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Thermal Energy Storage in Energy Communities: A Perspective Overview through a Bibliometric Analysis

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Abstract: The climate and energy crisis requires immediate countermeasures. Renewable energy communities (RECs) are capable of enhancing the consumption of renewable energy, involving citizens with a leading role in the energy transition process. The main objective of a REC is to maximize the consumption of renewable energy by reducing the mismatch between energy supply and demand. This is possible through the use of strategies and technologies including energy storage systems. Among these, the use of thermal energy storage (TES) is an efficient strategy due to the lower investment required compared to other storage technologies, like electric batteries. This study aims to define the role of TES in RECs, through a bibliometric analysis, in order to highlight research trends and possible gaps. This study shows that the existing literature on TES does not present terms related to RECs, thus presenting a research gap. On the other hand, RESs address the topic of energy storage in the literature, without focusing on TES in particular but considering the general aspect of the topic. Therefore, this leaves open a possibility for the development of research on TES as a possible technology applied to a REC to maximize the renewable energy sharing.

Keywords: renewable energy community; thermal energy storage (TES); bibliometric analysis

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1. Introduction

Year after year, the climate crisis represents an increasingly concrete threat against which it is now urgent to take countermeasures. In the stocktaking at the last UN Climate Change Conference (COP 28), the goal of peaking global greenhouse gas emissions by 2025 and reducing them by 43% by 2030 and 60% by 2035 compared to 2019 levels in order to limit global warming to 1.5 °C was confirmed [1].

In the context of climate change mitigation, energy is one of the sectors where emission reductions can have the greatest short-term effects. This is why there is an increasing need for a transition to renewable energy sources and a consequent shift away from fossil fuels.

The European Union manifested this objective in recent years through the "Clean Energy Package" [2] and the "Fit for 55" [3], measures promoted by the European Commission that set a perspective of climate neutrality from fossil fuels from 2050 onwards. The Clean Energy Package focus aims to transform the economy and society according to a new sustainability paradigm, in which citizens should be encouraged to actively participate in the energy market, even in aggregated forms, to foster their empowerment and make them responsible for their consumption. To achieve this objective, consumers should be able to directly manage their energy.

In this context, renewable energy communities (RECs) [4] represent a social innovation capable of advancing more equitable models for managing, consuming, and producing energy, enhancing democratic decision-making and control over renewable energy, and placing it in the hands of communities and individuals. This citizens' empowerment further contributes to increasing social acceptance of renewable energy generation plants thanks to the underlying participatory approaches that provide citizens an active role in the decision-making process [5].

Introduced by the European Renewable Energy Directive (RED II), RECs are autonomous legal entities, in which the members and stakeholders controlling it can participate openly and voluntarily, staying close to renewable energy production plants. This participation must not generate financial gains, but can give economic, social, environmental, and energy benefits. Members of an energy community can be classified into energy producers, energy consumers, and energy prosumers, i.e., producers of energy that self-consume on site. The main objective of a REC is to maximize the sharing of energy produced through renewable energy sources (RESs) in a collective self-consumption scheme [6]. However, the use of RESs entails the usual problem of solving the time mismatch between production and user demand for energy.

In this context, the so-called power-to-X strategies [7] consist of energy carrier conversions in order to efficiently use the available energy storage technologies. Power-to-heat [8] is an example of a strategy for which thermal energy storage (TES) systems play an important role. With the use of a heat pump, it is possible to convert electrical energy into a heat carrier, storing it to meet the heat demand of a utility. In these systems, TES [9] consisting of hot water tanks is a simple and economical solution for storing excess renewable energy [10].

This can be a way of increasing the sharing of renewable energy within a REC. In fact, the use of TES allows for storing the excess electrical energy produced by the plants of the producers that are part of the REC. Thus, the use of energy from renewable sources is guaranteed to the different consumers of the REC, not only in the periods of electrical energy demand peaks, but also in the thermal energy demand peaks.

This solution proves to be more sustainable than the installation of an electric storage battery. This is evidenced by Fambri et al. [11], who in their study compare the use of an electric battery and a heat pump thermal energy storage system in a REC.

However, the use of TES also has additional benefits. For example, it can decrease the thermal energy demand of buildings; counteract the randomness of renewable energy production, both thermal and electrical; and constitute a source of heat recovery [12].

Furthermore, in a larger field than the individual building, e.g., in the case of districts [13–15], more relatable to a REC, they can foster the diffusion, development, and flexibility of district heating and cooling systems powered by renewables, providing thermal energy to all consumers in them.

This study shows that although there is an energy saving from increased self-consumption of renewables through electrical storage, the economic benefit is not such as to justify the investment. On the other hand, the use of TES, despite having lower results in terms of energy savings, proves to be more cost-effective. The use of TES in a REC is also taken up in other works as a strategy to utilize surplus energy [16–18].

The aim of this paper is to give a detailed overview and report on the state of the art in the role and involvement of TES within RECs. Thus, a bibliometric analysis, which is a recognized technique of interest used in order to study scientific advances in a given topic, is carried out. A quantitative analysis is conducted regarding the number of publications, authors, and institutions researching this topic.

The results show that studies about the integration of TES to RECs, two very recent topics that have grown considerably in recent years, are still only marginal, as evidenced by the small number of papers about it.

Furthermore, to the best of the authors' knowledge, there are still no papers in the literature that fill this gap, nor are there any that do so through the bibliometric analysis approach.

The objective of this study is also to provide a guide for researchers wishing to investigate the main networks and institutions working in the field of TES as a tool for sharing renewable energy within RECs, and to use the main research gaps identified to inspire future research on this topic, filling this deficit.

This research can also be for industries, public administrations, and private citizens who intend to become part of a REC, seeking to deepen their understanding of TES as a tool for sharing renewable energy surplus.

2. Materials and Methods

This section reports the methodology applied to develop the bibliometric analysis shown in the following sections. For this work, Scopus was preferred as the reference database. Web of Science was not considered due to its low number of documents on technology topics [19], while ResearchGate and Google Scholar were also not considered due to their low reliability in the bibliometric field [20]. In order to identify research trends and gaps in the application of TES in energy communities, bibliometric data were collected using two queries (Table 1) on the database Scopus, with the last access on 12 January 2024. A first query was used to collect bibliometric data related to the studies on TES in buildings including districts [21]. Compared to the work by Borri et al. [17], the query used in this study includes both buildings and districts, whereas previously, these categories were analyzed separately. In addition, the category "roads and bridges" is not considered here. Moreover, in this case, the transport sector was excluded in the query. The analysis of TES was carried out regarding its application to buildings and districts, in order to consider not only the dimension of the individual building but also a broader one, as a community.

Table 1. Queries used for the Scopus database.

Topic	Query
TES in buildings and districts	TITLE-ABS-KEY ("thermal energy storage*" AND ("building*" OR "built environment" OR "district*" OR "municipal*" OR "neighbo$rhood") AND NOT ("aircraft" OR "transport* application" OR "transport sector"))
Renewable energy communities	"energy communit*" AND "renewable*" AND NOT ("renewable energy forecasting" OR "building energy community" OR "energy corridors" OR " solar renewable energy community" OR "NGH" OR "Cu2Se"OR "SDG 7"OR "computational intelligence (CI) community" OR "MEG" OR "nuclear" OR "materials, chemistry, and renewable energy communities")

A second, more specific query, was then formulated to draw the state of the art in TES, specifically in energy communities. The concept of "energy community" was combined with the aspect of "renewable" sources. This is because renewable energy communities are often referred to simply as "energy communities". However, the term "renewable" is added, as sometimes the term "energy community" may refer to a broader and diversified concept of community, understood as a group of researchers and scientists in the specific field of energy, which is different from the concept intended in this paper. Therefore, the query excludes the keywords "building energy community", "solar renewable energy community", "computational intelligence (CI) community", "materials, chemistry, and renewable energy communities", and "energy corridors". Similarly, terms such as "nuclear", "MEG", "NGH", "Cu2Se", and "SDG 7" were excluded, as they are related to papers not relevant to the research in question.

In this study, bibliometric data were used to identify the main trends in the number of publications. In order to identify the research gaps, keywords were visually mapped and analyzed through the open-source software VOSviewer (version 1.6.20) [22]. Through the latter, it is possible to graphically visualize and analyze bibliometric networks based on the links between different items of the research publication. These links can be about co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation. The elements available for generating maps from publications include authors, institutions, countries, and keywords. The practicality of these analyses conducted with VOSviewer is that the output data can be easily exported and displayed in other resources [23].

Furthermore, the great advantage of VOSviewer is that through its ease of use and accessibility, it enables accurate bibliometric analyses using clusters even for those without extensive knowledge of clustering or software skills [24].

For this reason, VOSviewer is considered a validated tool for investigating gaps and research opportunities in the scientific literature. In particular, it is interesting to see how this software is already used to support bibliometric analysis within studies concerning energy storage [25–28], and also those concerning prosumers and energy communities [29–32].

In this paper, the findings regarding the co-occurrence of author keywords are presented through a network visualization. Each element (author keyword) is represented by a colored circle, with its size reflecting its weight in terms of occurrences or link strength. The colors denote the clusters to which different elements belong, and the distance between circles indicates the relationship between the items. Finally, the two indicated queries were merged within VOSviewer and analyzed together in order to highlight possible points of contact between the two topics and possible research gaps.

