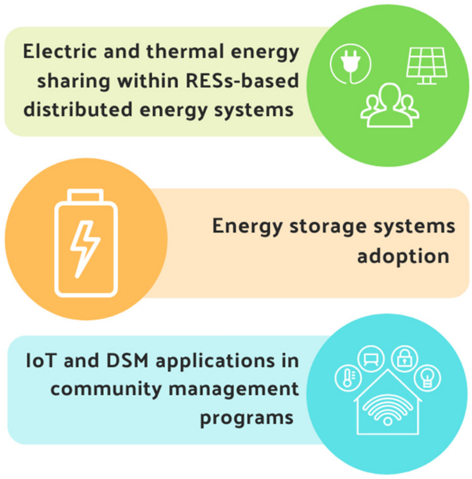


**Figure 5.** Categorization of common characteristics of SECs.

#### 2.2.1. Electric and Thermal Energy Sharing within RESs-Based Distributed Energy Systems

SECs allow individual subjects to efficiently share and manage common energy resources thanks to the creation of bottom-up institutions [32]. The sharing approach has attracted a lot of interest before SECs had been fully recognized by the European regulatory framework. For instance, an Italian study purposed an analysis to increment the number of operating hours per year of buildings micro-CHPs for multi-users in the Mediterranean area [33]. The study considers two end-users, specifically a tertiary and a residential building, coupled via a district heating-microgrid. A similar analysis was realised by Angrisani et al. [34], who investigated the advantages coming from the introduction of a thermal micro-grid connecting several users in order to increase the hours of operation of a micro-CHP adopted in buildings with high envelope qualities. Specifically, the work couples two end-users: a multi-family house and an office building. Recent studies have renewed their interest for the application of sharing economy principles to the energy sector by paying more and more attention to distributed energy generation [32]. DESs can satisfy users' both electrical and thermal energy demands through several power and heat generation technologies, including RESs and storage units. By connecting multiple DESs through local electricity and heating networks, it is possible to build up a SEC [35]. In most cases, the SECs involved in literature studies are solar-based systems. In [36], Ceglia et al. assess the performance of a small size SEC in Naples (Southern Italy), composed of two offices. Both use an individual electric heat pump (HP), which has a thermal capacity of 14.1 kW and a cooling capacity of 13.3 kW, coupled with a PV plant. The peak power of the PV field on the roof of the first office is equal to 9.0 kW, while the second PV field has a 14.3 kW peak power. In addition, this office is also equipped with a charging station of 3.3 kW, used to charge an electric vehicle (EV). Both offices are bi-directly connected to the grid, and the sharing of PV electricity is allowed by a microgrid. Plaza et al. [37] analyse the extent to which the sharing of energy generation of one or more PV plants allows operators to cope with many challenges deriving from individual SC, such as users' temporary absence. The authors compare two scenarios and focus on seven consumers, each one equipped with a 7.0 kW PV plant, located in Southern France. In the first configuration they act as individual

PV prosumers, in the latter a collective installation is considered. The obtained results motivate the development of new models for the implementation of SECs projects where the distributed energy SC is optimized. In this regard, Martirano et al. [38] introduce a new *Power Sharing Model* to optimize community's SC, by the simulation of a SEC including two public administration's buildings located in Campobasso (Italy) which share a PV array for power production. In [35], the interest of the authors is addressed to a SEC in the United States, which includes four customers belonging both to residential and commercial sectors. The purpose is to optimally dispatch distributed generation units within the DESs, in order to minimize SEC's total energy costs. Each DES is equipped with PV panels, a battery storage, a CHP unit, an auxiliary boiler, a HP, and a thermal storage. In [39], Giordano et al. propose an optimization model to minimize energy costs in a DES made up of three buildings located in a University campus in Southern Italy, by comparing two scenarios: one where the three users exchange power only with the grid, and the second one where they can interact and exchange power with each other. Two of the considered buildings are each equipped with a PV plant, of 4 kW and 8 kW, respectively, and an ESS, of 6 kWh and 12 kWh, respectively.

#### 2.2.2. Energy Storage Systems Adoption

The exploitation of "non-programmable" RESs', i.e., uncertain RESs such as solar or wind energy unlike other types of RESs such as geothermal energy, is often an off-the-board underdog by the mismatch between energy generation and demand [40]. The adoption of ESSs and of DSM programs is broadly recognized to fulfil the necessity of overcoming this issue, hence boosting the spread of RESs in energy systems [41]. ESSs allow the increase in community SC, by making available unconsumed energy when there is a lack of generation or during high demand periods [42,43]. Although storage units commonly serve individual users, communitarian storage installations are rapidly spreading [32]. Effectively, several benefits arise from the use of community energy storage (CES). For example, economies of scale for batteries, which could even improve the profitability of a PV-battery system [44,45]. According to [46], the use of ESSs in SECs enhances the local energy dispatching and acts as a peak shaving, because ESSs can contribute to cover extra energy demand and improve the SC. ESSs solve the intermittence in renewable energy generation and prevent back-feeding, which occurs when electricity flows in the grid in the reverse direction as expected. Moreover, by sharing the surplus energy among SEC's members, grid negotiation is avoided and thus long-distance transportation losses too [25]. In [47], it is assessed that regardless of the higher costs, the increase in the penetration of battery energy storage systems will be necessary to achieve energy transition. Therefore, in the case study analysed, the authors pay attention on the usage of batteries in three apartment buildings located in Perth (Australia). Each microgrid consists of a central PV and a battery for the individual electricity distribution, whose sizes have been chosen both for minimizing buildings' dependence on the grid and depending on apartments number in each building. Specifically, the first building has been equipped with a 9 kW PV plant and a 10 kWh Lithium-ion (Li-ion) battery, the second one with a 54.6 kW PV plant and a 150 kWh Li-ion battery, and the third-one with a 16.6 kW PV plant and a 40.0 kWh Li-ion battery. Moreover, the possibility to limit winter community electricity imports from the grid, through the design of hybrid solutions including hydrogen fuelled fuel cells, is discussed. Yet, alternative ESSs can be also considered. In [48], the use of EVs' batteries as decentralized ESSs is analysed. Indeed, the possibility of combining the energy requests of both civil and transport sectors using PV electricity to recharge EVs is recognized to be a key driver for SECs' development [36]. SECs' sustainability can be further increased through the combination of RESs and other types of vehicles, such as hydrogen ones. Liu et al. [49] describe a "zero-energy" community thought as a hybrid renewable system in which stationary batteries and hydrogen vehicles are included for improving renewable energy SC, integration, and load coverage. The simulation is carried out in Hong Kong, assuming PV and wind electric energy generation. In case the electricity "production" exceeds the self-consumption, the surplus is delivered to a stationary battery for its charging, until a full state of charge is reached. Then, it is further used for the activation of three groups of electrolysers for hydrogen production. Hydrogen is transported to stationary hydrogen storage tanks by primary compressors, which are in turn activated by renewable-based electric systems. Secondary compressors deliver hydrogen to hydrogen vehicles while they are parked and until they reach their maximum state of charge. Eventually, residual renewable electricity is fed into the grid.

