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Review

Thermal/Cooling Energy on Local Energy Communities: A Critical Review

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Abstract: One of the most crucial factors for energy transition and the incorporation of renewable energy sources into the existing energy map is citizen engagement. Local energy communities (LECs), which are cooperative-based coalitions aimed at reducing the carbon footprint of the residential building sector, have received increasing attention in the past decade. This is because residential buildings account for almost half of the total energy consumed worldwide. A resounding 75% of it is used for thermal energy consumption, heating and cooling, cooking and bathing. However, the main focus of the literature worldwide is explicitly on electrical LECs, despite the fact that the significant increase in natural gas and oil prices, creates instability in the heating and cooling prices. The scope of this study is to provide an overview of the research field regarding Thermal LECs, using both a thorough literature review as well as bibliometric analysis (VOSviewer software), in order to validate the findings of the review. The results indicate a collective scarcity of literature in the field of thermal/cooling energy communities, despite their proven value to the energy transition. A significant lack of directives, research background and state initiatives in the context of LECs incorporating thermal/cooling energy production, storage and distribution systems, was also observed. Case studies and the applications of such systems are scarce in the available literature, while published studies need further feasibility assessments.

Keywords: local energy community; thermal energy; local production; VOSviewer; bibliometrics

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1. Introduction

In the past 50 years, global CO_2 emissions have reached an all-time high in human history. In 2015, the Paris Agreement (PA) positively interfered and rendered incumbent the adoption of a greener energy roadmap [1] for all member states. Industry, the building sector and transportation became the main actors of the planet's radical climate change. The building sector accounts for 40% of the total energy consumption, with thermal energy being 75% of it [2]. Additionally, housing settlements with at least one member above 65 years of age, present an increase of 8% in thermal energy consumption yearly [3].

Since 2016, the world has moved rapidly towards sustainable technologies specifically to address some of the issues raised both technologically and socially [4]. Smart cities, net-zero buildings, renewable fuel production technologies, renewable energy production technologies for electricity and thermal energy [5,6] have been at the forefront of Grant Funding and the main focus of researchers around the globe. Over EUR 90 billion from the Horizon Europe 2021–2027 research funds are allocated to the advancement of the aforementioned. Efforts are being made to overcome the legal and technological barriers of the production and storage of thermal and electrical energy locally/collectively, whether short or long term.

The collective, local aspect of energy is not a novel concept. A number of studies recognize the significance of local energy communities as a key milestone towards carbon neutrality [7–10]. The terms "energy communities" and "Local Energy Communities" (LECs), are gaining increasing attention. Since 2012, when the term "LEC" (Local Energy Community: "a legal entity that is based on voluntary and open participation, effectively controlled by shareholders or members who are natural persons, local authorities, including municipalities, or small enterprises and microenterprises. The primary purpose of an energy community is to provide environmental, economic or social community benefits for its members or the local areas where it operates rather than financial profits. An energy community can be gaged in energy generation, distribution, and supply, consumption, aggregation, storage or energy efficiency services, generation of renewable energy or provide other energy services to its shareholders or members." [11]) was introduced, it made sense to broaden the spectrum of interest, due to the fact that a new distributed energy system emerged. LECs should not be confused with "energy hubs", which have a broader meaning in the sense that a hub does not necessarily mean that it can be an LEC (energy hubs are "functional units capable of transforming, conditioning and storing several kinds of energy (electrical, heating, cooling))" [12]. The European Union on its Clean Energy package, underlined the importance of collective-local production, storage and consumption of the energy, in a decentralized business model [4,13].

For the part they play in this local energy map, the participants of LECs are described in the existing literature as prosumers (from the words *produce* and *consume*) [14]. Nonetheless, issues of electrical energy production are addressed exclusively, while thermal/cooling energy is addressed only in the context of distributed heating or cooling system [15]. It is meaningful to approach thermal/cooling energy communities according to the European directives' norms in a systematic way, in order to accelerate their incorporation to the changing energy map.

The trigger for the current study was the fact that little literature is available regarding local energy communities, which incorporate thermal/cooling energy multisystems, either to produce and/or store energy locally (LEC) [15]. Thermal energy came a long way in integrating into the existing energy map [16–18]. Some of the most important novelties in the field of thermal/cooling energy storage are actions such as the sophisticated approach of seasonal storage (1959), the idea for underground storage of solar energy (1965), the Agenda 21 for climate action (1992), the Kyoto protocol (2005), the Denmark Energy Strategy for 2050 (2011) and the Paris Agreement (2015) [19]. The Paris Agreement marks a key milestone to the planet's collective plan towards sustainable energy transition [1]. Until the signing of the PA, thermal energy had been advancing in an economically and technologically feasible manner through the advancements reported later in this paper. As far back as 1959, thermal storage was established, but the scale was small and the technology too expensive to become commercially available. The integration of subsurface thermal storage fed by solar energy was established in 1965 with the Oil Crisis of 1973 which delineated the high priority of the storage of thermal energy any way possible [20]. Several research programs, European or otherwise, followed and in 2011, Denmark was one of the first countries to establish a clear vision about its energy roadmap towards 2050, addressing ownership structure issues and the lack of national legislation and financing [21,22].

Our review study aims to (1) investigate the local energy roadmap in terms of thermal energy communities and (2) provide the state-of-the science in terms of thermal/cooling energy norms by presenting the outline of the research focus, using bibliometric analysis. This paper is structured as follows: Section 2 is the Background work which contributes to the points made in this paper; Section 3 is the Methodology of the literature revie; Section 4 is the Results and Further Discussion where the findings of the bibliometric evaluation of the literature review are examined; Section 5 refers to the Conclusions and Recommendations.

2. Background

Reza et al. stated that occupancy energy consumption improvements along with a multigeneration system with storage technologies, both electrical and thermal, provide an energy and exergy efficiency of over 60% and over 45%, respectively [23]. Hachem C. et al. investigated the impact of solar thermal collector technology along with thermal storage system in existing communities. The results indicated a 70% coverage of the system's energy demands which underlines the importance of further study [24]. By proposing a smart district, electrical and heating model, Good N. et al. highlighted the importance of thermal storage facilities integrated within buildings, as a means of reducing the effects of expected thermal discomfort in the built environment [25]. Thermal storage, in a seasonal model, was examined for a community level system also by Koohi S. et al. Their novel study concluded in underlining the necessity of seasonal storage for the advancement of the energy transition. In this study, it was stated that in many community cases, a mix of long and short term storage solutions might be investigated as the technology is still under improvement [26]. The same conclusion was reached by Acheilas I. et al., who assessed a decision support tool for district heating from geothermal sources in existing cities. Their study indicated that carbon reduction at the community level can be achieved primarily by incorporating a high share of renewables and thermal energy storage technologies [27].

Part of the research focused on the thermal aspects of the local production of energy, the study of the techno-economic feasibility of such efforts. Aguilar J. et al., in the context of the thermal energy community, compared techno-economically a PV-CSP (photovoltaic-concentrated solar panel) hybrid system with thermal storage, and a conventional PV-battery system. Despite the greater initial cost of investment in the case of PV-CSP hybrid system, the LCOE (levelized cost of energy) was 26% lower than the conventional system, making it a more feasible solution for remote communities with extensive loads [28]. Kim M. et al. in their investigation for a net zero energy community, mentioned the importance of a high solar fraction for thermal energy communities, specifically incorporating appropriate volumes of thermal storage. In their case study, they achieved a 73% primary energy source penetration while calculating a total of 1600 m^2 solar collectors with 2000 m^3 of seasonal thermal storage, according to their base load. Significant CO_2 reduction was also one of the major findings of their study, as the emissions dropped by over 60% [29].

The emission reduction issue is present not only at the production end of the technology but also in the transmission of it. That was the case of Etienne S. et al., who designed a model-based control strategy which adjusted the electrical energy consumption of various parts of a local thermal/cooling energy production system, such as the pumps and the terminal fan coils. Their model presented a nearly 50% reduction of CO_2 emissions just by modifying the control sequences of this equipment [30]. The social, as well as the technical aspect of thermal energy communities and community storage concepts were addressed by Koirala B. et al. They compared two different commercial thermal storage technologies both from the legal aspect and from the feasibility one. The importance of their findings was that they not only addressed the challenges of the legislation and tax-related issues but they also specified the technical difficulties of the case studies' installation, operation and performance. Citizen empowerment and engagement appear to be two of the important challenges even in novel systems such as these [31].

