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Assessing the Complexity of Decarbonised Power Systems as a Means Towards a Sustainable Society: Trends and Hotspots

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ABSTRACT:
This paper aims to assess the complexity of decarbonized power systems by mapping the trends in the field of low carbon electricity over the period 2000-2023 employing an analysis of the scientific publications. This paper addresses the power sector as it plays an essential role in supporting global efforts towards a sustainable society. The paper provides an overview of decarbonised electricity trends by a quantitative analysis of publications, extracted from Dimensions database and explores relevant literature employing VOSviewer as a visualisation tool. The scientometric analysis reveals the main literature streams by using a semantic map, citation and co-citation analyses. The paper shows an increased preoccupation in the field, starting with 2000, and reveals the most relevant works. Moreover, by aggregating bibliometric data, the paper uncovers the social networks associated with the field and points the interested researchers towards the most influential works. By doing so, the paper provides a better understanding of the complexity of the field of decarbonised power system and allows the identification of current research directions and paves the way towards future research paths.

Keywords: sustainable development, decarbonised power, quantitative research; climate change

1. Introduction

The energy systems are in a continuous change due to coalescence of many factors involving the evolution of technologies, new policy paradigms, decentralisation, security of supply, digitalisation and the effect on climate. All over the world the climate change represents a major concern, and aspirational targets are set to limit the emissions of greenhouse gases (GHG) (United Nations, 2015; United Nations, 2023). The European Union (EU) aims to become climate neutral by 2050 (European Commission, 2021) meaning a decarbonisation of all sectors that emit GHG. The transition to green technologies is a key factor in the pursuit of the sustainable low-carbon economy. Decarbonised electricity refers to the sector of electrical energy in which low carbon sources are employed as renewable energy sources, nuclear power and hydrogen (European Commission, 2022). By greening the energy system of the EU, climate neutrality (European Court of Auditors, 2024), but also reduced energy dependence (Momete, 2006), increased energy security and competitiveness (Momete, 2023) will be hopefully achieved. But the energy transition towards green puts supplemental strain on

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energy systems which are becoming more complex and more uncertain for industry and government decision makers (Soutar, 2021; Gumte et al., 2024).

Digitalization and decentralisation (the 2Ds) have as core issue technology innovation in energy which relates to computer science, artificial intelligence, control engineering and communication network. These involve the integration of different types of communications (for instance device-to-device, device-to-cloud) from various ecosystems (smart houses/buildings, smart transport, smart energy). But these 2Ds must be promoted by a consumer-friendly interface which is able to implement energy efficiency in daily usage, therefore the new technology must go hand in hand with society if a real change is aimed that will lead to the mitigation of climate change. These changes have impact all over the world where the energy systems are based on conventional carbon-intensive infrastructure, but more on the developing and emerging economies which have no infrastructure or cannot perform a rapid transition to decarbonised electricity. Therefore, difficult choices are to be made between global environment and security of supply, especially in regions lacking resources or infrastructure. In Africa, for example, there are countries where the access to electric power of any kind is for less than 10% of the population (Nousala et al., 2024), therefore a transition towards sustainable energy must go hand in hand with decent living.

The United Nations adopted in 2015 a resolution to transform the world into a more sustainable one by 2030, containing 17 sustainable development goals (SDGs) (United Nations, 2015). Energy and climate have specified goals, SDG7 (affordable and clean energy) and SDG13 (climate action) respectively, but contribute to the attainment of most 17 SGDs. The renewable energy, despite a certain growth, is not yet on the track to meet the SDG target by 2030 (United Nations, 2023).

To meet the SDGs targets there is a need of a synergic approach of the 17 SDGs, especially as 2030 is approaching. The climate action must be integrated into national and international frameworks, but this has not happened yet, as the current practices and consumption patterns are very different, and many challenges are to be overcome. To reflect its importance but also urgency, this was the topic of a UN Forum on sustainable development organised in July 2024 (United Nations, 2024), which promise to issue a report relating SDGs synergy with climate. Bridging the gap between all SGDs, as for instance SDG7 (clean and affordable energy) and SDG 1 (zero hunger) or SDG7 (clean and affordable energy) and SDG13 (climate action) is a way to ensure "no one is left behind", the promise of the Agenda for sustainable development (United Nations, 2015).

At the same time, the national policies must be aligned with industry and EU, recognising its importance, adopted a new legislative package "Fit for 55" (European Parliament, 2023) which includes the reformation of EU Emission Trading System, a new carbon leakage instrument and a climate fund to be created in 2026 to deal with energy poverty.