#### 2.2.3. IoT and DSM Applications in Community Management Programs

The ever-increasing development of DESs paved the way for the reorganization of energy systems management, by the enhancement of the flexibility ensured by every involved part [50]. DSM programs can encourage modifications in end-users' load profiles by the exchange of signals between them and the grid [51]. This approach reduces grid congestions by shifting users' consumption to non-peak hours [52]. In addition, demand-side resources enhance SEC reliability and resilience, i.e., the ability to keep operating normally in case of an outage and to preserve users' comfort [53]. Demand-response programs, which are responsible for energy costs reduction and energy SC optimization [54], necessitate for their execution the users' virtual aggregation to make their capacity available. The control is entrusted to an aggregator, which in turn receives signals from the system operator [55]. The aggregator is described in [56] as a third neutral entity bi-directionally connected to the grid; its function can be performed by the energy provider, the retailer, or the entity responsible for the system balance. Moreover, aggregator's action appears to be quite diversified in the literature: it could be aimed to manage and to control various SEC technological components, to balance demand and supply, or to optimize SEC's goals, such as the minimization of prices or the maximization of SC. The role of the aggregator is also described in [52], where Reis et al. simulate the operation of residential users involved into a SEC through a *Multi-Agent System* framework. In such a system, participating users are autonomous and can adjust their actions by means of input signals received from the surroundings. End-users are basically the residential prosumers and simple consumers, centrally coordinated by an entity that manages community's energy resources and interaction with an electricity retailer. Therefore, IoT and ICT devices play a fundamental role in the management of the existing electricity grid and in enhancing its resilience, sustainability [41] and efficiency [25]. Broadly speaking, IoT-based devices increase systems' efficiency and schedule properly different appliances [57]. Nowadays, they represent one of the main contributors to the digitalisation of energy systems and have become fundamental in the development of sustainable solutions and in RESs diffusion [58], thus also enhancing the development of energy system based on local RESs [59]. For example, the interaction among the users is expected to make the delivering of energy services more economic. Nevertheless, for the enjoyment of such benefits, cheap technical solutions for the effective control of energy loads and supply profiles are essential, also because of people's reluctance to the adoption of such devices [60]. One of the most diffused devices within the SEC context are smart meters. They allow users interaction with utilities, while monitoring their energy consumption, typically on an hourly basis, and thus assisting them in reducing energy costs [57]. In [61], the combination of smart metering with smart charging is assessed. In fact, the aggregator allows the smart charging of the EV when the users' energy demand is lower than the community generation. The SEC considered is made up of four residential members: three prosumers and a consumer. Each prosumer is equipped with a PV plant of 2.3, 4.5 and 6.3 kW, respectively. The consumer owns an EV in the second configuration analysed, whose batteries rated power and rated capacity is equal to 50 kW and 40 kWh, respectively.

#### 2.2.4. Discussion about SECs' Common Characteristics

To sum up, according to the reviewed case studies, electric load sharing, thermal load sharing, exploitation of RESs, high efficiency CHP systems usage, installation of ESSs, DSM programs execution and ICT implementation emerged to be the main common characteristics of SECs. These results are summarised in Table 3, where the selected references are listed in the first column. In the subsequent columns, the recalled main features of SECs are listed according to the categorization adopted to identify the subsections developed for their investigation. In particular, the check mark is used to state the presence of a specific topic in the selected paper, the cross mark its absence. As was to be expected, each row of the second column, which corresponds to the electric load sharing topic, is filled with the check mark. In fact, all the reviewed papers consider SECs characterised by this feature. Instead, only the second and the seventh rows of the third column, which refers to the thermal load sharing topic, is filled with the check mark. In fact, among the considered studies, only [35,43] deal with SECs implementing both electric and thermal load sharing. The fourth column lists the type of RES exploited in each reviewed case study of SEC. Excluding [48], all references deal with solar energy exploitation; moreover, in [49], wind energy is exploited too. The fifth column of Table 3 is about the usage of high efficiency CHP systems within the analysed DESs. A CHP is adopted only in references [35,50]. The sixth column refers to the type of ESS adopted in each case study. The authors of [36,48,61] deal with EVs as ESSs. Only three check marks appear in the penultimate column, which addresses the execution of DSM programs. In fact, excluding references [43,52,53], none of the others deal with this topic. Similar considerations apply to the last column of the table, which checks the implementation of ICT. This topic is considered only in references [50,52,61].