At the National energy and climate plans for 2021–2030 (NECPs), the importance of citizen engagement was addressed "*exchanges of energy increasingly take place between consuming sectors—for instance, energy customers exchanging heat in smart district heating and cooling systems, or feeding in the electricity that they produce individually or as part of energy communities*" [32]. For example, special amendments to the energy targets were made due to the increase in citizen contribution and participation, "*Greece provides contributions for 2030 of at least 61% in renewable electricity (against 29.2% projected in 2020), 42.5% in the heating and cooling sector (against 30.6% projected in 2020) and 19% in renewables in the transport sector, including multipliers for the contribution of advanced biofuels and RES electricity (against 6.6% projected in 2020). Across sectors (electricity and heating and cooling), there is particular emphasis on promoting the role of local energy communities*" [33].

3. Methodology

The research methodology in this review, was prepared using peer review research papers, extracted from the databases of Scopus and Google Scholar, the total number of which was 1245 according to the keywords used. In order to properly access the volume of available literature, the current study is divided into two parts: (2.1) Literature Review and (2.2) Bibliometric Analysis. In the first section, a literature review was carried out, using a part of the 1245 papers (31 most relevant research papers), in order to investigate the state-of-the-science in thermal/cooling LECs. The most relevant research papers were selected through elimination using the criteria addressed in Table 1. The second section, incorporates bibliometrics via a database-analyzing software (VOS Viewer) in order to verify the results of the literature review and to define the main focus of the scientific community in the research area. The main keywords selected targeted the fields of renewable energy, local production and the consumption of thermal and cooling energy as well as local energy community/ties formation. The keywords used in the present study are represented in the graphical representations of Figures 1–3:

- Research Question 1: Established legal precedent on LECs. Result: **1110 papers**.
- Research Question 2: Majority of research, done in the field of thermal/cooling LECs. Result: **108 papers**.
- Research Question 3: Possible integration of thermal energy systems in LECs. Result: **27 papers**.

Table 1. Literature selection criteria.

Number	Criteria
1	Publications only from 2000 onwards
2	Books, conference papers and theses are excluded
3	Publications written in English only are considered
4	Publications that do not address LECs or renewable LECs directly are excluded

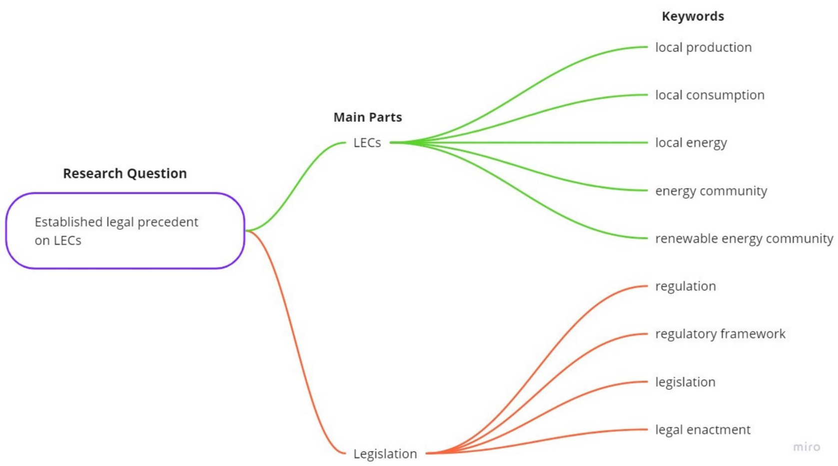

Figure 1. Graphical representation of the keywords targeting the 1st research question.

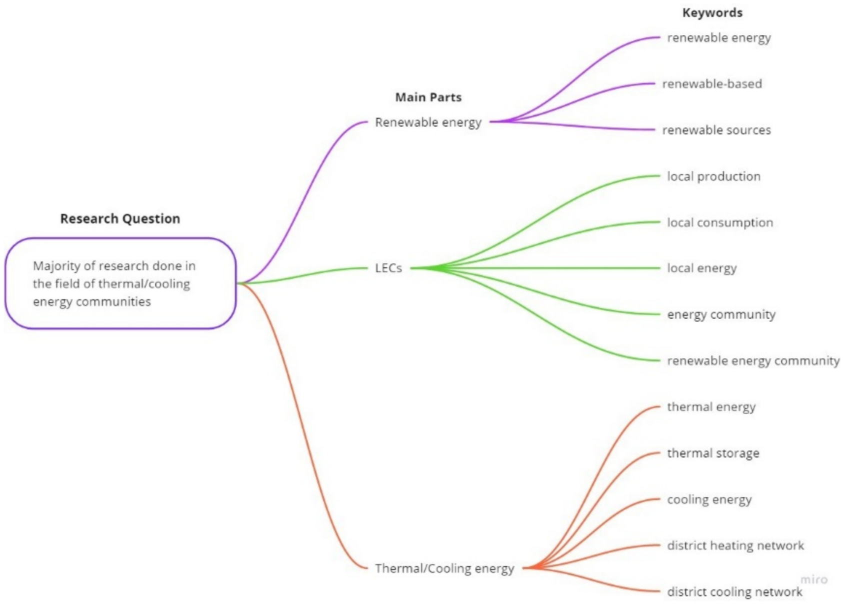

Figure 2. Graphical representation of the keywords targeting the 2nd research question.

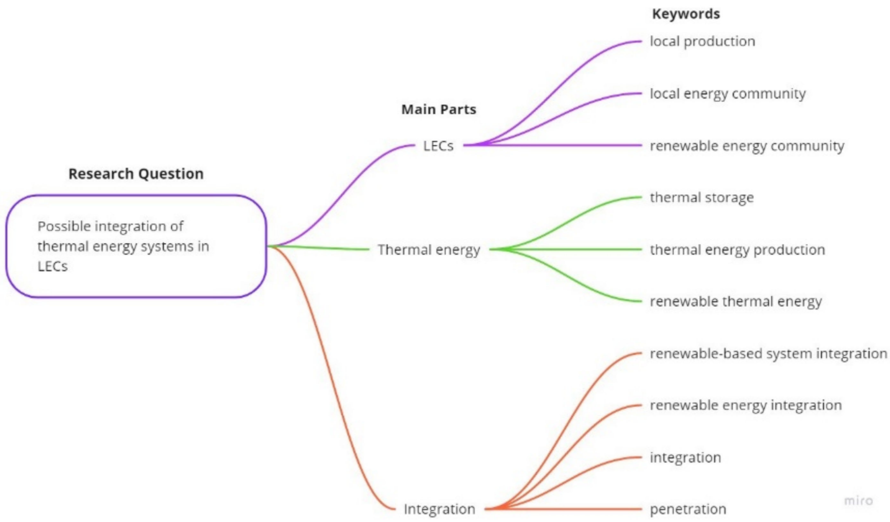

Figure 3. Graphical representation of the keywords targeting the 3rd research question.

3.1. Literature Review of Thermal/Cooling LECs

The literature review followed a snowball-effect methodology by studying the most relevant works (selected by the criteria of Table 1) and tracking down the references used in them as shown in the unified map shown in Figure 4 [34–36]. Due to the sparsely published material in the field of thermal/cooling energy integrated in LECs, few findings contributed to the points presented in the current study [5,6,37].