3. Results and Discussion

3.1. TES in Buildings and Districts

This section reports the results of the bibliometric analysis carried out with the methodology described in Section 2. Figure 1 shows the number of documents published in the field of TES applied to buildings and districts. The trend indicates a rapid increase in the number of publications per year since 2009, with over 500 publications in the year 2023. This demonstrates that TES is gaining momentum in built environment applications, becoming a pivotal component of the energy transition.

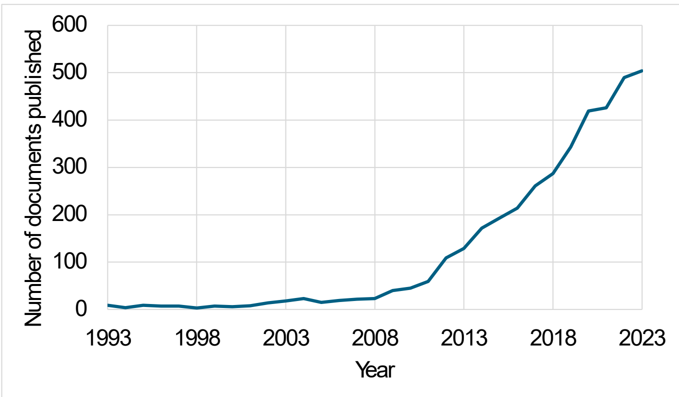


Figure 1. Number of documents published per year in thermal energy storage.

Figure 2 illustrates the publication trend over the years for the leading territories that have published papers on TES for building and district applications. As already illustrated by Borri et al. [17], the data reveal that the United States (USA) began publishing documents related to TES before 1990, whereas Europe and China commenced their publications after 2008. In the USA, most cited publications are focused on phase change materials (PCMs) [33–35], optimizing the control of TES [36,37], and the use of TES in district heating and cooling systems [38].

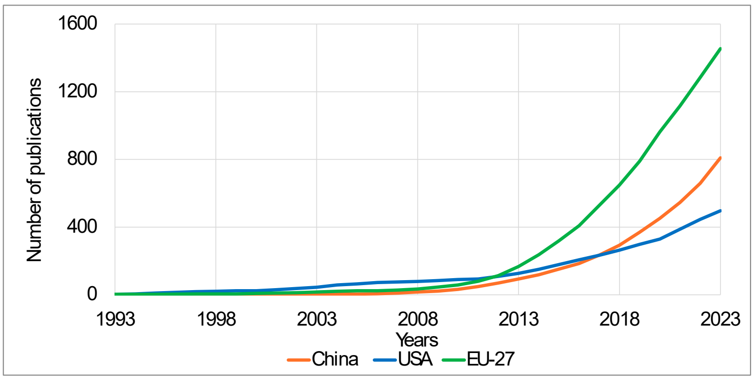


Figure 2. Number of publications over the years on TES in buildings and districts for the top 3 territories between 1993 and 2023.

Research on this topic in Europe has increased rapidly as a result of directives about the energy performance of buildings and energy efficiency introduced by the European Union [39,40]. The most cited papers from Europe on Scopus predominantly consist of review articles focusing on PCMs in buildings [41–44].

In addition to these, within the same scope lies the most cited article, published by Cabeza et al. [45] in 2011, which constitutes a review on the use of this technology, classification of materials, materials available, and problems and possible solutions on the application of such materials in buildings. Additional highly cited documents include general reviews on TES and the materials used in their application [9,46].

From Figure 2, it can be observed that China follows a similar trend to that of the European Union, albeit with a lower number of publications. This is because, like Europe, China has implemented a substantial plan to reduce emissions from fossil fuels by 2030 compared to those in 2005 [47].

Among the most cited articles in this field, there are general reviews on TES [48] and the application of latent heat thermal energy storage [49]. Additionally, numerous reviews regarding the study and use of PCMs [50–53] are available on Scopus. The most cited paper concerns precisely this topic and was published in 2012 by Zhou et al. [54]. In Figure 3, the main European countries publishing documents regarding the application of TES in the context of buildings and districts are shown.

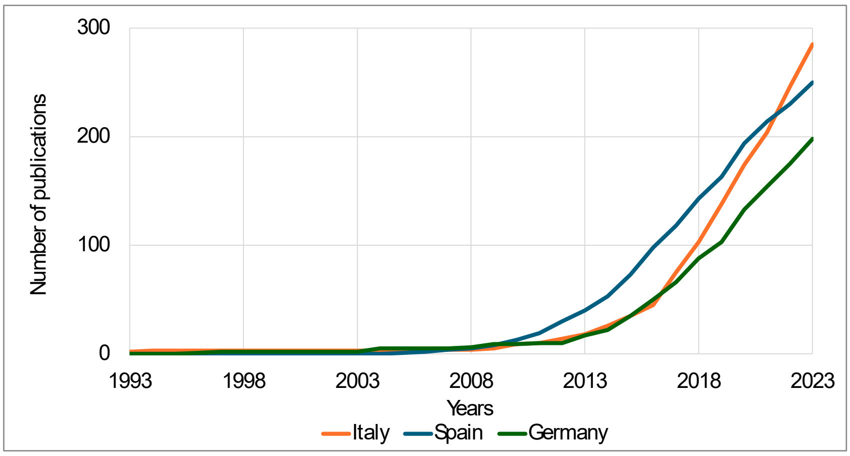


Figure 3. Number of publications over the years on TES in buildings and districts for the top EU27 countries between 1993 and 2023.

It is possible to notice that Spain, Italy, and Germany have a similar trend of publications that started to rapidly increase after 2010. As of 2023, Italy is the country with the highest number of publications, among which the most cited ones focus on energy management strategies [55–57], cogeneration [58,59], district heating and cooling systems [60], and the use of thermal energy storage techniques in thermal insulation [61]. The second country with the highest number of publications is Spain, whose studies focus PCMs [62,63] and the application of TES in the domain of buildings [64,65].

Finally, the third country with the highest number of publications is Germany, which covers various topics including the application of TES to buildings to enhance their development [66,67], the study of PCMs [68,69], aquifer TES [70], TES for solar power plants [71,72], and district heating [73].

Figure 4 illustrates the journals with the most publications related to TES applied to buildings and districts. The best is *Energy and Buildings*, with 297 publications as of December 2023. It is interesting that the journal *Energies* appears in Figure 4, with 143 open-access publications. The most cited paper from this journal was published in 2020 by Enescu et al. [74]. The authors and the institutions with most publications on TES applied to buildings and districts are shown in Tables 2 and 3, respectively. The author with the most publications is Luisa F. Cabeza, affiliated with the "Universitat de Lleida", in Spain, with 121 publications as of December 2023. Her most cited article on TES applied to buildings and districts dates back to 2011 and it shows a review of the publications on the use of PCMs in buildings [45]. Some of his other most cited works concern the application of PCMs [75–78] and TES technologies integrated [79,80] to the field of buildings. This makes Universitat de Lleida the affiliation with the highest number of publications on this topic.

The second most published author is Ahmet Sari, affiliated with Karadeniz Technical University, Turkey, which is also among the affiliations with the highest number of publications on TES in buildings and districts. His most cited articles focus on the thermal properties of PCMs [81–84]. As China is the second most published territory, two Chinese affiliations are among those with the most published articles: the Ministry of Education of the People's Republic of China, and Tsinghua University.

Figure 5 shows the co-occurrence of keywords obtained through the software VOSviewer for the first query related to TES in buildings and districts. As stated in the methodology, the keywords belonging to the same topic were grouped to represent the macro-areas of research. In order to obtain the results displayed in the figure, the keywords were filtered with a minimum occurrence of 10. In the right part of the figure (green cluster), it is possible to notice that a lot of studies are related to the development and the improvement of storage materials, in particular PCMs. On the left side of the figure, it is possible to notice that the bigger cluster (red) is related to TES applications, including keywords such as "control", "optimization", "demand side management", "numerical model", and "district heating". The blue cluster is related to the applications of TES as a system in buildings, including keywords such as "heating", "cooling", "buildings", and "energy saving". The other main cluster (yellow) is related to methods to analyze improve the thermal parameters of storage materials.

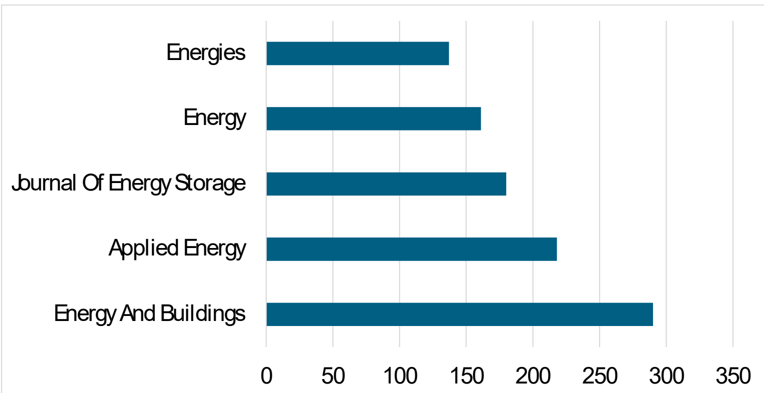


Figure 4. Top 5 journals publishing on TES applied to buildings and districts.

Table 2. Top 5 institutions with documents published on TES in buildings and districts.