**Table 3.** Main common characteristics of SECs arising from the reviewed case studies.

| Reference | Electric and Thermal Energy Sharing Within RESs-Based Distributed Energy Systems | | | | Energy Storage Systems Presence | IoT and DSM Applications in Community Management Programs | |
|---|---|---|---|---|---|---|---|
| | Electric Load Sharing | Thermal Load Sharing | Type of RES Exploited | High Efficiency CHP Systems Usage | Type of ESS | DSM Programs | ICT Implementation |
| [13] | ✓ | X | PV | X | X | X | X |
| [35] | ✓ | ✓ | PV | ✓ | A battery and a thermal ESS | X | X |
| [36] | ✓ | X | PV | X | EV | X | X |
| [37] | ✓ | X | PV | X | X | X | X |
| [38] | ✓ | X | PV | X | X | X | X |
| [39] | ✓ | X | PV | X | Electric | X | X |
| [43] | ✓ | ✓ | PV | X | A buffer and a thermal ESS | ✓ | X |
| [44] | ✓ | X | PV | X | Li-ion batteries | X | X |
| [47] | ✓ | X | PV | X | Li-ion batteries | X | X |
| [48] | ✓ | X | X | X | EV | X | X |
| [49] | ✓ | X | PV<br>Wind energy | X | Stationary batteries and hydrogen vehicles powered by hydrogen tanks after electrolysis reactions | X | X |
| [50] | ✓ | X | PV | ✓ | X | X | ✓ |
| [52] | ✓ | X | PV | X | Static ESS | ✓ | ✓ |
| [53] | ✓ | X | PV | X | X | ✓ | X |
| [61] | ✓ | X | PV | X | EV | X | ✓ |

### 2.3. *Aims of Smart Energy Communities*

The sharing approach had already been proved to be environmentally, economically, and socially sound before REDII launch. In [33], it emerged that the adequate selection of users suitable for sharing their electrical and thermal loads leads to satisfactory performance from an energetic point of view thanks to the reduction in primary energy demand by 18.8% in Benevento (Italy) and 17.2% in Milan (Italy). In addition, the proposed system involved also environmental advantages, thanks to the 26.9% and 25.2% reduction in $CO_2$ emissions in Benevento and Milan, respectively. In [34], the authors showed the load-sharing approach to increase energy SC, thus reducing grid perturbation and providing economic benefits. In addition, the increased SC reflected in the saving of primary energy and $CO_2$ emissions. The primary energy saving was equal to 6.2% in Naples (Italy) and to 8.8% in Turin (Italy), while $CO_2$ emissions were reduced by 6.7% and 8.3% in Naples and Turin, respectively. These results anticipate SECs' primary target according to the REDII, which is to offer their members environmental, economic, and social benefits rather than financial profits [52]. Starting from this assumption, in this section an overview of the principal purposes of SECs will be defined. The discussion will be developed by defining three categories, listed as follows:

- Energy, technical and environmental aims;
- Economic aims;
- Social aims.

Each one of these categories will be detailed in the following subsections, according to the recent literature review and in the best of authors' knowledges. Section 2.3.1 aims to detail the energy, technical and environmental objectives of SECs, while Section 2.3.2 defines the economic aims and Section 2.3.3 defines the social ones. In the last subsection, Section 2.3.4, the analysed aims of SECs will be briefly discussed.

#### 2.3.1. Energy, Technical and Environmental Aims

Some of the principal purposes of SECs from the energy and technical point of view are listed in the following bulleted list:

- Decrease in global energy consumption due to the adoption of DESs [62];
- Massive use of RESs-based energy conversion systems [63];
- Improvement of energy grid stability [64];
- Widespread exploitation of RESs in energy networks [65];
- Development of hybrid energy systems that will increase the steadiness of RES-based energy conversion systems in supplying the energy requests [66].

According with the first bulleted aim, the support of DESs leads to positive environmental outcomes [67]. Franzoi et al. [43] argue that the broader diffusion of on-site energy generation units arising from SECs' spreading is one of the key drivers in buildings' carbon footprint reduction. According to [49], with respect to the baseline scenarios where RESs exploitation is neglected, "zero-energy" scenarios involve strong carbon emissions and costs reduction. In detail, the former ranges between 71.2% and 90.9%. On the other hand, the improvement of energy grid stability is a consequence of the energy sharing and the interaction among SEC participants. In the absence of the SEC configuration, the surplus of decentralized energy "generation" is sold to power grid, thus worsening its instability [68]. Instead, within the SEC, the use of the surplus energy by other consumers/prosumers or in CESs is allowed. Therefore, users' SC and SS increase, as proved in [36]. In fact, thanks to the reduction in PV electricity exports allowed by the energy sharing, the amount of energy consumed on-site rises between 60.7 and 74.4%, and the amount of electric load covered by PV electricity grows to values between 77.8 and 81.3%. Both results are due to greater exploitation of surplus electricity, which is distributed within the community. Additional advantages in terms of grid stability enhancement are found with ESSs. Starting from the assumption that ESSs are essential for the proper integration of renewable energy generation, both imports and exports, and thus the interaction with the grid, can be further reduced when ESSs are implemented as CESs. In [44], it is demonstrated that the adoption of CESs reduces monthly imports by 91.0 MWh, whereas the reduction is limited to 59.0 MWh with the adoption of household batteries. In parallel, CESs reduce communities' monthly exports by 102.2 MWh, whereas the reduction allowed by household batteries is limited to 80.5 MWh. Nevertheless, CESs total storage size is equal to 8.5 MWh in the community scenario, thus lower than in the household scenario, where it is equal to 13.0 MWh. The reason for this is the community aggregating affect, by which 39.0% of households do not need any batteries. More generally speaking, the integration of polygeneration systems and different ESSs in multi-energy districts can provide the following:

- Better management of variable local energy demand;

- Improvement of the service reliability;
- Optimal use of local RESs [69];
- Further mitigation of energy system's carbon footprint [70].