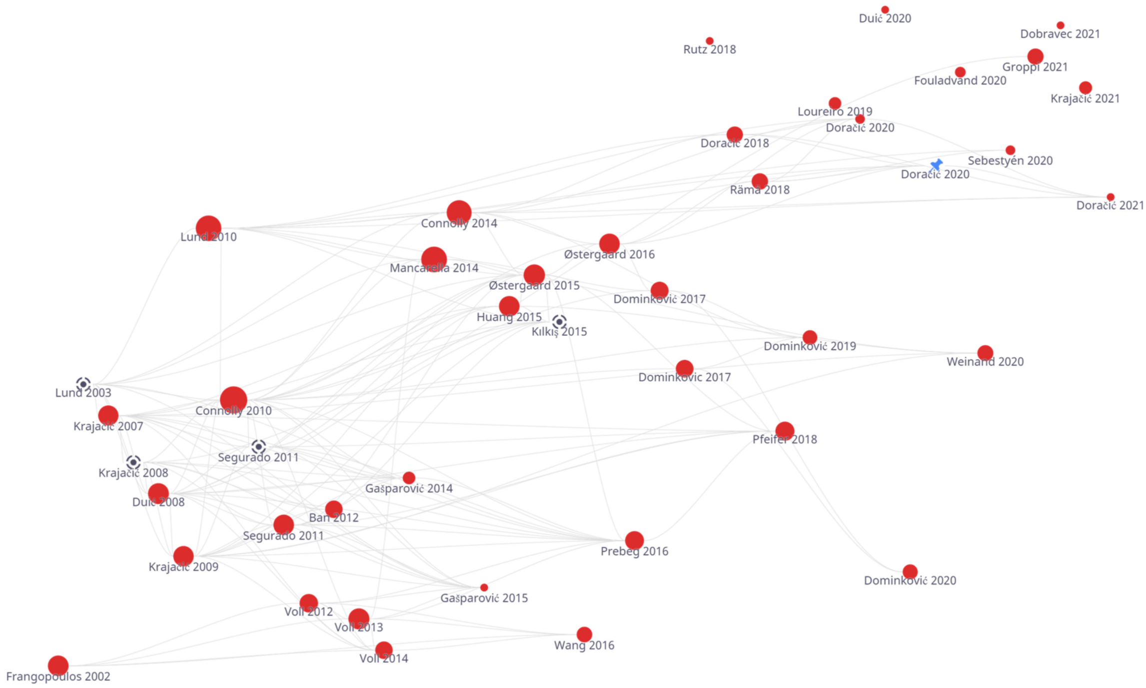

Figure 4. Overview model of the snowball-effect research methodology, considered in the present study.

The term LEC is widely used in electrical energy applications [9], mainly because the legal framework has changed towards decentralization of the electrical energy market in many European countries. The matter of legislation on the local production of energy was only recently addressed and enacted. The reason appears to be the lack of proper directives which will guide law-makers to enact such actions [38]. Directive 2001/77/EC promoted the production of electrical energy via renewable energy sources—no local production proposition [39]. Directive 2009/28/EC, proposed funding schemes for energy infrastructures built locally, as part of the European Climate and Energy Package [40]. Some major contributions of the directive were the definition of differences between existing centralized energy production and distribution systems and the proposed, decentralized model. Only a handful of countries have enacted policies that enable the fast integration of energy production, storage and consumption [4]. As LECs are gaining legal ground in the enactment of policies allowing them to proceed and penetrate the society's blocks, the very notion of them is still under definition [38].

The research works dedicated to LECs in the context of thermal/cooling energy use are presented in Table 2. The majority of works are dedicated to the distributional aspect of locally produced energy and mostly address matters of district heating technologies. There has been little work carried out in the field of renewable-based, local thermal/cooling energy grids, or storage of that energy locally, as shown in Table 2. The research focuses present an increase of attention in the exploration of technologies, allocation of energy and other goods of the community, connection with main actors such as the grid or other energy transfer and deployment systems, as well as mathematical modeling regarding responses to the instantaneous demand for energy [41,42]. The aforementioned appear the most, along with the term LEC, indicating the rise of an emerging micro-energy field of study which tackles most of the distributed energy systems' problems but creates new, interesting issues to be addressed, such as spatial planning for the integration of thermal/cooling energy systems or commercial production and storage technologies [42].

Table 2. Main publications and their contributions per year to thermal LECs.

References	Field of Study/Main Contributions
[22,23,27,30,31,43–50]	• District heating/multigeneration systems/local energy
[24,29,51–56]	• District heating/bidirectional heat grids
[28,47,57,58]	• Heating pipeline/distributed energy resources
[12,25,26,59–61]	• Seasonal storage/multi-energy/combined electrical thermal

The first mention of locally exploited thermal energy to cover community needs, was made by Duic N. et al. in 2006. In their work, they proposed a design methodology, called RenewIslands, which aided the formalization of the design process by incorporating extensive questionnaires (qualitative approach). The results of their study in three different islands highlighted the importance of the meticulous study of the design possibilities for stand-alone applications as well as the significance of storage facilities in the increase of energy sufficiency of the case studies [44]. A case study from Europe and specifically regarding the Danish energy transition to 100% renewable energy exploitation was presented by H. Lund et al. They investigated possible domestic energy production scenarios, as a first step towards decentralization of the energy map, in order to identify the mix of energy sources capable of achieving the 100% RES penetration. The conclusions of the study indicated that a scenario where domestic users are capable of satisfying their thermal energy needs is physically possible [47].

The importance of district heating and its role in energy systems was investigated also by H. Lund et al. In 2009, they proposed a scenario where 25% of the building sector substituted fossil fuel equipment and became integrated with an extensive district heating system, capable of covering their thermal energy needs. Several technologies were investigated for providing the district network with sufficient, economically viable thermal energy and the results of the study underlined the need for reduction of the heating load from the consumption side as well as further advancement of the district heating technologies [53]. Marko b. et al. researched the significance of cooling energy and its storage in the building sector. The increasing cooling energy demand was mentioned as a vital issue for the existing energy map, and the proposition of the authors was to include cooling thermal energy storage (CTES) technologies to reduce peak loads. The findings of their mathematical modeling, indicated that CTES is a solution worth investigating further as it presents significant reductions to peak loads but currently, due to technology gaps, is not economically viable [59].

Voll P. et al. in 2012 proposed a mathematical model targeting optimizing the design of thermal energy distribution systems. The model resulted in interesting outcomes. When the economy of scale proposed larger over smaller equipment sizing for the coverage of needs, the model favored different system layouts and additional smaller equipment sizes to cover the same needs, resulting in significantly lower initial investment costs [45]. H. Lund et al., addressed the 4th Generation District Heating (4GDH) as a key concept towards energy sufficiency in the building sector, with no reference to the communal aspect of 4GDH. They reviewed the status of smart thermal grids, which is the main difference between the 3GDH and the 4GDH, and presented a unified definition of the 4GDH. In their definition, the importance of an institutional and organizational framework was noted as a key factor for the development of the 4GDH [54].

In 2014, Kilkis S. conducted a research study in the context of net-zero exergy districts (communities of up to 20,000 people) which will produce the same amount and quality of energy as they consume annually. The findings of the case study presented concluded that such cooperatives (districts) can significantly reduce the exergy resources as well as the CO_2 emissions. The concluding remarks stated that these districts can "be the change-agents of a more sustainable energy system" [46]. The methodology for establishing such cooperatives (districts)/communities, was presented by Huang Z. et al. In the study published in 2015, the framework for establishing and continuing an energy community, in both electrical and thermal context, was mathematically structured [55].

The context of district heating and its advantages over existing heating infrastructures were also investigated in China by Xiong W et al. Three different heat strategies were compared and the findings indicated that district heating in the urban environment can decrease the building sector's energy consumption by up to 60% with significant cost reductions for heating services [56]. A Hungarian case study by Viktor M. was used as a use case for the development of a multienergy system (electricity, heat and transport) in order to make the city of Pecs self-sufficient (stand-alone community). The results of the study indicated that if the economic indicators become feasible, a scenario where the city of Pecs is 100% self-sufficient is possible [57]. Energy hubs (clusters of energy production technologies) for addressing heating, cooling and electricity demands in building case studies, were investigated by Iman G. et al. The performance of the created model resulted in the improvement of the system's energy flexibility [12].