Affiliation	Publication	Country
Universitat de Lleida	123	Spain
Ministry of Education of the People's Republic of China	108	China
Tsinghua University	71	China
Karadeniz Technical University	59	Turkey
King Fahd University of Petroleum and Minerals	58	Saudi Arabia

Table 3. Top 10 authors on documents published on TES in buildings and districts.

Author Name	# Publications	Affiliation	Country
Cabeza, L.F.	121	Universitat de Lleida	Spain
Sari, A.	84	Karadeniz Technical University	Saudi Arabia
Barreneche, C.	40	Universitat de Barcelona	Spain
Tyagi, V.V.	37	Shri Mata Vashini Devi University	India
Fernández, A.I.	34	Universitat de Barcelona	Spain
Hekimoğlu, G.	34	Karadeniz Technical University	Turkey
Kim, S.	33	Yonsei University	South Korea
de Gracia, A.	28	Universitat de Lleida	Spain
Gencel, O.	25	Bartin Üniversitesi	Turkey
Pisello, A.L.	25	Università degli Studi di Perugia	Italy

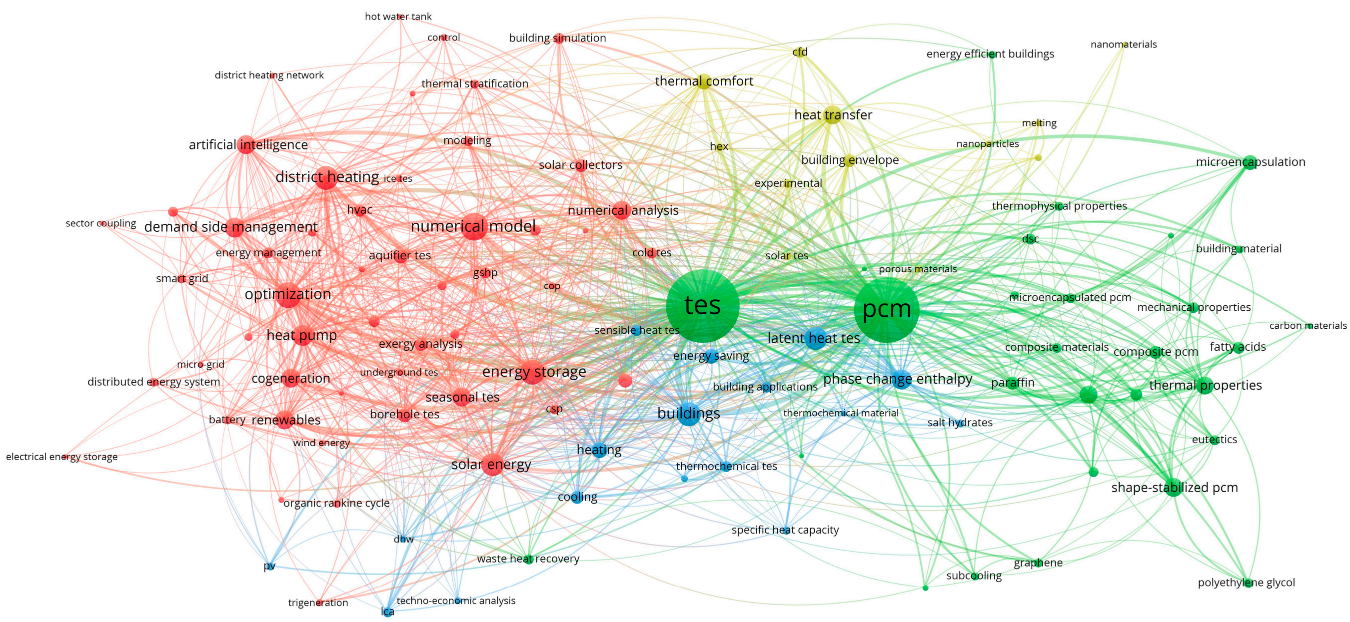


Figure 5. Network visualization of author keywords on "TES on buildings and districts" elaborated with VOSviewer.

Table 4 shows the author keywords with the highest number of occurrences on "TES on buildings and districts". While the keyword with the most occurrences is obviously "TES", it can be seen that the second is "PCM (phase change materials)". This is evidenced by the large number of articles that were published on this topic in different territories and countries. A further keyword with a high occurrence is "numerical model", due to the widespread use in the literature of numerical modelling techniques to simulate the behavior of TES, in particular PCMs [35,85–87].

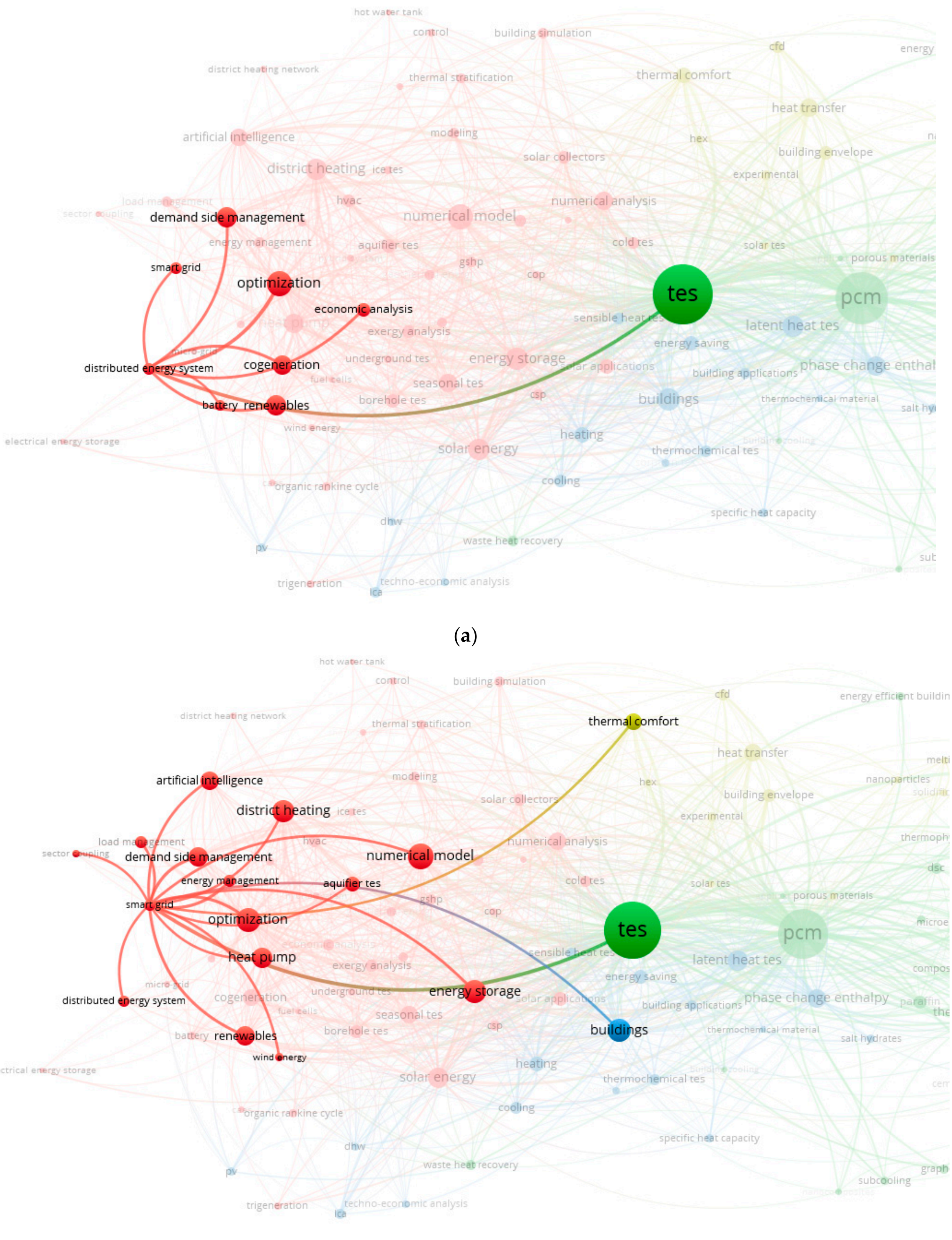
Table 4. Highest number of occurrences on "TES on buildings and districts".

Keyword	Number of Occurrences
TES (thermal energy storage)	1609
PCM (phase change material)	1257
numerical model	230
optimization	204
energy storage	184
district heating	168
latent heat TES	164
solar energy	155
heat pump	138
phase change enthalpy	124

The keyword "optimization" mainly refers to optimization studies for the integration of thermal storage in building systems, in order to reduce the mismatch between demand and supply of renewable energy and minimize costs [67,88–91]. The scope of the districts taken into consideration through the query is highlighted by the keyword "district heating". Among the most frequently cited articles with this keyword are applications of TES to combined heat and power (CHP) systems for district heating [15,92,93], review articles [38,60,94], and studies on the thermal inertia of buildings as thermal storage in district heating and cooling systems [95,96].