Given technical and economic constraints which could make power grid extension unviable, RESs are recognised as having a fundamental role in rural electrification plans [71]. In this respect, community-based energy systems allow a greater energy access than centralized ones, even in areas with no access to the national grid [72]. As an example, solar-driven SECs may represent an interesting alternative in meeting off-grid rural communities' electricity demand with sustainable electricity, thus boosting the decarbonization of energy islands, i.e., areas with poor or inexistent connections to the grid [70], where the electricity generation relies on diesel-fuelled systems [73]. In [74], a SEC is designed to increase energy SS, stability and flexibility of the Italian island of Ischia. The SEC is based on an organic Rankine cycle plant interacting with a geothermal source at medium temperature. In contrast to the traditional system, where the electricity demand would have been met by the national power grid, the considered system provides electric energy for both pure electric and thermal load by the exploitation of a "programmable" RES, often insufficiently exploited within the Italian territory. The results confirm the great environmental benefit expected: the proposed system leads to a large $CO_2$ emission saving, equal to 29.9 $tCO_2/y$. The accomplishment of this result is facilitated by the fact that small island electricity networks are characterised by lower complexity, hence representing ideal places for improving pilot projects of SECs [75].

#### 2.3.2. Economic Aims

From the economic point of view, SECs lead to significative reduction in both systems costs, thanks to profitable economy of scale [76], and electricity costs, because of load aggregation and shifting [77]. The load-sharing approach is proved to be very cost effective in [39], where the economic saving is equal to 71.0% as a consequence of a 28.0% increase in energy SC and the reduction in the energy demand in certain hours of the day. In fact, the increment of community SC makes the imports reduction prevail on the income loss deriving from the reduced energy exports [68]. Similarly, in [35], it results that by allowing DESs to sell electricity to the grid and to interact with each other it is possible to minimize the total operating energy cost and the net energy cost. In fact, the energy sharing maximizes the usage of the electricity "produced" by the CHPs. Moreover, SECs may play a significative role in making the decarbonization of energy islands affordable, as proved in [78]. This study evidences that the design of a multi-vector energy system to supply the energy demand of a community in Neom (Saudi Arabia) allows the surplus of electricity to be used to charge a battery and/or to produce hydrogen that can be used during deficit periods. It results that the cost-effective and reliable design of the proposed system leads to a reduction in costs by around 67.3%. SECs also allow the reduction in system costs for ESSs [76]. In turn, the adoption of ESSs makes the incentives gained for improved SC by SEC's participants increase, especially when ESSs act as CES [44]. The adoption of decentralized EVs as decentralized ESSs is analysed in [61] from the economic standpoint. It results that the recharge of the EV daily costs EUR 1.58 when the consumer acts individually, whereas the cost is largely lower and equal to EUR 0.03 when the consumer operates at the community level. Therefore, the presence of EVs leads to significative economic savings, which can be shared within all members of the SEC, according to their agreements. This cost-saving solution, together with the enhancement of local RESs exploitation [73], demonstrates that SECs may improve local economy. In addition, SECs have the potential of unlocking private investments and financing renewable energy generation units, thus increasing their pervasiveness and social acceptability [79].

#### 2.3.3. Social Aims

SECs allow the shifting of responsibilities from centralized to decentralized entities [50], and thus the sharing of benefits and governing powers among their members by aligning the concepts of "energy community" and "energy democracy" [72]. In fact, SECs have a great potential in transforming current socio-technical centralized regimes into distributed and decentralized organizations [80], whereby energy democratization is a principal consequence [81]. Prosumers' main concern is to guarantee sustainable energy provisioning and to contribute towards innovation and local value creation [82]. In this regard, driving the implementation of DESs, prosumerism is ever more considered as a fundamental solution to energy systems' challenges [83]. Therefore, new business models have been defined to deliver value and reduce the costs of "merit goods" [62,84]. Their principal characteristics are the following:

- Elasticity for including various types of co-investors;
- Respect of REDII instructions;
- Fair sharing of both responsibilities and benefits [79].

The concept of "community" includes the sharing of investments, infrastructures and expertise for the creation of local value [85] by guaranteeing the energy access and mitigating the energy poverty in vulnerable contexts [52]. The improvement of SS is indeed one of the main reasons for users to participate into a SEC [86]. In [87], it is demonstrated the fundamental role which can be played by SECs in electrifying poor rural communities, characterised by dispersed settlement patterns and significative poverty levels which challenge rural citizens grid connections affordability. In [72], Ambole et al. analyse the role which SECs can play in counteracting strong energy access gaps in Sub-Saharan Africa, which in turn worsen poverty and health issues. In this context, where the access to electric energy is missing for about 600 million people and about 890 million still use unsafe traditional fuel-based devices for energy provision, SECs are gradually emerging as an instrument to enhance households' sustainability and resilience, by providing them cheaper electricity and globally extending energy access. By entrusting SECs' members with ownership and control, the community is given the possibility of improving local economy and entrepreneurship. Moreover, the ownership of RESs-based generation units and infrastructure projects increases their value in the eyes of community, thus facilitating their commitment [88].

#### 2.3.4. Discussion about SECs Aims

Local investments and income generation are recognized to be two of SECs' most important drivers, together with environmental and ethical commitment, by SECs' participants interviewed through an online survey whose results are discussed in [89]. SECs' members were also asked which were, according to their opinion, the most important factors characterizing the community. Emerging from this is their focus on the positive environmental impacts following from the SEC constitution, which reflects the fact that no financial benefit is perceived from the SEC. The same approach has been adopted in [90], which is a documentary study based on an online survey conducted in nine EU countries to highlight the current state of EU energy cooperatives. Regarding SECs' key drivers, over 60% of respondents answered that their main purpose was to tackle the climate change problem. In fact, environmental benefits, together with increased comfort, energy independence, greater participation into the electricity market, reduced energy bills and increased energy supply reliability can enhance consumers' participation to SECs [82].