The scenario of smart energy supply in cities with a focus on district heating was addressed by Dominkovic D. et al. Their work indicated that district heating scenarios with the implementation of heat pumps, can solely cover the thermal energy needs of the case study [60]. Kallert A. et al., presented a model of a small-scale district heating system for a block of buildings (community). The findings of the study concluded that exergetic as well as energetic evaluations of the system result in better design strategies and that a renewable energy-based heating system is feasible when compared to fossil-based. The economic viability, however, should be investigated further [48]. In 2019, the community cooling energy demand satisfaction was studied by Dominkovic D. et al., who compared district cooling solutions to existing individual cooling technologies. The results of the research underlined the importance of the district (communal) character of the cooling energy because of the flexible scenarios it produced [61].

While exploring the techno-economic implications of the expansion of district heating in the urban environment, Dominkovic D., concluded that thermal energy storage integration as well as the interconnection of adjacent district systems, can rapidly increase their socioeconomic feasibility [49]. One of the most important works in the field, that of Sebastyen T. et al., made the literature connection between prosumers (in a small village/LEC) and district heating systems. In that novel work, the importance of a bilateral relationship between the consumption-side (prosumer) and a district heating actor (DH Company) was highlighted. The innovation of the study, however, lies in the fact that the feasibility and economic viability of a prosumer/district heating actor scenario was proven and the price for heating decreased by over 17%, as a local thermal energy market was established [50].

The main findings of the thermal/cooling LEC related works, according to the studied material are formed as:

(1) Thermal and cooling energy are important actors of the energy map.
(2) Existing fossil-fuel based technologies are neither environmentally viable, nor economically feasible when compared to renewable energy-based systems.
(3) District heating/cooling networks have proven their importance to the energy market in small and large scale, respectively (Small-scale: up to 3 households/prosumers, Medium-scale: a neighborhood (approx. 10–20 households/prosumers, Large-scale: a city [11]).
(4) Storage technologies (such as CTES or thermal energy storage—TES) accompanying district heating and cooling networks can aid the increase of the feasibility and economic indicators of these systems.
(5) Community level interconnection of energy production systems and central district networks is a proven and viable solution towards CO_2 reduction and economic blooming.

In the definition of LECs, "an energy community can be engaged in energy generation, distribution, and supply, consumption, aggregation, storage or energy efficiency services, generation of renewable energy or provide other energy services to its share-holders or members", the aforementioned points are also addressed. The importance of technologies to produce the required thermal or cooling energy should be followed by the establishment of a district grid in order to distribute the produced energy to the stakeholders/prosumers. The storage of that energy when no load is introduced to the system, is also a key addition to the formation of an LEC to provide the necessary buffering between production and consumption.

In the studied material, however, certain points remain partially unaddressed:

(1) Community engagement and self-sufficiency works are scarce and not addressing thermal energy communities directly, however the clear indication and need for such cooperatives. Very few works, such as Fouladvand J. et al., directly mention thermal energy communities and only in the context of formation and continuation parameters of such cooperatives [15].
(2) Legal matters of such cooperatives remain largely unaddressed, as the literature available mainly focuses on mathematical modeling and case studies exploring scenarios of viability of local thermal/cooling energy exploitation. The distributional aspect of thermal energy (district heating/cooling networks) is studied intensively in the literature; however, the social and economic indications of such cooperatives remain under-studied.

3.2. Bibliometric Analysis

The term Local Energy Community (LEC) is used widely from 2015 onward, especially in the context of electrical energy communities. As presented in Figure 5, there is an increase of use of the term "LEC" as we approach 2021. The increase in the use of the term "LEC" was 13.33% and 15.56% from 2017 to 2018, while from 2019 to 2020, the increase was 2.22%. The citation count of research papers regarding advances, mathematical models, regulation proposals and application/simulation results of LECs also gained a rapid increase. From 2017 to 2018, a 19.57% increase in total citation count was observed, while from 2018 to 2019, a 21.74% increase. A decline of 25.12% was calculated for the years 2019 to 2020. The decline is attributed mainly to the pace at which the legislation worldwide is progressing. This relatively slow progression is discouraging for significant research work as the hypothesis and case studies cannot have any real application without legal enactment [15].

The bibliometric analysis of the aforementioned research area was undergone by analyzing the databases of Scopus and Google Scholar with Vos Viewer software (VVS) [62]. VVS is a free bibliometric software, specifically designed to produce maps of input data (such as bibliographic data). The outputs of VVS are three different sets of maps, each visualizing a different aspect of the provided data, the first being a "Network" diagram which provides insight into the interconnections of the data provided as well as proximity approximations regarding the relevance of the data correlated. The second map is an "Overlay" map which provides the information of the yearly dispersion of the data. The third map is a "Density" map (also known as "Heat map") and visualizes in a cluster format the intensity areas around groups of interconnected and closely depicted areas. These areas are color-coded, from shades of blue for less intense areas of the map, to shades of yellow and red for the more intense ones.

For the purposes of the current study, the maps of "Overlay" and "Density" are used, as the "Network" map carries no significant information for the purposes of the current study. The "Overlay" map has been selected because of the yearly dispersion information of the data it includes; the "Density" map has been selected for the identification of the most intense/research-focused areas of the provided data.

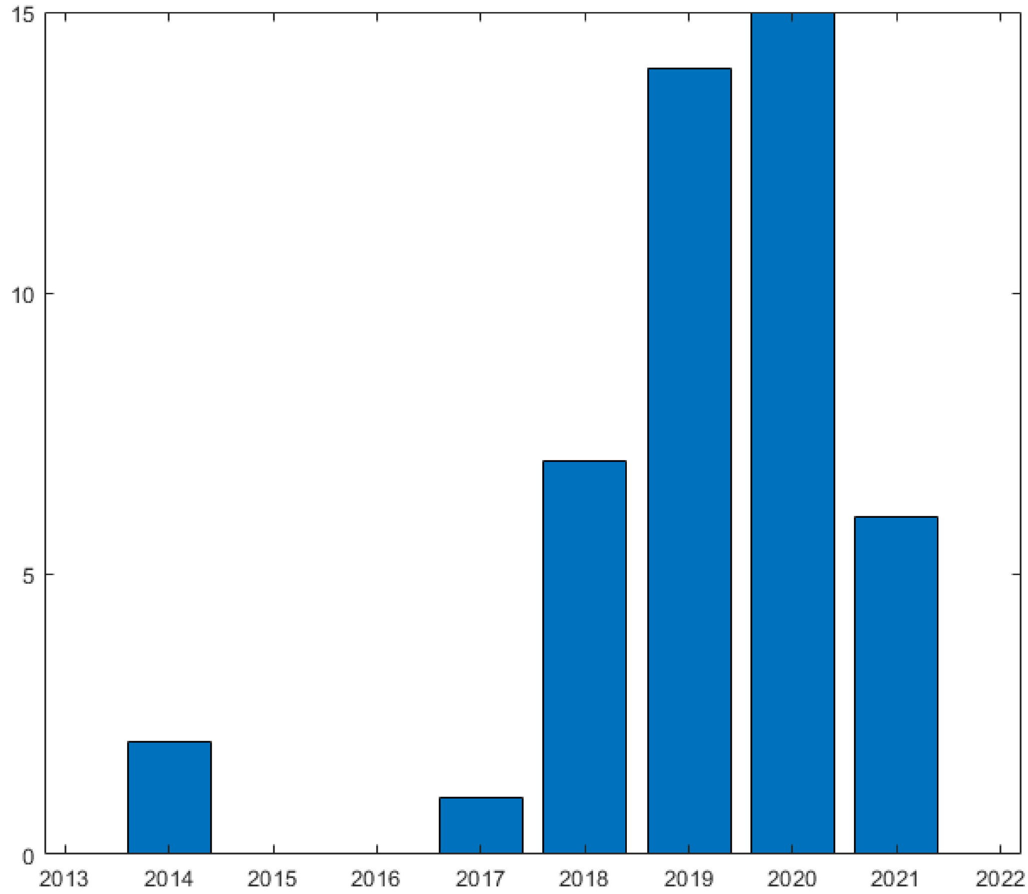

Figure 5. Bar chart presenting the total times "LEC" was used as a keyword in the existing bibliography.