This paper addresses the power sector as it plays an essential role in supporting global efforts towards a sustainable society which is far from being green (Yao et al, 2022). Currently, the world still relies on carbon-based fuels (fossil fuels, mainly coal and gas), to generate electrical energy. From 15,665 TWh in 2000, to 29,480 TWh in 2023, the global production of electrical energy almost doubled (88% increase) in the last 24 years (Statista, 2024). However, the share of the electrical energy coming from fossil fuels remained about the same, from 64% in 2000 to 61% in 2023, with coal being the main source of electricity generation. Despite an increase in the production of renewable energy, their contribution to the electric power mix remains modest in comparison with fossil fuels. Moreover, the past and present human behaviour connected with unsustainable practices put humanity on the road to a sustainability crisis (Whitmore, 2024) and the power sector plays an essential role in supporting global efforts towards a sustainable society.

This study was motivated by the need to understand the challenges and hotspots in decarbonised power systems, to assess the technology trends and to identify the future frontiers. To this end, the paper uses a scientometric analysis to grasp the dynamics and basic characteristics of the literature in the field. This study aims to map the research in the field of decarbonised electricity, to provide an emphasis on the growing of this field within the last years, during the period 2000-2023 and answers the following research questions (RQ):

RQ1: How has the field of decarbonised electricity progressed in the last years?

RQ2: Which are the most relevant terms in the field of decarbonised electricity?

RQ 3: Which are the most relevant literature streams in the field of decarbonised electricity based on citation and co-citation?

Scientometrics is based on the quantitative analysis of the scholarly literature and involves the analysis of the research effect, by exploring terms and citation inter-relationships (Ghaleb et al, 2022; Leydesdorff & Milojevic, 2015). Citations are a manifestation of influence (Leydesdorff & Milojevic, 2015) and by citing, the authors built further development on previous existing knowledge. A rich representation of a field can be obtained through co-citation analysis but taken together with a semantic map of terms. To this end, this research analysis the term map along with citation and co-citation. By doing so, the paper provides a better understanding of the complexity of the field of decarbonised electricity and allows the identification of current research directions and paves the way towards future research paths.

The rest of paper is divided into three sections covering: methodology which contains the steps needed to collect and analyse the bibliometric data, the results and discussion section which describes the mapping and time evolution of the field of study, and the conclusion section which reveals the findings, limitations and future directions of research.

2. Methods

To answer this research's questions, an inquiry was performed in June 2024 on the Dimensions data base (Digital Science, 2018) that conduced to the retrieval of a list of relevant academic publications for the field of decarbonised electricity. The selection of Dimensions database is justified by the fact that is a comprehensive database that can provide the broadest coverage of current literature as it can be freely used by all the researchers, in contrast with Web of Science or Scopus, which are subscription based. In order to cover most of the publications in the field of decarbonised electricity, after an initial screening of several keywords and combinations, the logical sequence of terms was restricted to: ("decarbonised" OR "decarbonized" OR "low carbon sources") AND ("electricity" OR "electrical energy") to cover similar terms. The search was conducted on full data and limited to English publications (title, abstract, keywords, text). Dimensions database provided 9,775 of initial entries, from which 7,098 publications were selected referring only to articles, chapters, books and preprints and proceedings.

The scientometric analysis was performed on VOSviewer software (version 1.6.20) (Waltman et al., 2010; van Eck & Waltman 2023), which was adopted for visualising the terms and citation-based analyses. VOSviewer is a powerful visualisation tool which helps building clusters and bibliometric networks based on citation and co-citation relationship among researchers, journals and institutions. The VOSViewer is based on the keywords/researchers which occur most frequently on data extracted from selected database covering all fields of study. To provide valuable insights and the latest findings Dimensions data base was employed, considering articles, conference papers, working papers, books and chapters in all fields of study. In VOSviewer the extraction of terms is based on English language, while the researcher analysis is based on their names and maybe some improvements are needed to better capture a more exhaustive picture of evolving research areas. Figure 1 represents the flow diagram of the methodological steps of the research.

The following analyses were performed on VOSviewer: keywords co-occurrence (term map), author citation and co-citation clustering analysis; the number of records was reduced based on the number of citations/number of occurrence of a term (n = the number of records in figure 1). The performed analyses provide a general description of the field and lay out the most relevant works. The results from analyses can be used as starting points for future research in decarbonised electricity.