A research gap emerges from Figure 5. In fact, there are no terms or keywords related to RECs. However, there are keywords such as "distributed energy system", "smart grid", "micro-grid", and "sector coupling", which are related to a broader concept than the single building and can be approached as energy sharing. Indeed, these terms are related to a collective dimension of energy consumption and management, attributable to the concept of RECs. The keyword "distributed energy system" refers to a system based on small-scale installations distributed across the territory, in stark contrast to the traditional model of centrally produced power plants. It is precisely on this basis that the REC is built, aiming to facilitate the spread of renewable energies in the territory, meeting both environmental and community needs [97]. The concept of a "microgrid" is instead linked to energy communities through the themes of energy self-sufficiency and energy sharing. The members of an energy community are no longer seen as mere consumers, but become "prosumers", meaning they are energy producers who consume and are capable of exchanging energy with each other through "peer-to-peer" sharing mechanisms [98,99]. Furthermore, through energy efficiency systems and smart management energy systems, linked to the maximization of renewable energy sharing, "smart grids" become a fundamental tool for RECs [100–102]. Lastly, the possibility of having a highly integrated energy system, capable of maximizing the use of renewable energy produced either through storage [103] or across different consumption sectors [104,105], makes "sector coupling" a fundamental element in optimizing energy communities.

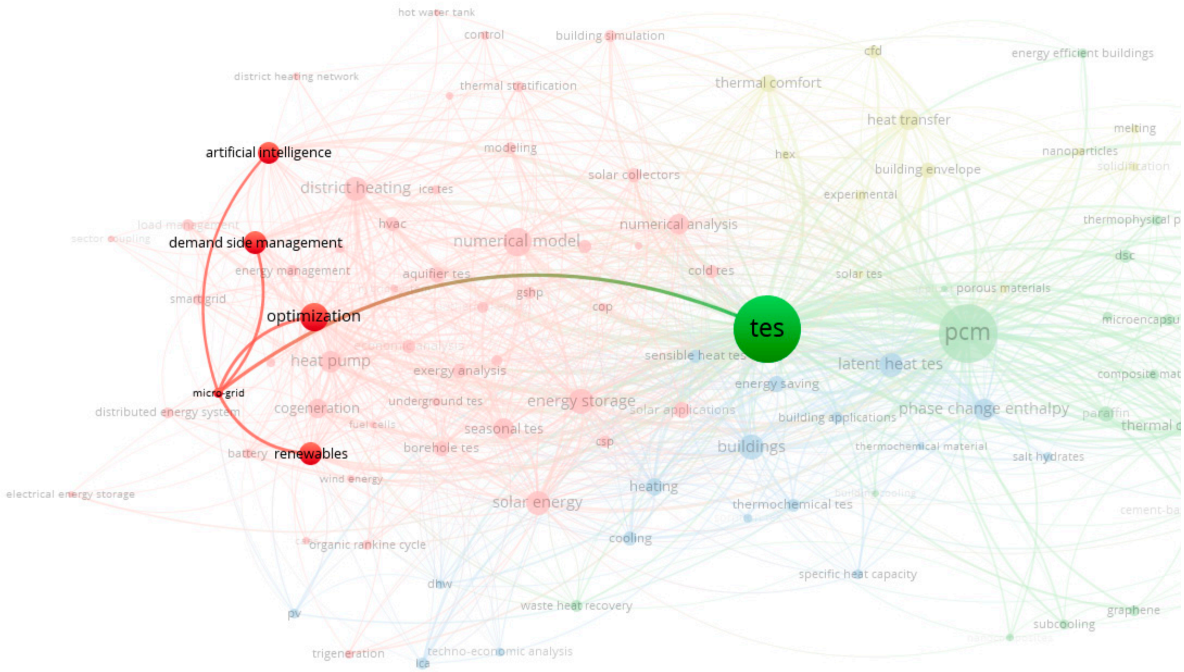
Figures 6 and 7 show the co-occurrence of these keywords and their links. The figures highlight, given the small number of links, the low relevance of these terms in the literature. Figure 6 shows the co-occurrence of the keyword "distributed energy system". The few links present all concern the red cluster, in the context of TES applications. The most cited paper on distributed energy systems applied in TES was published in 2020, from Wirtz et al. [73], and it is about a low-temperature network of buildings equipped with heat pumps, chillers, and heat exchangers for thermal energy storage, connected to minimize annual energy costs and to reduce emissions. This concept is very close to that of RECs and is also approached by other studies on this topic [106–108].



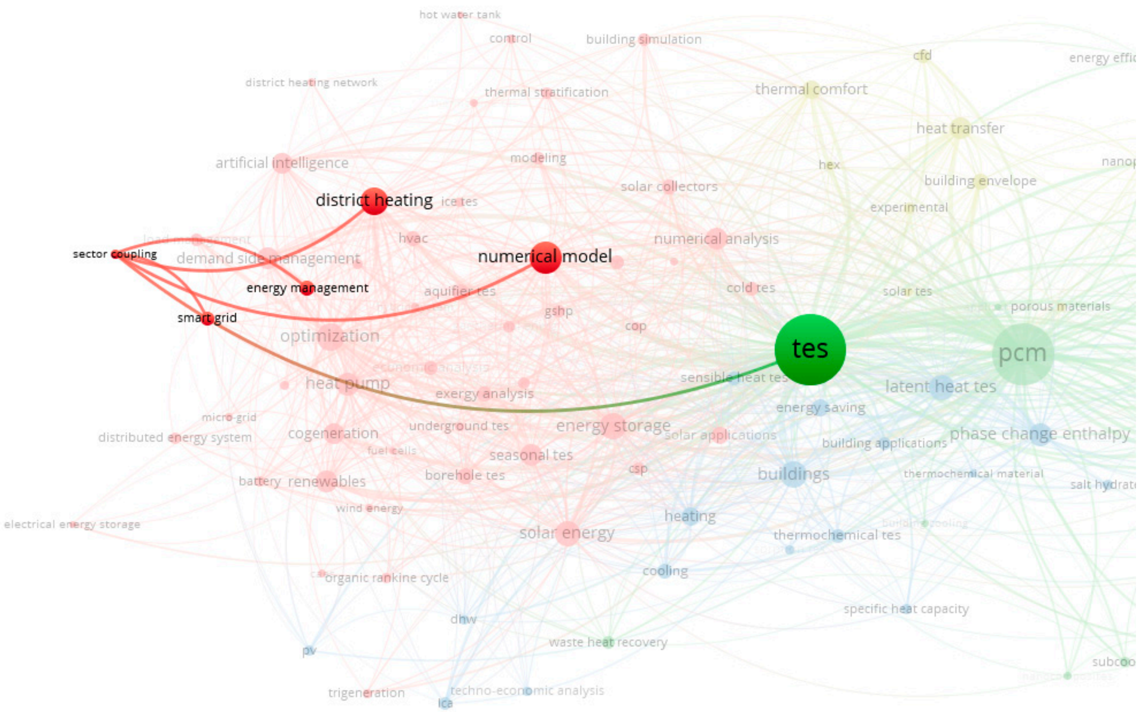
(**a**)

(**b**)

Figure 6. Co-occurrence and links concerning the keywords (**a**) "distributed energy system" and (**b**) "smart grid".



(**a**)



(**b**)

Figure 7. Co-occurrence and links regarding the keywords (**a**) "micro-grid", and (**b**) "sector coupling".

Figure 7 shows how microgrids and sector coupling have the lowest occurrences and thus represent research gaps in the applications of TES. In fact, the term microgrid has only four links besides TES: "demand side management", "artificial intelligence", "optimization", and "renewables". It is no coincidence that the main studies of TES on this topic concern optimal energy management models applied to microgrids [109–111]. Also, the term sector coupling has just four links besides TES, and they are "district heating", "energy management", "numerical model", and "smart grid". It is interesting to note that the most cited article related to this keyword in the context of TES, published by Bartolini et al. [112] in 2020, has as its subject the concept of an energy community based on a multi-energy system to which various storage technologies are applied.

The most cited article in the field of microgrids applied to TES dates back to 2021 and was published by Li et al. [113]. The most cited article on sector coupling applied to TES is by Zeyen et al. and it explores strategies to mitigate winter heating demand peaks in the European Union, crucial for cost and emissions reduction goals [114]. In the field of materials development, they are all related to the keyword "TES", while in the field of TES applications, they are related to terms such as "demand side management", "optimization", and "numerical model".

3.2. Renewable Energy Communities

The number of documents published related to renewable energy communities (RECs) is shown in Figure 8. The trend shows a steady and progressive increase in publications since 2018. This shows how the energy community is considered a key tool in the energy transition process.

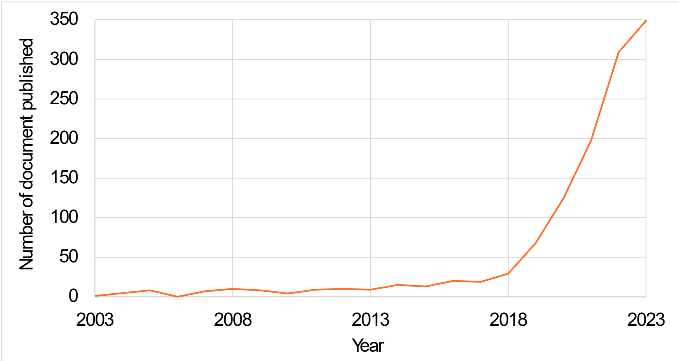


Figure 8. Number of publications per year in RECs.

Figure 9 illustrates the trend in publications for the main territories that have published on renewable energy communities (RECs). The trend shows that, compared to the United States and China, the European Union has significantly increased the number of publications on RECs since 2018. This increase is due to the European Parliament approval of Directive 2018/2001/EU (RED II) [115] and Directive 2019/944/EU (IEM) [116]. These directives are part of the Clean Energy Package [2], a collection of regulations adopted by the European Union in 2019 to decarbonize the European energy system. Through the RED II and IEM directives, the concept of an energy community was introduced in Europe as well as the concept of renewable energy sharing.