The input data were the 1245 papers' results of the search with the combinations of the keywords mentioned above. The aim of this section is to validate the findings of Section 3 by combining the total 1245 papers and producing maps of data which will be presented in greater detail in the following subsections and are divided into three categories according to their content: (1) LEC—thermal/cooling energy, (2) thermal/cooling energy—local energy, (3) legislation—local energy.

3.2.1. LEC—Thermal/Cooling Energy Production/Storage

The maps of Figure 6 illustrate the focus of scientific interest for the search terms used in the field of LECs along with thermal energy. The main areas of interest being thermal/cooling energy and distributed heating systems. The terms of electrical grid and community generation systems are shown as obsolete because of the change of investigation focus from multigeneration systems (electrical and thermal) to exclusively thermal/cooling systems. The progression of the terms most frequently used in the current field present an increase in use of the term local energy community or communities which clearly suggests the shift towards the locality of the energy. The cluster density indicates the main focus of the research works which have been cast upon distributed energy systems and energy storage, however, without the presence of the term renewable energy or renewable resources, as there not sufficient studies published.

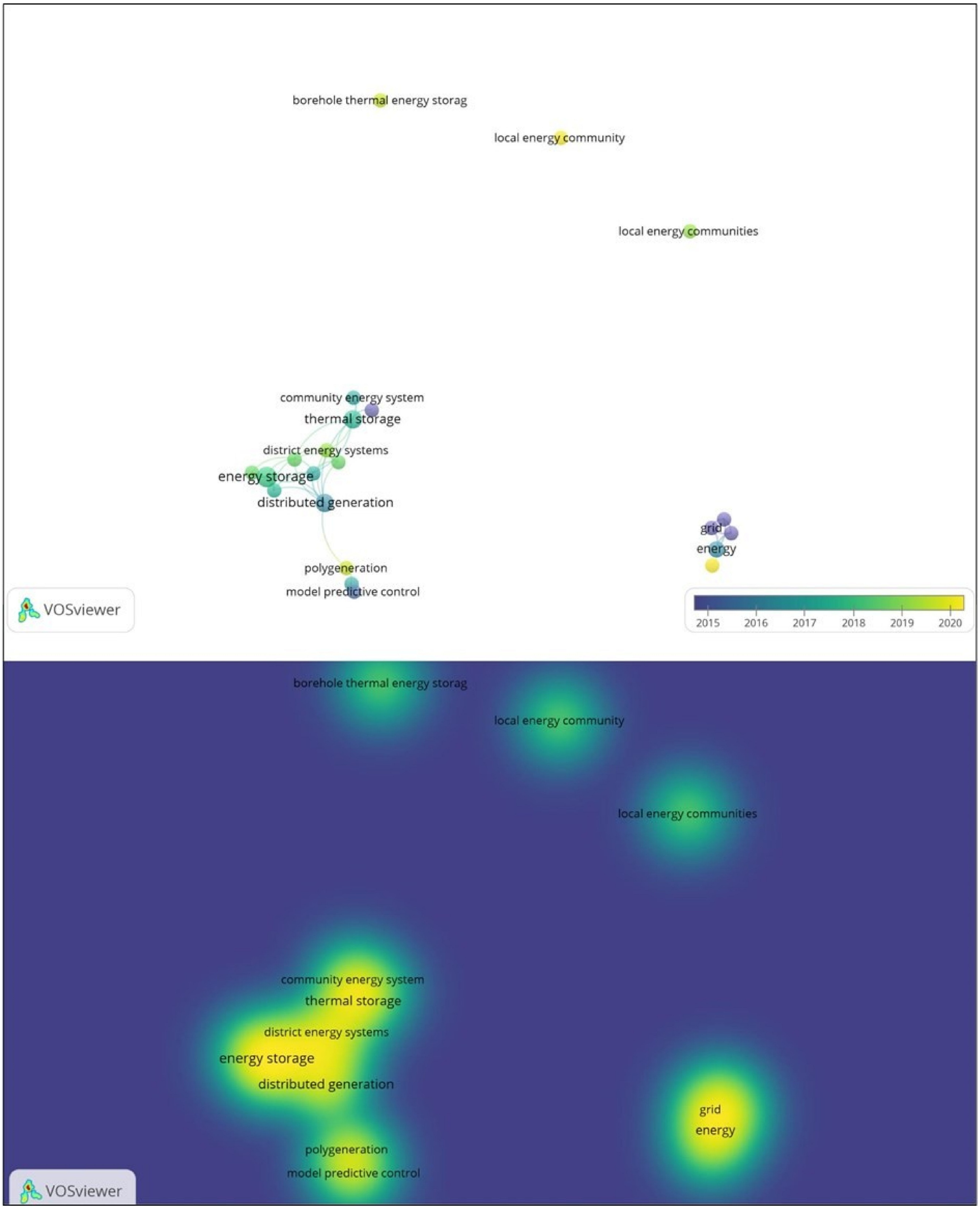

Figure 6. VVS output, overlay and density maps, visualizing the main keywords appearing in the bibliography in the context of LEC and thermal/cooling energy.

3.2.2. Thermal/Cooling Energy—Local Energy

In Figure 7, the focus of research appears to be, for the terms used in the search, the distributed heating systems and the energy storage accompanied by renewable energy resources. The progression of the field, however, focuses not only on distributed heating/cooling, but on the local renewable sources' availability also. From 2018 and onward, the main areas of research focus are mostly about district heating systems and renewable-based thermal/cooling energy storage. The cluster density presents an increasing amount of citation counts and keyword interconnection in the fields of district heating systems, energy storage and renewable energy. However, there is no link in the bibliographic research that connects local energy systems and thermal/cooling energy production and storage. The reason for this is the absence of a significant amount of research carried out in the field as legislation has not yet integrated it into the energy market.