To sum up, according to the case studies reviewed, energy, environmental and technical issues (energy demand reduction, increase in energy SS and SC, local RESs valorisation, GHG emissions reduction, power peak shaving and power quality supply enhancement), in addition to the reduction in the energy costs, the improvement of local economy, the transition to energy democracy and the resolution of existing gaps in energy access emerge to be some of the main purposes of SECs. These results are summarised in Table 4, where some selected references are linked to the previously listed goals of SECs. The synthesis is carried out by following the categorization adopted to identify the subsections previously detailed. The check mark states the presence of a specific topic in the selected paper, the cross mark its absence. Each reference is reported in the first column of the table, while each goal is listed in each column of the second row. The second column is about the energy demand reduction, and out of a total of twenty-four rows, only six are filled with the check mark. In fact, only references [35,39,43,49,68,74] deal with this topic. The number of rows filled with the check mark increases to thirteen in the case of the third column, which refers to the increase in energy SC and SS. This topic has been analysed in references [13,36–39,43,49,61,68,70,74,78,86]. The fourth column refers to local RESs valorisation, and accounts for eight check marks corresponding to references [36,49,69,70,72–74,78]. No more than ten check marks are found in all remaining columns. Specifically, the fifth one refers to power peak shaving and power quality supply enhancement, and is filled with five check marks corresponding to references [36,64,69,77,87]; the sixth one refers to GHG emissions reduction, and includes six check marks corresponding to references [70,73,74,78,89,90]; the seventh one is about the reduction in energy costs, which has been discussed in references [13,35,38,39,49,61,68,76–78]; the eighth one is about the local economy improvement, the penultimate refers to the transition to energy democracy and the last one refers to the resolution of gaps in energy access. The minimum number of check marks is found in the antepenultimate and penultimate column, where it is equal to two and one, respectively, corresponding to references [72,89]. Instead, seven references describe the SECs' goal of solving gap in energy access, namely [70–74,78,87].

**Table 4.** Aims of SECs emerging from the reviewed case studies.

| Reference | Energy, Technical and Environmental Aims | | | | | Economic Aims | | Social Aims | |
|---|---|---|---|---|---|---|---|---|---|
| | Energy Demand Reduction | SS and SC Increase | Local RESs Valorisation | Power Peak Shaving and Power Quality Supply Enhancement | GHG Emissions Reduction | Energy Costs Reduction | Local Economy Improvement | Transition to Energy Democracy | Energy Access Gaps Resolution |
| [13] | X | ✓ | X | X | X | ✓ | X | X | X |
| [35] | ✓ | X | X | X | X | ✓ | X | X | X |
| [36] | X | ✓ | ✓ | ✓ | X | X | X | X | X |
| [37] | X | ✓ | X | X | X | X | X | X | X |
| [38] | X | ✓ | X | X | X | ✓ | X | X | X |
| [39] | ✓ | ✓ | X | X | X | ✓ | X | X | X |
| [43] | ✓ | ✓ | X | X | X | X | X | X | X |
| [49] | ✓ | ✓ | ✓ | X | X | ✓ | X | X | X |
| [61] | X | ✓ | X | X | X | ✓ | X | X | X |
| [64] | X | X | X | ✓ | X | X | X | X | X |
| [68] | ✓ | ✓ | X | X | X | ✓ | X | X | X |
| [69] | X | X | ✓ | ✓ | X | X | X | X | X |
| [70] | X | ✓ | ✓ | X | ✓ | X | X | X | ✓ |
| [71] | X | X | X | X | X | X | X | X | ✓ |
| [72] | X | X | ✓ | X | X | X | ✓ | ✓ | ✓ |
| [73] | X | X | ✓ | X | ✓ | X | X | X | ✓ |
| [74] | ✓ | ✓ | ✓ | X | ✓ | X | X | X | ✓ |
| [76] | X | X | X | X | X | ✓ | X | X | X |
| [77] | X | X | X | ✓ | X | ✓ | X | X | X |
| [78] | X | ✓ | ✓ | X | ✓ | ✓ | X | X | ✓ |
| [86] | X | ✓ | X | X | X | X | X | X | X |
| [87] | X | X | X | ✓ | X | X | X | X | ✓ |
| [89] | X | X | X | X | ✓ | X | ✓ | X | X |
| [90] | X | X | X | X | ✓ | X | X | X | X |

### *2.4. Indexes for Smart Energy Communities Analysis*

A share of literature review was conducted by analysing the indexes and evaluation parameters used in scientific studies to compare and quantify the benefits of SECs, also with respect to other energy user configurations. Zhou et al. [91] define three parameters for SECs optimization. The first one evaluates the maximization of energy load of electric appliances in residential SEC, the second one measures the efficiency of electric storages in the SEC and the third one, the user credit index, calculates the product between the unit price of subsidy for participants and the rating energy of participants' appliances. In Khanna et al. [92], the demand response methodology is applied to a small smart electric grid and a minimization of net cost of electricity index is proposed. For calculating this index, the energy export earnings are subtracted to the consumed electricity costs, thus evaluating the economic advantage of energy sell. Karunathilake et al. [93] propose the evaluation of the Levelized Cost Of Energy parameter for describing the cost of energy production during the entire lifetime of the analysed facility. In particular, the index is calculated as the ratio of the present value of life cycle costs to that of lifetime energy generation. The evaluation of this parameter for different energy appliances makes it possible to compare them. The grid parity factor is set equal to 1.2 for guaranteeing the new renewable energy system Levelized Cost Of Energy not exceed the cost of grid electricity by more than 20%. Such a type of index is introduced also in [70], where it is defined the Levelized Cost of Energy Consumed ($LCOE_{consum}$) indicator, and it is used together with Energy Potency ($E_{pot}$), Energy Self-Sufficiency ($E_{SS}$) and $CO_2$ intensity ($CO_{2consm}$) indicators in assessing the sustainability and SS of multi-energy vectors used in energy islands. Specifically, the $E_{pot}$ index evaluates the efficiency of variable RESs integration in multi-vectors energy communities, $E_{SS}$ is introduced to complement $E_{pot}$ by evaluating the curtailment of solar and wind energy production and the $LCOE_{consum}$ index quantifies the costs due to the use of energy, including capital, fuel, operation, maintenance and imported energy costs. Lastly, $CO_{2consm}$ evaluates the average $CO_2$ emissions in each of the multi-vector energy community contexts. In Kahwash et al. [94], a renewable penetration indicator for electrical system only is defined as the ratio between the renewable power production and the difference between both the total and the unmet electric load. In a similar way, the thermal penetration index is defined. In addition, the excess ratio is evaluated for quantifying the surplus power coming from renewable energy generation plants. The SS and the SC indexes are defined by Mutani et al. [95]. The first index quantifies the amount of total energy consumption consisting in the share of locally self-consumed energy. The second one quantifies the amount of total RES energy generation shared for local energy SC. The same authors propose the definition of the energy exposure indicator for evaluating the user's dependence on the national electric grid. Ceglia et al. propose the evaluation of $s$ and $d$ indexes [36]. The former expresses the amount of electricity demand of SEC covered by the renewable energy production; the latter is the ratio between the renewable electricity self-consumed with respect to the total amount of renewable electricity produced. Maturo et al. [96] define other two indexes: the self-sustaining services ratio, which quantifies in percentage terms the self-consumed energy used for providing heating and cooling services and the SC ratio, which calculates the amount of self-consumed energy over the global energy production, thus resulting in related local energy production.