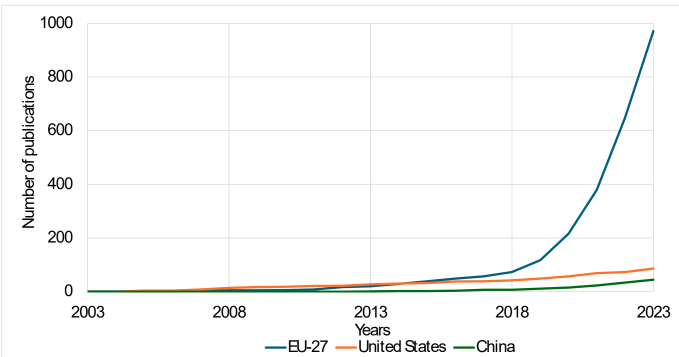


Figure 9. Number of publications over the years on RECs for the top 3 territories between 1993 and 2023.

The article with the highest number of citations in Europe was published by Lowitzsch et al. [117] in 2020 and contained a definition of the European regulatory context of the RED II and IEM directives, providing a preliminary practical interpretation while awaiting implementation by the member states of the European Union. Furthermore, the most cited papers focus on the innovations brought about by energy communities as a tool for transitioning towards renewable energies, from regulatory [118], economic [119], as well as environmental and social perspectives [120–123].

Despite significantly fewer publications, United States ranks second in terms of the highest number of citations. In the USA, there is a notable focus on research concerning net zero energy communities [98,124–126], where the primary goal is achieving zero emissions from fossil fuel combustion. Furthermore, several studies address the application in energy communities of optimization strategies [127,128] and of battery storage systems [98,129] for these communities. Regarding this topic, the most cited paper in the USA was published by Barbour et al. in 2018 [130].

Finally, China has started showing interest in RECs quite recently, since 2016, as seen in Figure 9. The most cited article is from 2020, authored by Feng et al. [127], and evaluates a coalitional game model to manage an energy community. The majority of the most cited articles in China also focus on net zero energy communities [131–135].

Figure 10 shows the main European countries by the number of publications between 1993 and 2023. Among these, Italy is the country that has increased its number of publications on this topic the most in recent years. In the figure, there is a noticeable positive deviation in the trend starting from 2018 and a further one starting from 2021. These two dates correspond to the implementation of the RED II and IEM directives in Italian legislation. In 2018, there was an early implementation through Law 8/2020 [136], while in 2021, there was the final implementation through Legislative Decree 199/2021 [137], which defined the characteristics of RECs in terms of energy and economics by establishing a shared energy incentive system [138].

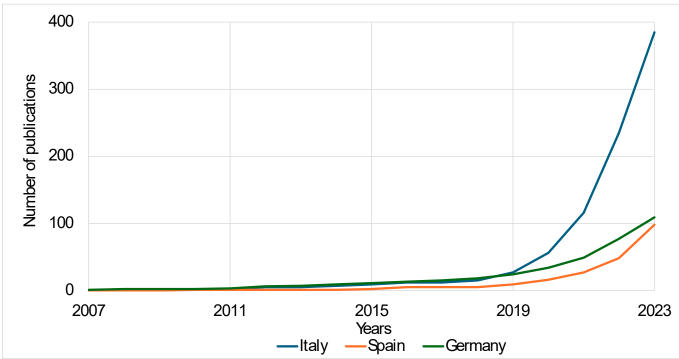


Figure 10. Number of publications during the year in RECs for the top 3 EU27 countries between 1993 and 2023.

The implementation of these directives in Italian legislation has provided a boost to research and development in energy communities as a new tool for energy management. The most cited Italian article is by Moroni et al. [139], dating back to 2019, and represents an introduction to energy communities through a taxonomic approach, attempting to explain what they are and their importance in the energy transition. Additional highly cited articles focus on the application of battery energy storage to RECs [112,129], smart energy systems in so-called "smart energy communities" [140,141], and the definition of optimization models for RECs [142,143].

In comparison to Italy, as can also be seen from Figure 10, in Germany, energy communities have represented a minor element of novelty, because they have already been established since the early 2000s in the German energy system, as "energy cooperatives" [144]. Furthermore, already in 2017, the Renewable Energy Sources Act 2017

(EEG) [145] defined self-supply and introduced the definition of an "energy community" into German legislation.

The most cited paper in Germany about RECs is from Lowitzsh et al. [117] and introduces the novelties of the Clean Energy Package in the European energy scenario. Further articles among the most cited focus on the importance of the new European directives [118,146]. In addition, as evidence of the established presence of energy communities in the German system, among the most cited articles is one by Schweizer-Ries et al. [147], dating back to 2008, which investigates the social dimension of the acceptability of renewable energies in the territory.

Spain represents the third European country in terms of the number of citations on the topic of energy communities. In 2019, Royal Decree 244/2019 [148] of April 5 established a legal definition of self-consumption and allowed for shared or collective self-consumption, both in the internal network and in nearby installations over the network. Indeed, Figure 10 shows an increase in the publication trend starting from 2019. The most cited article on energy communities in Spain was published in 2019 by Lezama et al. [119] and deals with the role of energy communities in local markets and how local markets can facilitate energy trading, thereby increasing the tolerable penetration of renewable resources and facilitating the energy transition. Among the most cited articles, there are also definitions of optimal REC models [149–151], as well as an analysis of sustainable energy communities, in a comparative analysis between Spain and Germany [151].

Figure 11 shows the main journals containing publications related to RECs. In this case, the top journal is *Energies*, with a total number of 124 publications updated to December 2023, all in open-access form. The authors and the institutions with the most publications on REC are shown in Tables 5 and 6, respectively. Looking at Table 5, one can see that among the affiliations with the highest number of publications on RECs, the top three positions are occupied by Italian universities. This is mainly due to the recent transposition of European directives and the introduction of the REC as a model in the Italian energy system. For this reason, several studies have been published in recent years to illustrate what a REC is and what its benefits are, introducing reproducible models and case studies in the national energy context [139,142,152–154].

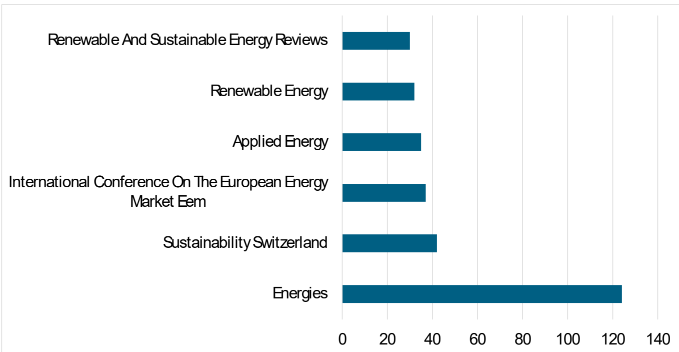


Figure 11. Top 5 journals publishing on RECs.

Table 5. Top 5 institutions with documents published on RECs.

Affiliation	Publications	Country
Politecnico di Torino	47	Italy
Sapienza Università di Roma	46	Italy
Politecnico di Milano	27	Italy
Delft University of Technology	26	The Netherlands
Technische Universität Wien	26	Austria

Table 6. Top 10 authors with documents published on RECs.

Author Name	# Publications	Affiliation	Country
Vale, Z.	20	Instituto Politécnico do Porto	Portugal
Ghiani, E.	16	Università degli Studi di Cagliari	Italy
Martirano, L.	15	Sapienza University of Rome	Italy
Menniti, D.	12	Università della Calabria	Italy
Pinnarelli, A.	12	Università della Calabria	Italy

Furthermore, the Politecnico di Torino university supported the research activity that led to the creation of the first energy community in Italy [155,156], in Magliano Alpi, in the province of Cuneo. It is interesting to note that Delft University of Technology is among the affiliations with the highest number of publications. The Netherlands, in contrast to Italy, is a pioneer state on the subject of RECs, having already introduced them into its legislation in 1998 and counting over 500 projects in the country [157]. The most cited article from that university was published in 2018 by Koirala et al. [122] and emphasizes the importance of citizen involvement in order to create a low-carbon community.

Figure 12 shows the co-occurrence of keywords obtained through the software VOSviewer for the second query related to RECs. The results shown in the figure were obtained by filtering the keywords with a minimum occurrence of 7. From the figure, it can be observed that the keyword “energy community” is linked to various types of energy-sharing schemes. Indeed, there are connections with terms such as “renewable energy communities” and “citizen energy community” (green cluster), types introduced in Europe through the RED II and IEM directives of the Clean Energy Package [118,158], as well as local energy communities (yellow cluster), understood as energy communities where citizens are extensively involved in local renewable energy system projects [158]. Table 7 shows the author keywords with the highest number of occurrences on “renewable energy communities”.