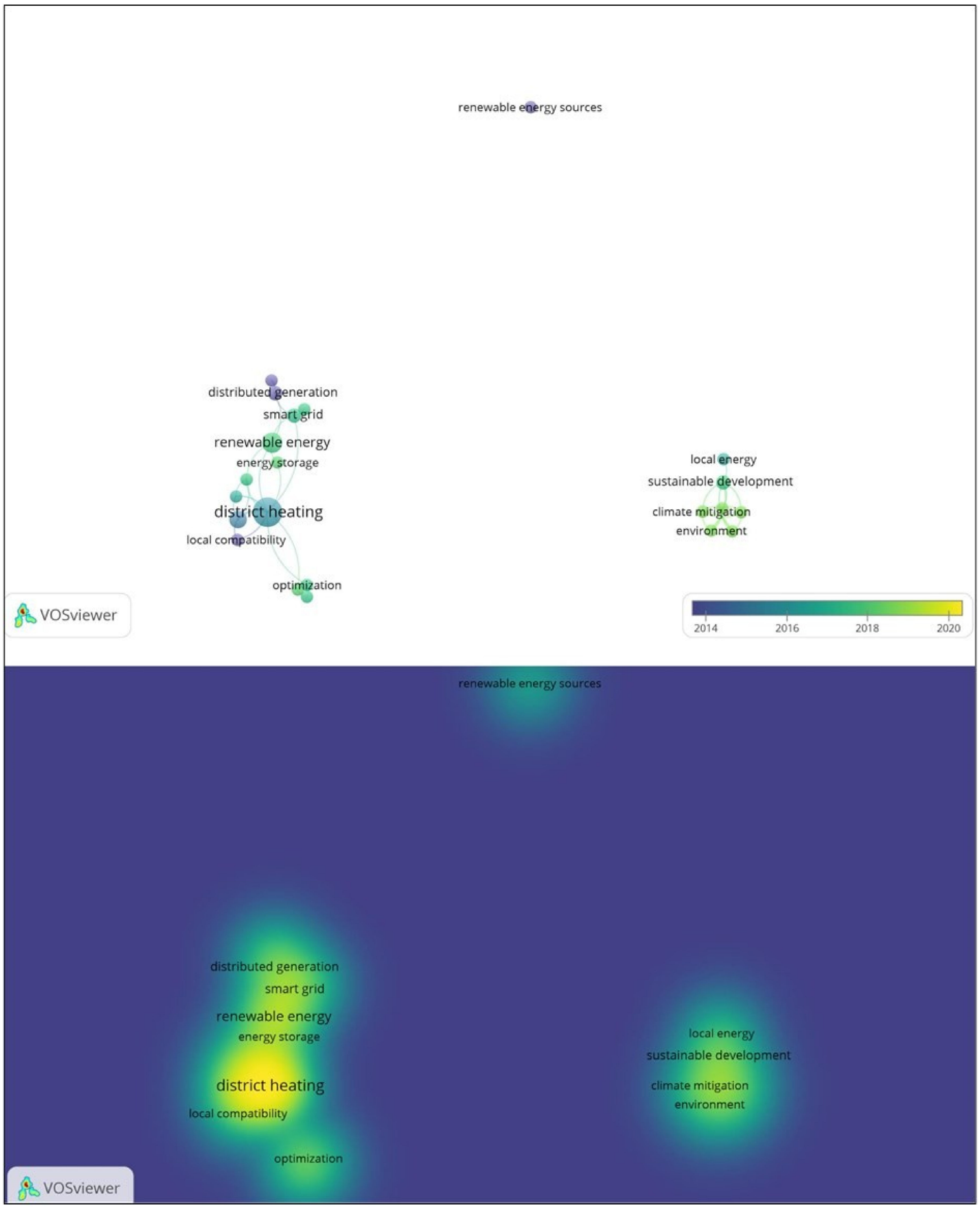

Figure 7. VVS output, overlay and density maps, visualizing the main keywords appearing in the bibliography in the context of thermal/cooling energy and local energy.

3.2.3. Legislation—Local Energy

As mentioned above, regulation around the world is still unfavorable for the advancement of either the local production of energy (thermal/cooling) or local storage, owned by the participants of an LEC. The scientific research focus is mostly concentrated towards electrical energy. Since 2012, the most relevant areas of interest to the terms searched have been the search for appropriate schemes in order to integrate the generation of electrical energy into new regulations. As time progresses, increasing attention has been given to renewable source-originated electrical energy, from 2016 forward. The citation count as well as the keyword interconnection indicate that the main area of interest subjected changes, especially due to the PA. The most recent area of scientific focus is alternative energy, renewable energy and storage of energy. There is no reference to the production or storage of thermal/cooling energy either in large scale (legislation missing) or in small, local scale. Manifestly, due to the lack of regulatory framework, and to the best knowledge of the authors, thermal/cooling energy production and storage achieved locally is still a pending issue (Figure 8).

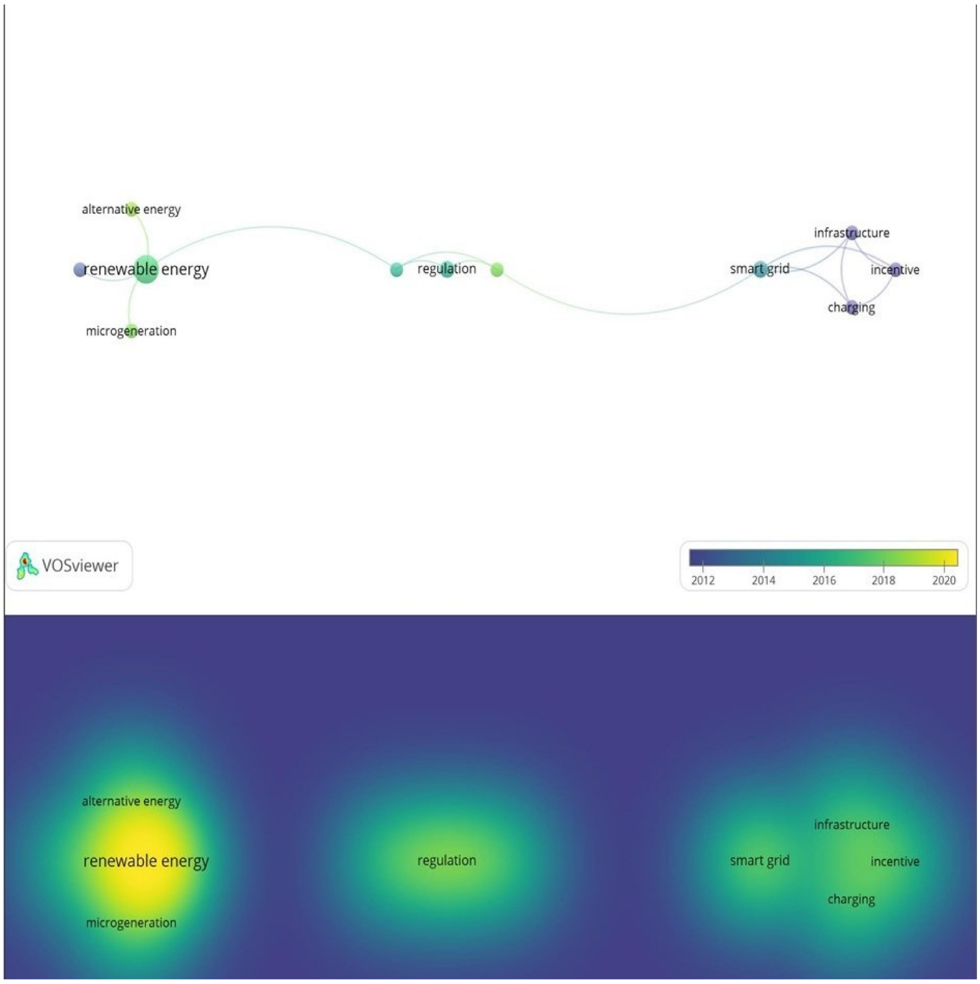

Figure 8. VVS output, overlay and density maps, visualizing the main keywords appearing in the bibliography in the context of legislation and local energy.

4. Results and Further Discussion

The main points of the literature review are summarized in a Venn diagram in Figure 9. As shown in this Figure, legislation is partially correlated with thermal/cooling energy production and is not yet incorporated into the legal framework. LECs are already mentioned in the context of renewable energy and their correlation with local production as well as with legislation has been carried out. Local production is incorporated with district heating and distributed heating systems but not in the context of renewable energy. Thermal/cooling storage is not yet correlated with legislation but is bibliographically connected to renewable energy (Figure 10). The results indicate that sustainable thermal energy communities have not yet been established in most parts of the globe. The main reason appears to be the lack of concise and coherent regulation across many countries, European or otherwise [38]. Several studies concluded that incentives, especially at the beginning of the formation of any LEC are essential for the outcome of the progression of the LEC as well as the number of participants it will attract [15]. The political, socioeconomic and techno-economic results of the literature review are presented in the Sections 4.1–4.3 respectively.