Wang et al. propose energetic, environmental, and economic SEC indexes [97]. From energy point of view, they define two indexes described as follows:

- Promotion on Energy Balance index, which quantifies energy exchanges with the distribution network both in form of imports and exports;
- Peak Reduction Index, which proves the maximum absolute power reduction achieved in the community scenario with respect to the reference case.

From an environmental point of view, they define the Emission Reduction Rate Index, which computes the waste emissions reduction rate with respect to the baseline case. From an economic point of view, they define two indexes as following description:

- Total Cost Reduction Index, which compares the community overall cost reduction rate with the reference values;
- Participation Intention Index, which measures in percentage terms the number of members who gain larger profits thanks to their participation to the new energy

trading schemes with respect to benchmark conditions, thus representing the overall willingness to join the alliance.

Luthander et al. [98] and Viti et al. [68] calculate an index that expresses the ratio between SS and SS as defined in [95]. In Braeuer et al. [99], the electrical SC rate, the degree of electrical self-sufficiency and the degree of electrical autonomy are employed. Furthermore, the Grid Interaction Index and the normalised Grid Interaction Index are calculated for assessing the self-generated energy usage in energy communities composed by multi-family buildings in Germany.

In Minuto et al. [100], two key performance indices (KPI) were defined to assess the economic and environmental performance of SEC in Italian condominium context. Dimensionless KPIs are defined as a weighted sum of economic and environmental parameters for the economic and environmental analysis, respectively. Specifically, for each scenario, the economic KPI is evaluated considering its Net Present Value, Internal Rate of Return and Pay-Back Time, whereas for the environmental KPI evaluation $CO_2$ emissions reduction, renewable electricity generation and energy consumption reduction due to increased energy efficiency are considered too.

In Table 5, all cited documents related to SEC indices are grouped in three classes of index's subject. Only Herenĉić et al. [70], Wang et al. [97] and Minuto et al. [100] define indexes that include all economic, environmental and energy aspects.

**Table 5.** SEC indexes categories.

| Reference | Energy Indexes | Economic Indexes | Environmental Indexes |
|---|---|---|---|
| [36] | ✓ | X | X |
| [68] | ✓ | X | X |
| [70] | ✓ | ✓ | ✓ |
| [91] | ✓ | ✓ | X |
| [92] | X | ✓ | X |
| [93] | X | ✓ | X |
| [94] | ✓ | X | X |
| [95] | ✓ | X | X |
| [96] | ✓ | X | X |
| [97] | ✓ | ✓ | ✓ |
| [98] | ✓ | X | X |
| [99] | ✓ | X | X |
| [100] | ✓ | ✓ | ✓ |

## 3. Discussion

### *3.1. Current Criticalities of SECs*

SECs represent innovative reorganisations of local energy systems, and they are intended to increase renewable and distributed energy sources integration [101]. However, besides their positive outcomes, from the literature analysis, several criticalities and still open questions emerged about their implementation. In this regard, in Table 6, the main findings are summarised. Each criticality is assigned to the category of analysis which it belongs to, according to the categorization adopted for defining the subsections of Section 2.2. The single or multiple causes of each critical issue are discussed within the third column, while in the last one its effects are reported.

**Table 6.** Critical issues of SECs arising from the literature analysis.

| Category of Analysis | Emerging Criticality | Causes | Effects |
|---|---|---|---|
| **Electric and thermal energy sharing within distributed energy systems** | (1) SECs are almost always based on the exploitation of solar energy. | (1) PV systems are affordable and easy-to-install, thus resulting optimum tools for boosting the renewable electricity sharing expected by the REDII. | (1) New SECs projects usually fail to make full use of local available RESs. Therefore, even the positive outcomes deriving from the development of local RESs-based energy systems are not fully achieved. |
| | (2) Only a few simulations or case studies analyse the exploitation of “programmable” RESs. | (2) All RESs are equally incentivized by the REDII. | (2) The positive environmental, economic and social outcomes deriving from the exploitation of local available “programmable” RESs, in addition to the valuable potential of counteracting “non-programmable” RESs’ uncertainty, are inevitably discarded. |
| | (3) The thermal load sharing results to be very rare. | (3) The electric grid is public and already existent, extended and branched. | (3) The creation of multi-vector energy systems is hindered, as well as the adoption of more efficient energy conversion devices for supplying multi-users’ thermal energy demand. |
| **Energy storage system adoption** | Within the SECs, the most diffused ESSs are electric. | The REDII national transposition in many countries focuses on the sharing of renewable electricity. | On the one hand, the adoption of reliable and affordable thermal ESSs to increase the SS and the SC of SECs is not properly promoted. On the other, the creation of a multi-vector energy system is further discouraged. |
| **IoT and DSM applications in community management programs** | The actual modernisation of SECs’ projects progresses more slowly than the technological advancement. | IoT and ICT devices are expensive. This issue is unavoidably more pronounced in poor and developing countries. | The development of community-based energy systems is further challenged by difficulties related to the management and the design of new SECs’ projects, especially in poor countries, where further issues related to the lack of proper technical skills exist. Moreover, the high costs of IoT and ICT devices may further reduce the social acceptability of new SECs projects. |