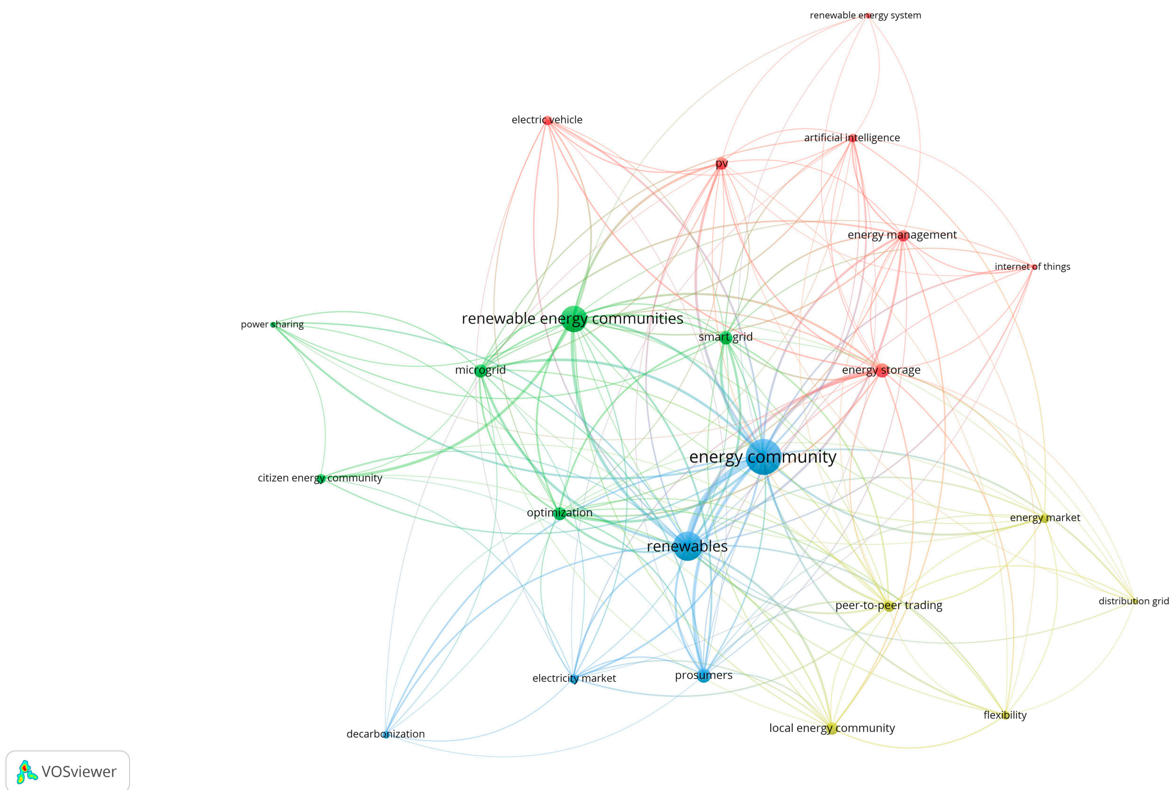


Figure 12. Co-occurrence of keywords related to RECs.

Table 7. Author keywords with the highest number of occurrences on "renewable energy communities".

Keyword	Number of Occurrences
energy community	401
renewables	258
renewable energy communities	219
energy storage	63
prosumers	62
smart grid	58
microgrid	57
optimization	55
energy management	43

Among the various items related to RECs, there is no specific reference to TES, but only the general term "energy storage" is mentioned. The subsequent Figure 13 illustrates the co-occurrence of the keyword "energy storage". Through Figure 13, it is evident that the keyword "energy storage" has a high number of connections both within the general scope of "blue cluster" energy communities and within the more specific realms of renewable and citizen energy communities (green cluster), as well as within the energy market and relationships among consumers of the CER (yellow cluster). Currently, the figure shows that the implementation of energy storage in energy communities is linked with "PV". Furthermore, there are some keywords that describe an optimization of the energy storage system as artificial intelligence and internet of things (red cluster).

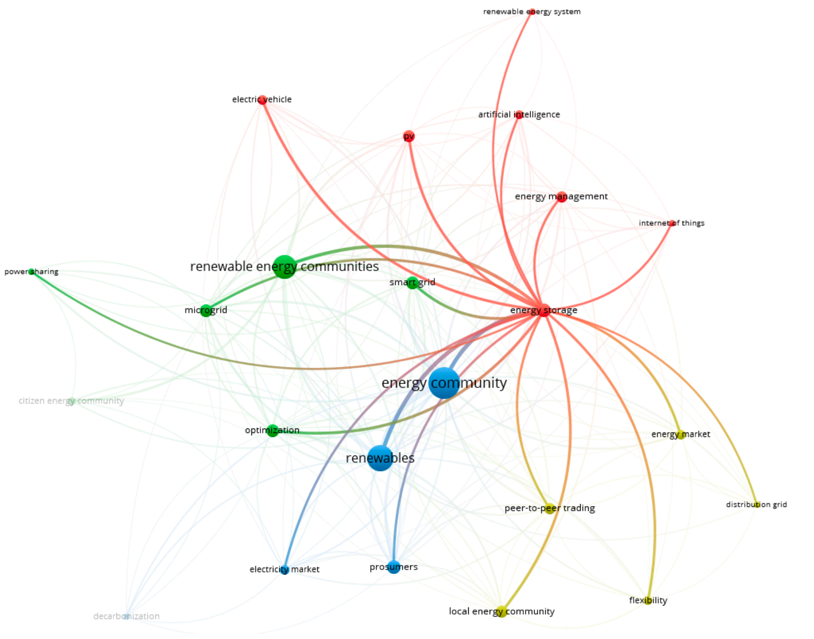


Figure 13. Co-occurrences and links with the keyword "energy storage".

The most cited article in the field of energy storage applied to RECs was published in 2018 by Barbour et al. [130] It highlights the necessity for the development of community-level storage technologies. While the literature predominantly features articles on battery energy storage [101,128,158–161], among the most cited articles is a study by Liu et al. [132], which applies a multi-energy storage system, both electrical and thermal, to achieve self-sufficiency in a net zero energy community. Additionally, Bartolini et al. [112] conduct a comparison between battery storage and TES to determine the optimal utilization of excess energy produced by a facility in a REC. The combination of battery and TES has also been taken up by further studies to create a hybrid system capable of maximizing the use of renewable energy [160,162,163].

In addition, Figure 13 indicates that energy storage applied to RECs is linked to the realm of smart grids and microgrids, corroborating what was previously analyzed in the co-occurrence analysis of TES. Finally, analyzing the latest publications on energy storage applied to RECs, it can be observed that solutions involving TES are increasingly prevalent, either in standalone systems or hybrid configurations with battery storage. For this reason, TES systems can represent a feasible possibility of application to RECs as a solution for maximizing renewable energy sharing.

3.3. Combined Results from Both Queries

Figure 14 shows the co-occurrence of keywords obtained by combining the queries concerning RECs and TES systems in buildings and districts into the VOSviewer software. The image shows how there is a clear separation between the two topics. It can be seen that the keywords related to the field of RECs are concentrated on the left-hand side, while those related to TES are on the right-hand side.