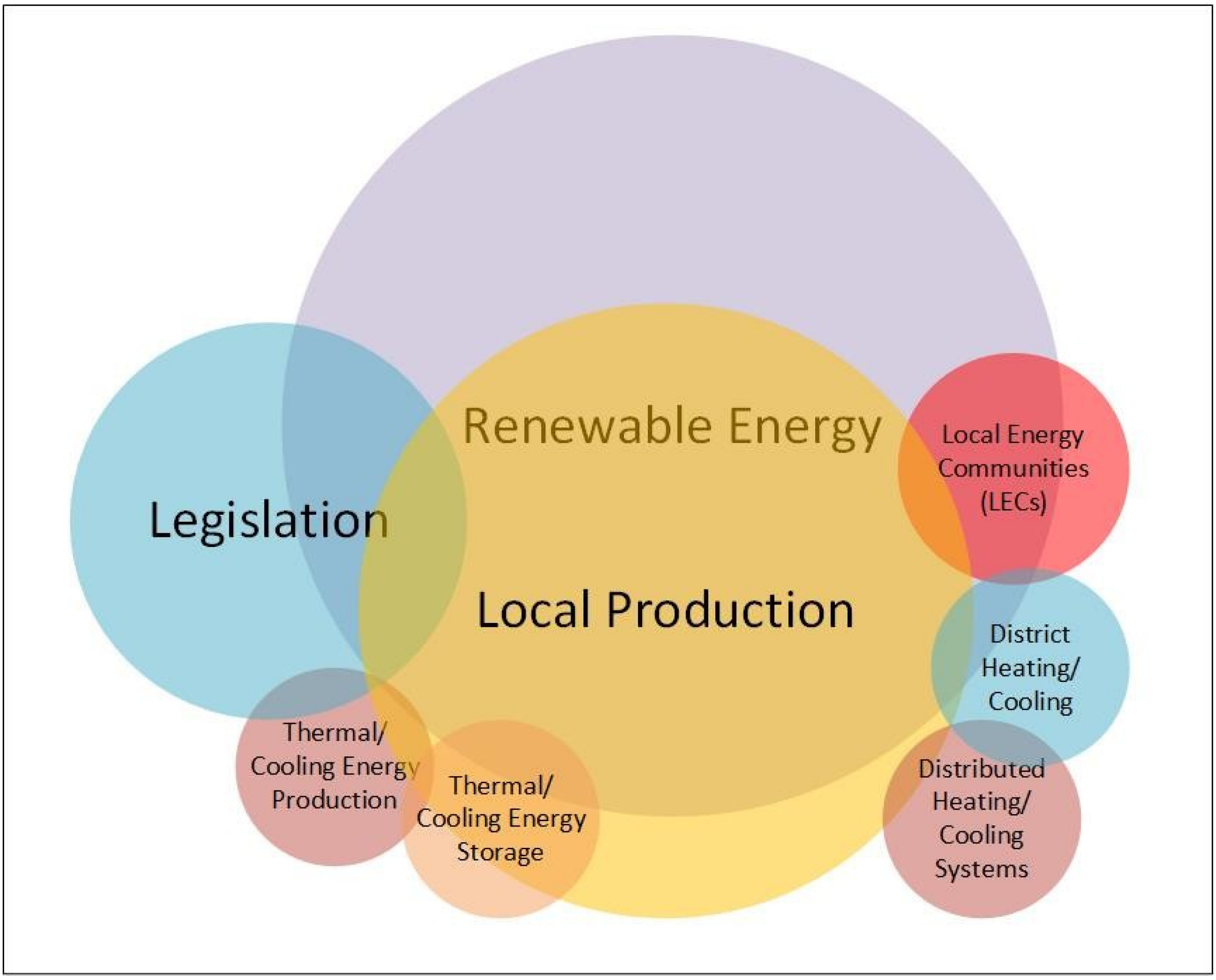

Figure 9. Venn diagram visualizing the results of the bibliometric analysis undertaken in this study.

4.1. Political-Regulation Aspect

The results of the bibliometric analysis indicated a lack of systematic and worldwide existence of appropriate policies regarding (a) installation of technologies which produce energy for local exploitation, (b) on and off grid connection of the LECs, (c) storage of the produced thermal/cooling energy and (d) initiatives for the establishment of an appropriate regulatory framework for thermal/cooling LECs. Europe has come a long way to enact LECs as part of the energy map as Belgium, Greece, Germany, the Netherlands, UK, Australia have deployed initiatives to promote the creation of such cooperations. Directives have been published (Directive 2001/77/EC, Directive 2009/28/EC) aiding the enactment of LECs without, however, providing a clear path to policy-makers.

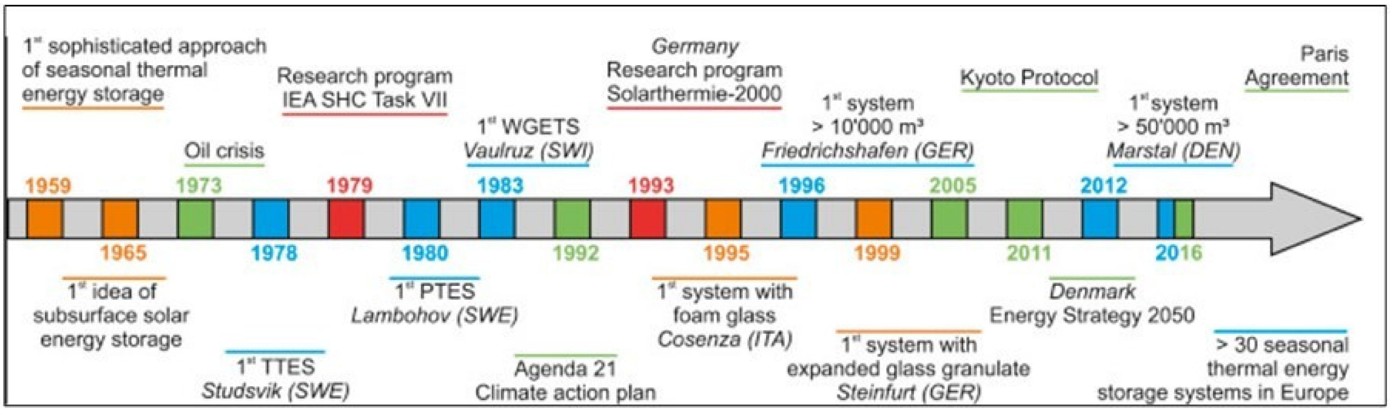

Figure 10. Timeline of the most important actions towards thermal energy storage (color-code as presented by Cristoph B. et al., green: climate actions, orange: inventions, red: research activities, blue: milestone projects) Reprinted with permission from Ref. [19]. Copyright 2022 Elsevier.

The analysis results indicate that while renewable energy has been established legally, local production of any kind of energy, including renewable based is still not enacted in the majority of renewable-frontier countries. As far as thermal energy communities are concerned, there is no policy in the European Union or anywhere that includes technologies and storage in a local manner.

4.2. Socioeconomic Aspect

The social aspect of energy communities is also addressed in the research. Motivation and incentives deemed of crucial importance, are lacking however, in most cases examined. Stakeholders—participants of LECs—also appear to have multiple objectives when entering into a cooperation such as an LEC, which often leads to high drop-out rates. Initial costs and the lack of proper funding schemes have been deemed to add to the non-participation or drop-out factors [15].

Another poorly addressed issue is the aspect of adopting this new energy system. If energy communities as a norm present the slightest resemblance to product launching phenomena, the adoption rate of this new era of energy map might not yet have reached the "Early adopters" phase, but it is still at the "Innovators" part of the curve. Clearly, except for European Horizon Projects, other, more marketing-based, techniques should be applied in order to spread the philosophy of the local energy attempt, to the public.

Other interesting opinions in the analyzed literature state that after the LEC formation stage, focus should be given to the satisfaction and the minimization of the drop-out rates, via incentivizing potential participants at the beginning of the "LEC formation". The after "formation" stage is thought to be structured in a way that aids the participation of new members as well [15].

4.3. Techno-Economic Aspect

Regardless of the lack of proper incentivization regimes or legal establishment, technology has yet to produce a viable, large scale effect on energy communities. Thermal/cooling energy production is well-established and researched thoroughly, but many of the most promising storage technologies are still in the R & D stage. Technologies such as thermochemical storage are in the R & D phase while molten salt and ice storage have not yet passed the commercial deployment barrier (still at demonstration and deployment stage). The research indicates that from the technologies under demonstration, both require significant amounts of funding and their costs of investment are still *over-the-commercial* sustainability [31] (Figure 11).