Regarding the category of electric and thermal energy sharing within RESs-based DESs, recalled in Table 6, it results from the literature review that SECs usually rely on the exploitation of solar energy. PV systems’ high affordability [102] and easiness to install are two of the main reasons of the lack of references dealing with RESs different from solar, excluding [49,74], which deal with the exploitation of wind energy and the geothermal source, respectively. Table 6 shows that only a few of the reviewed papers consider the exploitation of local available “programmable” RESs. In addition, the use of geothermal energy for direct thermal scopes such as Ischia and Japan examples is rarely considered [74,103]. Therefore, several economic and social benefits are discarded, as well as the environmental redevelopment of abandoned areas consequent to the provision of “programmable” RESs such as biomass or zootechnical waste. Nevertheless, the exploitation of “programmable” RESs may significantly counteract the uncertainty of “non-programmable” ones, which is one of the main challenges to the practical implementation of SECs' projects [104]. At the same time, very few papers (six among the reviewed ones) deal with thermal load sharing. This outcome reflects the fact that national transpositions of the REDII often provide incentives only for the electric energy sharing. In addition, as shown in the last row of Table 6, the modernisation of SECs' project consequent to the adoption of IoT and ICT devices is hindered partly by users' poor knowledge and information, partly because of the extra costs destined to them [105]. These issues are inevitably more pronounced in rural areas inhabited by low-income households, where bureaucratic and cultural questions interfere with the spreading of SECs by hiding their many merits. Such reasons of unacceptability reflect in the unreadiness of poor and developing countries to properly manage and design new SECs projects. In addition, several other issues and challenges for SECs diffusion exist in rural and poor areas such as Sub-Saharan Africa: still-existing top-down approaches, poor technical know-how, bureaucratic organization structures, unsupportive policy frameworks, lack of community engagement and governments' reluctance to liberalize the energy market, a key issue for empowering SECs [72]. Other main barriers to SECs diffusion emerging from the literature analysis concern the following:

- The self-selection of SEC's member, because of their poor technical expertise;
- The cooperation between the self-selected members;
- The lack of clarity about the type of organization required, which traduces into a serious misalignment between the EU Directives and the actions performed on national basis;
- The issues regarding physical and virtual SC;
- The loads' complementarity.

Based on these findings, it may be interesting to provide possible resolutions to the critical points highlighted by the literature analysis.

### 3.2. Future Challenges and Perspectives

In Table 7, the criticalities identified with regard to the state of the art of SECs are listed, together with the future perspectives expected to be developed in order to solve them. The categorization adopted follows the structure of the paper and recalls the paragraphs identified in the Section 2.3 about the aims of SECs: the first row refers to the energy, environmental and technical aims, the second one to the economic aims and the third one to the social aims.

**Table 7.** Comparison between the current criticalities and the future perspectives of SECs.

| Category of Analysis | Current Criticalities | Future Perspectives |
|---|---|---|
| **Energy, environmental and technical aims** | (1) Prevalence of PV-based projects.<br>(2) Prevalence of electric energy sharing.<br>(3) Prevailing cooperation of single user types for the energy sharing.<br>(4) Rare adoption of ESSs other thanelectric ones. | (1) Increasing projects based on hybrid systems.<br>(2) Increasing multi-vector energy sharing.<br>(3) Increasing cooperation of multi-user types for the energy sharing.<br>(4) Increasing adoption of diversified types of ESSs. |
| **Economic aims** | In many countries, the REDII national transposition incentivises only the electric energy sharing. | Increasing incentivization of thermal energy sharing by using "programmable" RESs. |
| **Social aims** | Improper and insufficient acknowledgement of social benefits. | Adequate and increasing emphasis on social benefits. |

Despite the use of solar energy, and thus the diffusion of PV-based projects of SECs, leads to a significative reduction in GHG emissions [106], it would be much more convenient to integrate into SECs projects other generation systems to increase both the efficiency of the energy system and consumers' benefits [107]. As already stated in Tables 6 and 7, nowadays, the projects of SECs are mainly focused on the exploitation of solar energy. Instead, the general intent should be to choose the RES to be exploited in the SEC by considering the "generation" of renewable energy bound to the context in which it takes place and taking advantage of the resources locally available for stimulating the local economy. The attention paid to local needs would increase the social acceptability of RES-based plants, and in this way, whenever viable, it would be also possible to promote the exploitation of "programmable" RESs and the sharing of thermal energy. The combined exploitation of different RESs in a hybrid system would ensure the most complete load coverage, as it would counteract the uncertainty characterising "non-programmable" RESs. Nevertheless, another factor essential to increase the exploitation of such RESs, which is not very frequent in the literature, is the combination of multi-utilities' load profiles. In fact, the analysed papers mostly refer to SECs including one user type. Instead, the combination of multi-users belonging to different sectors and characterised by complementary load curves, would not only improve PV systems' profitability [108], but also maximize the renewable energy SC. The increasing energy SC would traduce in greater benefits both from the economic and the environmental point of view, as it would reduce the purchase of electricity from the grid and thus mitigate the GHG emissions related to non-renewable-based energy generation systems. In addition, the increased SC would maximize the economic gains due to the sharing of energy. Yet, in many countries, the national law provides economic incentives only for the electric energy sharing. Hence, the diffusion of district heating networks to meet the thermal energy demand of users belonging both to the buildings and the industrial sector is insufficiently promoted. Again, from the literature analysis, the sensitivity to the context emerges to be essential in developing adequate government instruments to support the achievement of local energy [109], social and economic benefits [109,110], but also to deal with SECs' main barriers, shortcomings and challenges which are indeed political, informational, and socio-cultural [107]. A strategic approach must be adopted to globally increase SECs' social acceptability and the interest of common people in their development. For instance, to the best of the authors' knowledge, there is a lack of rewards for SECs that employ the "programmable" RESs locally available and which, in turn, do not recognize the potential role of SECs in reducing the energy dependence and in promoting both the energy and social redevelopment. In this regard, when dealing with the SEC concept, in addition to the energy, environmental and economic analysis, it would be interesting to broaden the field of research including users' willingness of entrusting their energy choices to the community they will join. None of the reviewed papers introduce social indicators for evaluating SECs' positive outcomes, despite the many social benefits which could follow from their implementation. A strategic solution could be the use of social indexes coming from economic fields of research. For instance, the Social Return On Investment (SROI) index could be adopted since, as far as the authors know, it has never been used for the evaluation of SECs' projects. This index measures the outcomes of a changing according to the priorities of both people and organizations who experience it, and it is usually used by non-profit or social economy belonging organizations, private companies, donor and investors and public administrations [111]. In the case of SECs, the SROI index could borrow from the usual fields of application the ability of:

- Quantifying and maximizing the social value of the actions performed;
- Identifying adequate resources for not expected and both positive and negative outcomes;
- Proving the importance of being part of the group which creates the changing;
- Establishing a dialogue between the activity participants, thus giving them responsibilities, and involving them in the project design phase.

In conclusion, a local-oriented approach must be adopted when dealing with SECs, which must be able to consider all the peculiarities which differentiate the potential of SECs according to the context. In doing so, greater attention must be paid to the social aspects.

## 4. Conclusions

This review paper aims at describing the state of the art of Smart Energy Communities. The references selection has been carried out through the "Preferred Reporting Items for Systematic reviews and Meta-Analysis" methodology. The review has been organized to give a two-fold characterization of Smart Energy Communities. On the one hand, their main features and common characteristics have been defined. On the other, a comprehensive description of their principal purposes has been given by using a literature investigation of simulations and real case studies. In addition, the principal indexes used in the literature for their evaluation have been presented. It results that Smart Energy Communities have been introduced in the European regulatory framework by the Renewable Energy Directive and the Internal Electricity Market Directive. As innovative and decentralised organizations, their main goal is to encourage the spreading of renewable energy plants to supply the electric and thermal loads of the civil sector through the implementation of sharing economy principles. In most of the papers reviewed, Smart Energy Communities rely on the exploitation of photovoltaic energy, in part because of the interest paid by the recast of the Renewable Energy Directive on renewable electricity generation, and in part thanks to the easiness to install and the affordability characterizing photovoltaic systems. As a consequence of energy system's decentralization, innovative technologies and devices included in the fields of Information and Communication Technologies and Internet of Things have become essential to increase both energy systems flexibility, for example through the implementation of demand-side management programs, and energy supply security. In this regard, the adoption of energy storage systems emerges also useful. The combination of these factors allows the deployment of several energy, technical, environmental, economic and social goals, spanning from the decarbonization of the energy system to the reduction in the costs of energy until the energy democratization. These benefits are particularly significative when dealing with energy islands or rural areas inhabited by low-income households, characterised by critical issues in accessing energy. Nevertheless, the positive outcomes arising could still be hindered by policy, informational and technical barriers. Therefore, two main actions appear to be essential in the development of Smart Energy Communities. Primarily, it appears fundamental to develop projects well focused on the peculiarities of the site in which the community will be established. The adoption of such an approach would mean, for example, an increase in the exploitation of "programmable" renewable energy sources and a broadening of the application of thermal load sharing. In turn, this approach would maximize the positive local benefits arising from the community itself, especially from the economic and social point of view. Indeed, the second still open issue concerns the weak emphasis placed on the achievement of the set goals among community participants, which does not mitigate the social scepticism sometimes characterizing both the installation of renewable plants and the implementation of Smart Energy Communities. According to the results of the review analysis, the literature appears to be focused on the use of energy, environmental and economic indicators when evaluating the realization of such projects. Instead, conscious about all the positive outcomes that Smart Energy Communities are expected to realize from the social standpoint, it would be interesting to develop novel indicators or to borrow already existent ones from other fields of research for their measurement. Therefore, in future works, innovative indexes for the evaluation of the social advantages of Smart Energy Communities will be proposed. In addition, according to the critical issues emerged in this study, novel real and/or simulated case studies of Smart Energy Communities exploiting in major part "programmable" renewable energy sources, implementing the thermal load sharing and using different types of energy storage systems will be discussed.

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## Nomenclature

| | |
|---|---|
| *Abbreviations* | |
| $CO_{2consm}$ | Carbon dioxide intensity ($kgCO_2$/kWh) |
| $E_{pot}$ | Energy Potency (-) |
| $E_{SS}$ | Energy Self-Sufficiency (-) |
| KPI | Key performance index (-) |
| $LCOE_{consum}$ | Levelized Cost Of Energy Consumed (EUR/kWh) |
| SC | Self-consumption (-) |
| SS | Self-sufficiency (-) |
| *Acronyms* | |
| CES | Community energy storage |
| CHP | Cogenerator |
| DES | Distributed energy system |
| DSM | Demand-side management |
| ESS | Energy storage system |
| EU | European Union |
| EV | Electric vehicle |
| GHG | Greenhouse gas emissions |
| HP | Heat pump |
| IEA | International Energy Agency |
| ICT | Information and Communication Technologies |
| IEMD | Internal Electricity Market Directive |
| IoT | Internet of Things |
| Li-ion | Lithium-ion |
| PRISMA | Preferred Reporting Items for Systematic reviews and Meta-Analysis |
| PV | Photovoltaic |
| REDII | Renewable Energy Directive |
| RES | Renewable energy source |
| SEC | Smart Energy Community |
| SROI | Social Return On Investment |

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