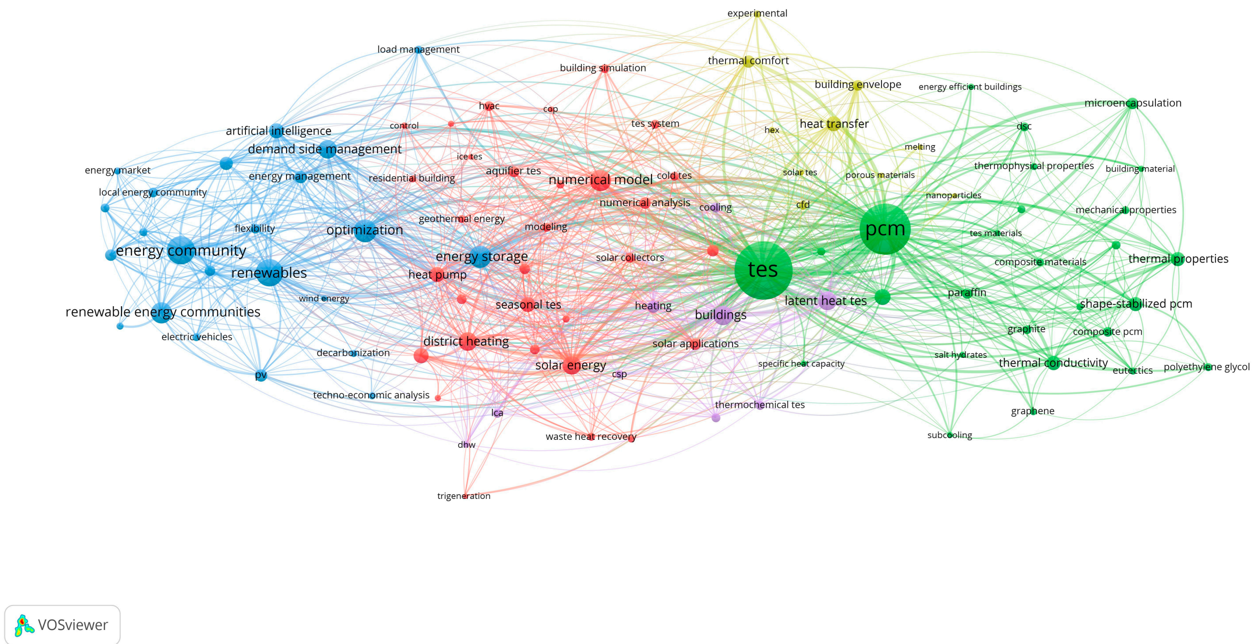
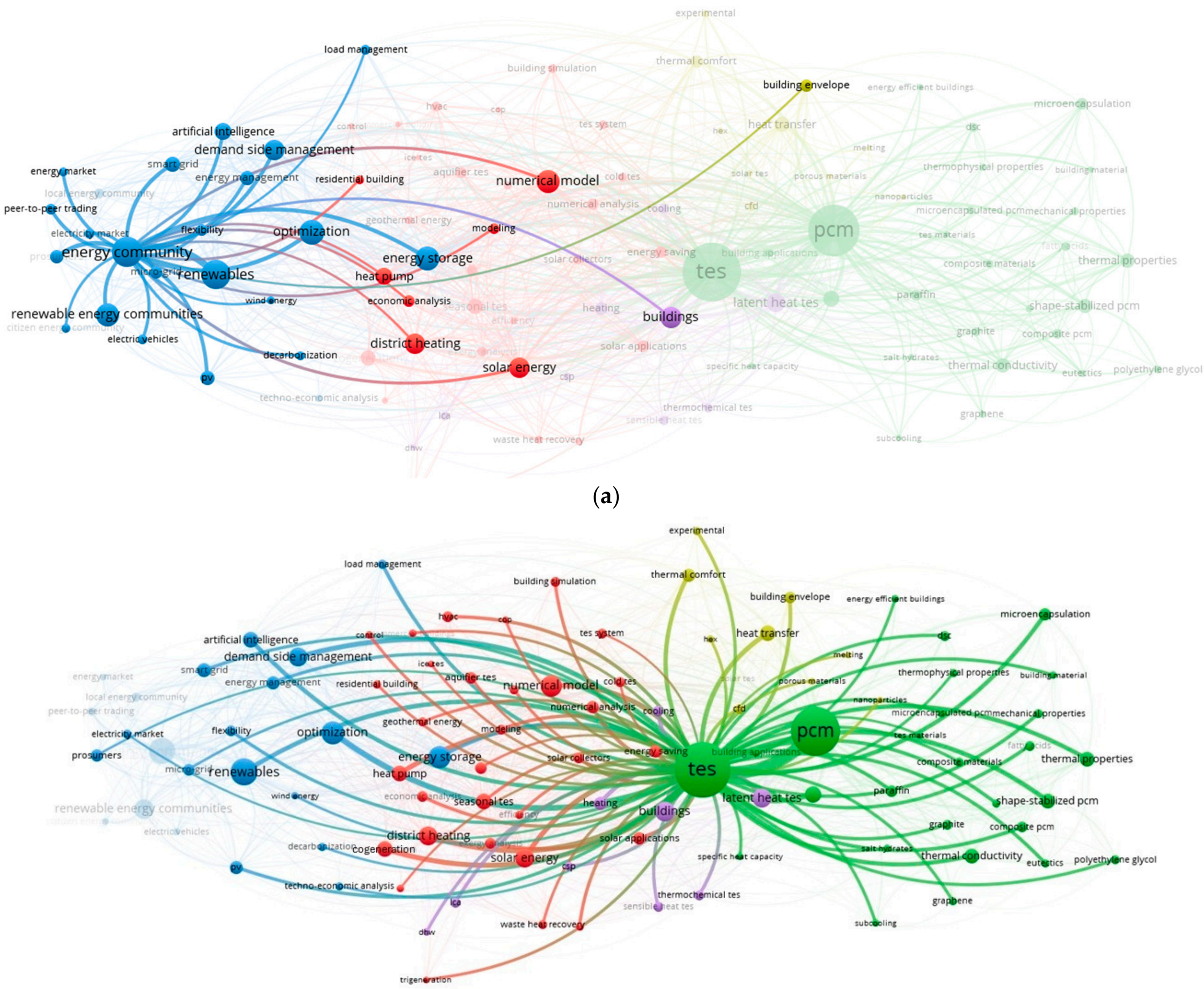


Figure 14. Co-occurrence of the keywords related to the merged queries.

This gap of the implementation of TES in RECs is confirmed with Figure 15, highlighting the main links to the keywords "energy community" and "TES". It can be seen that the two keywords are not related to each other. Furthermore, numerous keywords related to the sphere of TES are clearly separated from RECs. A clear example is "PCM", located on the opposite side of the figure from "energy community". However, it is possible to highlight several common points between TES and RECs that can be starting points for future research developments. For example, the term "TES" has links to the words "prosumer", "smart grid", "microgrid", "pv", and "demand side management", which are related to the field of RECs and the collective sharing of renewables.

One of these is the keyword "energy storage", the co-occurrence of which is shown in Figure 16a. As already shown in the previous section, most of the REC publications devoted to energy storage mostly concern electric storage batteries, as also shown by the terms "electric vehicle" and "electricity market", so a further gap is evident. Furthermore, the presence of the term "seasonal tes" indicates that from the perspective of TES systems, the focus of research is more on large systems, in contrast to smaller, distributed technologies that are more suited to the scope of RECs. However, the keywords "heat pump", "cogeneration", "trigeneration", and "district heating", also present in the co-occurrence of another common keyword, "solar energy" (Figure 16b), open up future research possibilities not only on the electrical side, but also on the thermal side. For this reason, the topic of energy storage could represent a bridge between TES and RECs. "Heat pump" is an important common point, which means that electrification of heating systems in energy communities could be the main focus of TES implementation. The keyword "district heating" once again highlights the importance of TES in areas of application greater than the individual building, expanding the possibility of sharing renewable thermal energy between several consumers. Finally, the terms "cogeneration" and "trigeneration" refer to the already mentioned possible benefits of theses in terms of recovering surplus heat.



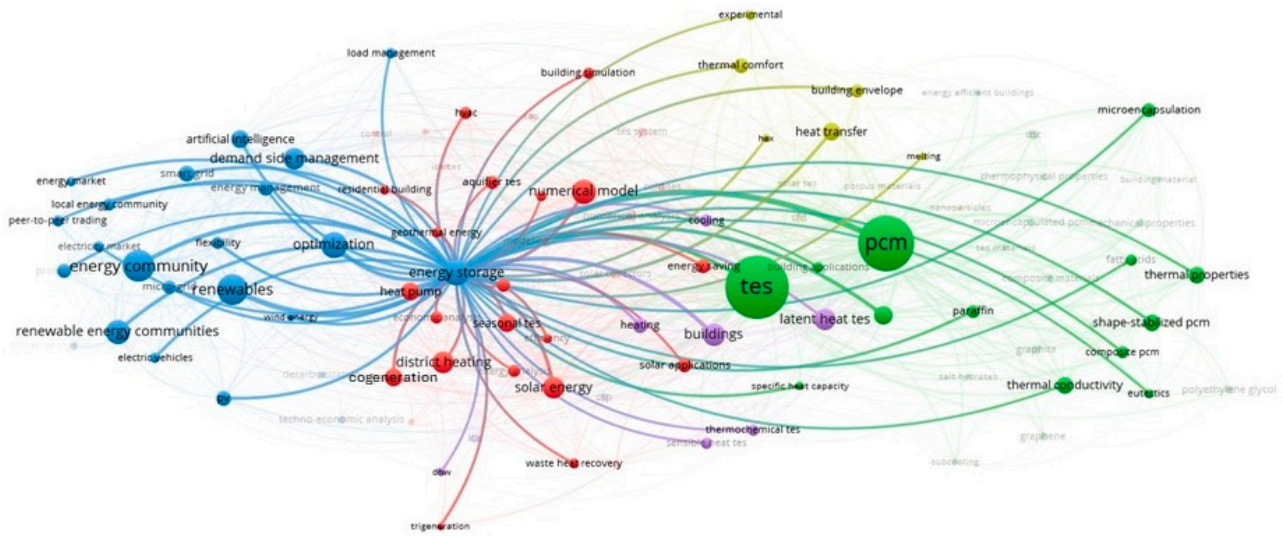
(**a**)

(**b**)

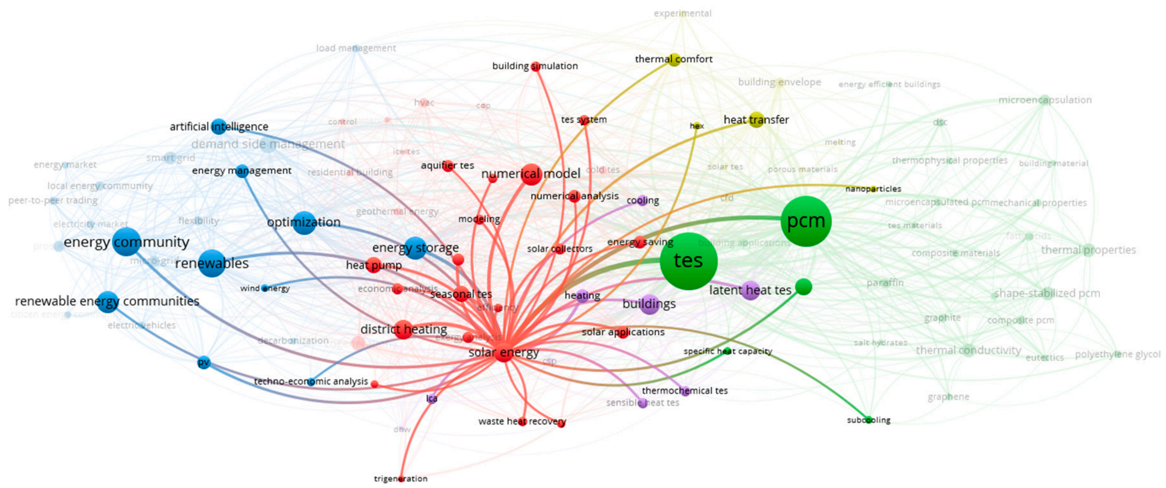
Figure 15. Co-occurrence of the keywords (**a**) "energy community" and (**b**) "TES".