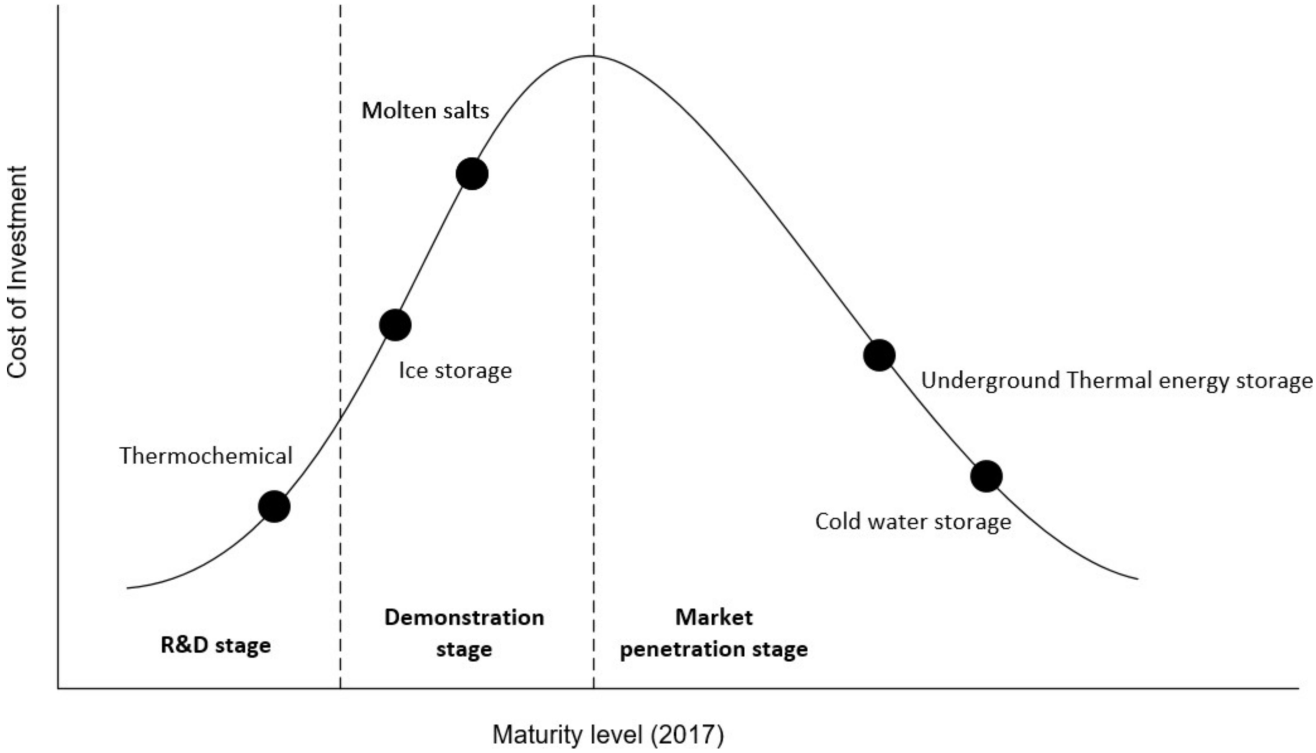

Figure 11. Graph representing the different stages of maturity level of various thermal/cooling energy storage technologies [63].

The financial implications of the current maturity level of the thermal/cooling energy storage technologies affect the creation and sustainability of future LECs. According to the accumulated research studies in the field, however, a lot of effort has been given for the commercialization of these technologies. In the 6 years between 2014 and 2020 (to date), an estimation of over 8000 research papers were published on the subject of thermal/cooling energy storage technologies (thermochemical storage, phase-change materials, underground large scale storage, cold water storage, as mentioned by Dincer et al.) according to Scopus and Google Scholar database results [63]. The number of studies per year increases at a steady rate of approximately 2.08% which, if the linear regression method is used for the end of the year 2021, results in approximately 9745 total published papers on the subject (see Figure 12).

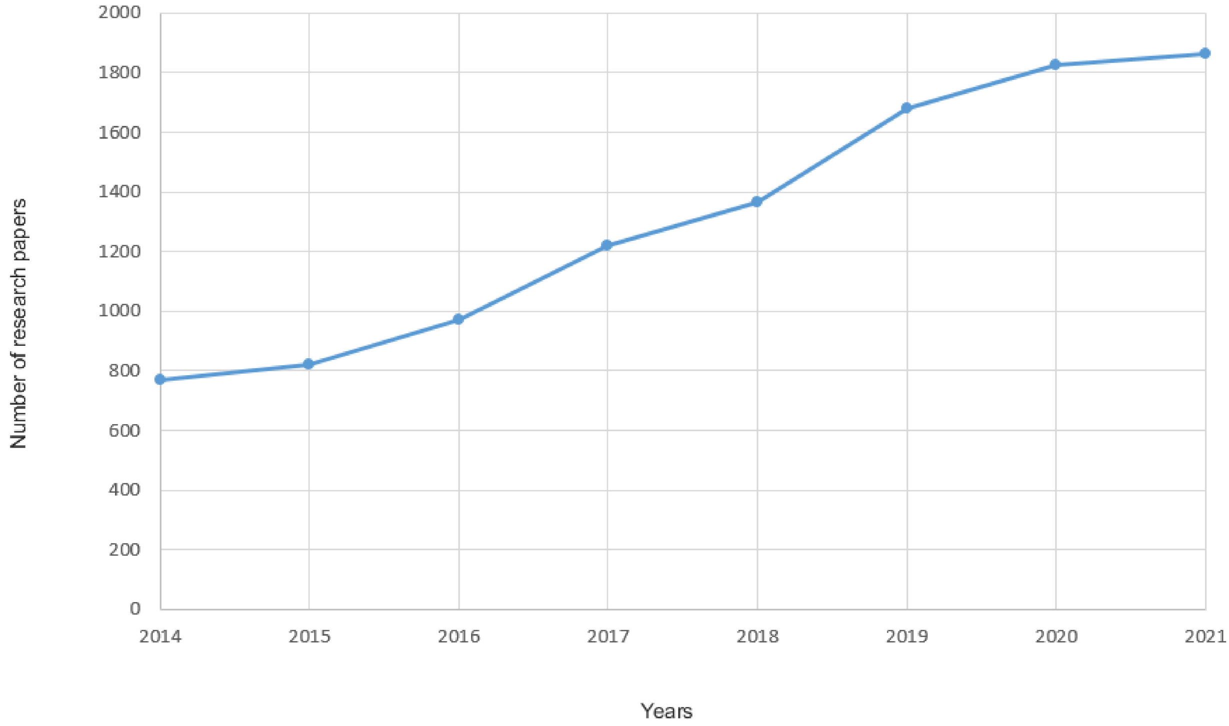

Figure 12. Timeline of research papers in the field of thermal/cooling energy storage from the year 2014 onward (source: Scopus database).

5. Conclusions and Further Study

The aim of the present study was, first of all, to provide an overview of the current state of thermal and cooling LECs including legal and technological aspects. While massive funds are allocated towards the promotion of these cooperations, policies have been established in a few countries and there is no collective enactment in unions such as the European Union. Incentivization schemes are absent, as researchers in human psychology and technology advisers are still investigating the different solutions for normal transition. The decentralization of the energy network brings up many legal and cooperative issues as far as LECs and green energy neighborhoods are concerned and the cooperation of existing state (or privately)-owned centralized energy networks do not comply with the current state of legislation, thus creating a significant, intricate task for the policy-makers.

Another key remark of the study was the attempt to investigate the established research field, in the subject of thermal energy communities. The findings of this research showed that LECs incorporating electrical energy production/consumption systems are an established area of study. Thermal energy communities are also addressed but the lack of district networks and the unfeasibility or economic viability of the available production and storage technologies are preventing a quick transition. The main context under which thermal energy communities are addressed, is the one of district heating/cooling, rarely using renewable resources as primary source of energy. The advancement of thermal/cooling energy storage technologies is ongoing and soon more technologies will be available, to be sustainably incorporated into the formation of future thermal/cooling LECs. Large-scale storage technologies for thermal/cooling energy are still sparsely researched and the aforementioned new technologies are thought to be covering only a portion of households. The techno-economic feasibility of such systems has yet to be reached.

The democratization of the energy system and the empowerment of the people will require significant changes and tools to aid the transition. A collective tool that informs future LECs about the estimation of the initial cost of investment as well as the applicable technologies for the case under consideration, might be one of the most important additions at state and international level. That way, the potential cooperations will be capable of sophisticated decision-making for the establishment of their LEC. Advanced demand–response systems for the allocation of the available thermal/cooling energy (the existence of storage or not should be investigated in such scenarios), might also be one useful addition to that tool. The data collected and analyzed for a few pilot thermal energy communities in order to better understand the nature of the arising issues (LEC expansion, drop-out rate reduction, energy demand satisfaction, payback period fluctuation etc.) will aid the procedure. However, the raising of citizen awareness regarding energy behavior/use will be of utmost importance as the shift towards renewable energy will demand a shift of energy behavior on the part of the users.

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