Figure 17, on the other hand, shows the co-occurrence of the keyword "numerical model", for which there are several links to both RECs and TES. However, this shows a further gap, as it highlights the absence of the experimental field in the application of these two topics.

Finally, it is interesting to note that terms such as "building envelope", "thermal comfort", and "energy efficient buildings", which can be traced back to the residential sector, are repeated in the occurrences of these keywords common to TES and RECs. This could represent a further possibility to research the use of TES as a domestic solution to achieve energy efficiency for consumers and members of a REC.



(**a**)



(**b**)

Figure 16. Co-occurrence of the keywords (**a**) "energy storage" and (**b**) "solar energy".

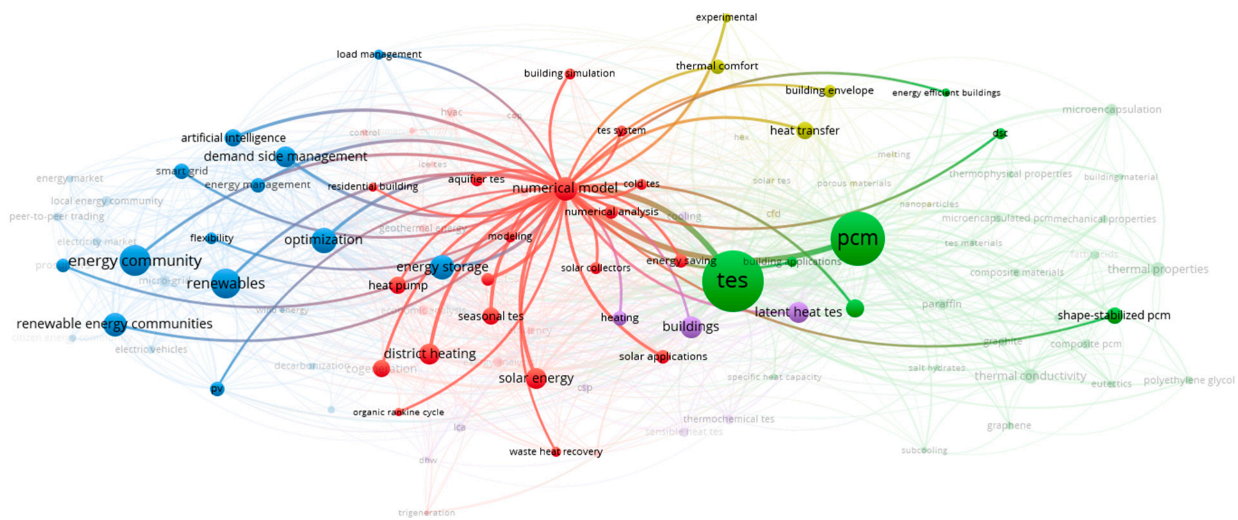


Figure 17. Co-occurrence of the keywords "numerical model".

Figure 18 shows the overlay visualization created using the VOSviewer software, allowing for us to observe the trends of different research items. It is evident that both TES and RECs are relatively recent research topics. As we move from TES to RECs from right to left, RECs appear to be an increasingly recent topic. While terms related to materials in TESs, such as "thermal properties", "fatty acids", and "building material" are positioned in 2017 [164–166], the items in the field of RECs, including "prosumer", "peer-to-peer trading", "local energy community", and "citizen energy community", are very recent, dating back to 2021 [167–170]. It can be concluded that the application of TES in the field of RECs is still relatively unexplored at the research level. However, it represents a recently emerging topic, still in its initial phase, with several possibilities for expansion and exploration in the future.

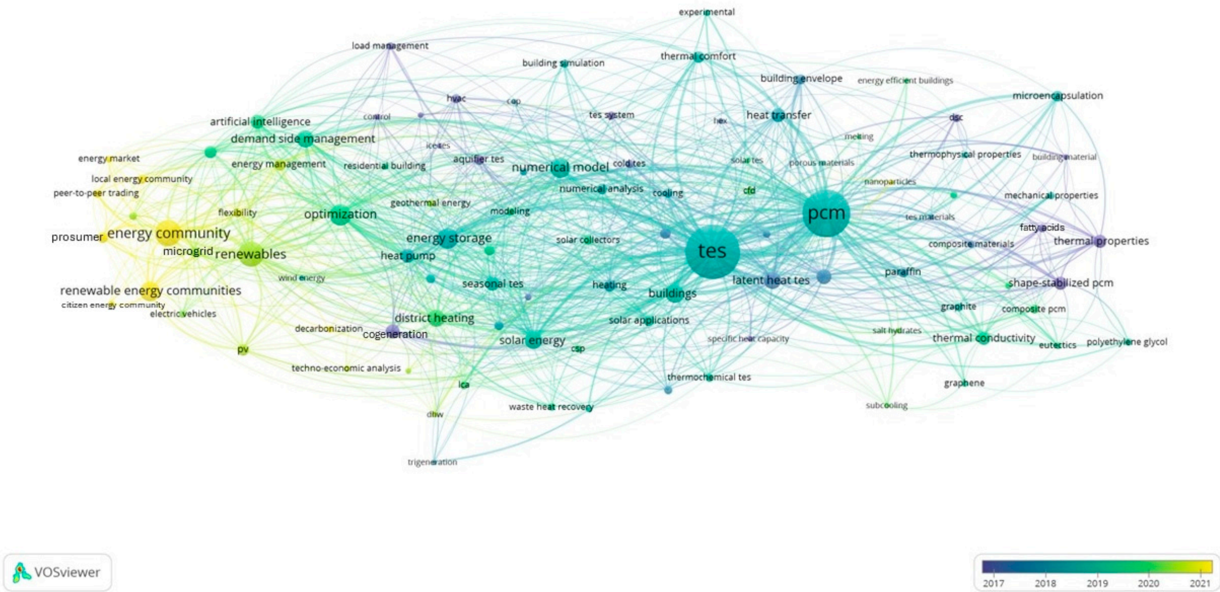


Figure 18. Overlay visualization for merged queries.

4. Conclusions

Renewable energy communities (RECs) represent a fundamental tool for the energy transition to renewable energy sources. Thanks to the distributed generation of renewable energy and the involvement of community members, who are no longer mere consumers but active and aware participants, they can effectively constitute a new paradigm for energy production, management, and consumption. This paradigm starkly contrasts with the fossil fuel-dependent model, addressing not only environmental and energy needs but also social ones.

The main goal of a REC is to maximize the sharing of renewable energy among its members. To achieve this, it is necessary to align periods of energy demand and supply. In this regard, there are various strategies, including the use of energy storage systems. Among these, TES represents a solution. Thanks to the power-to-heat strategy, which involves converting excess electrical energy into heat; its versatility; and its lower cost compared to other types of storage such as battery storage, TES presents a tangible opportunity to maximize the utilization of renewable energy in a REC. Furthermore, in a collective dimension of self-consumption such as RECs, TES systems can represent an opportunity for the implementation of district heating and heating systems fueled by renewables, providing flexibility and the possibility of bridging the mismatch between demand and availability of energy.

This study aimed to define the perspective of TES in RECs with a detailed bibliometric analysis. An analysis of TES systems was carried out regarding their application to buildings and districts, in order to consider not only the dimension of the individual building but also a broader one, traceable to a community. An initial analysis of the results shows that these two topics are very recent, with a significant increase in the trend of publications only in recent years. TES research, for example, has seen a considerable increase in publications since 2010, especially in Europe, following the approval of energy efficiency targets. Even more recent is the development of REC studies, which have grown exponentially since 2018, also based on the approval of European directives.

For this reason, most of the publications on these topics are very recent.

This work showed that energy communities constitute a research gap in the TES literature. In the co-occurrence analysis of keywords referring to TES, no terms related to RECs emerged. However, the presence of some terms characteristic of a larger storage dimension than the individual user, like "district heating", "smart grid", and "micro grid", leaves open the possibility of research in the area of collective self-consumption, not only from an electrical point of view, but also from that of thermal energy.

Furthermore, through bibliometric analysis, it became apparent that energy storage is applied in RECs, although it is referred to in the literature, through keywords, by this general definition, without focusing explicitly on thermal storage. However, among the most cited publications were several papers on the comparison between battery storage and TES. Moreover, more recent studies focus more on thermal or hybrid battery–TES systems. This allows for not only reducing the unreasonable investment costs of battery storage, but also for maximizing the sharing of renewable energies, through another energy carrier, towards increasing self-sufficiency.

Analyzing the merged keywords related to TES and RECs underscores the gap between these two topics. However, it also shows how the concepts of "energy storage", "solar energy", and "numerical model", which are relevant to both, could be a starting point for future research. These common points, with the big novelty that characterizes the subject, give room for potential investigation of TES technologies applied into RECs, in particular in Europe, where the research of these two topics is focused.

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