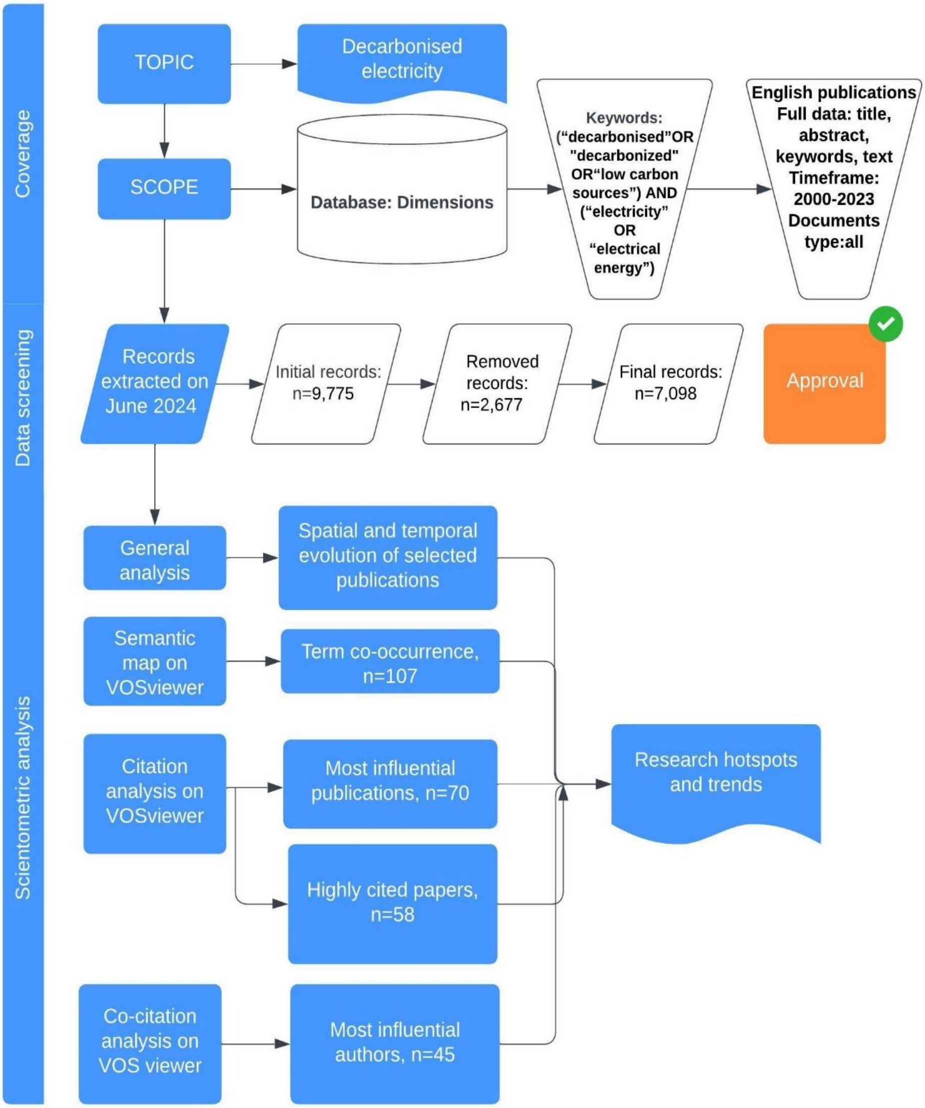

Figure 1. Flow diagram of the methodological steps of the research. (Source: realised by the author with the aid of Lucidchart.)

3. Results and discussion

3.1 General analysis

From Dimensions database 7,098 academic publications referring only to articles, chapters, edited books, monographs, preprints and proceedings were extracted and the spilt of the publications is presented in figure 2. Figure 3 reveals the evolution of number of the publications in the period 2000-2023. A main observation is that the number of publication increased dramatically from 5 articles/year in 2000 to 1265/year in 2023, recording an upward trend, with a consistent increase since 2020. The 7,098 publications were authored by 131,101 authors coming from 2,082 organizations throughout the globe. Moreover, 35% of the publications are in engineering field of research (Australian and New Zealand Standard Research Classification - ANZSCR 2020 - code 40) (Australian Bureau of Statistics, 2020). The publications by research area of engineering field are rendered in figure 4, showing that the largest contribution is coming from the field 4008 – electrical engineering.

The data were further analysed by employing VOSviewer which allows the construction of networks revealing clusters of scientific publications and journals, authors/researchers, keywords, organizations and countries. The connection between the nodes of a network is linked to citation and co-citation (van Eck & Waltman 2023).

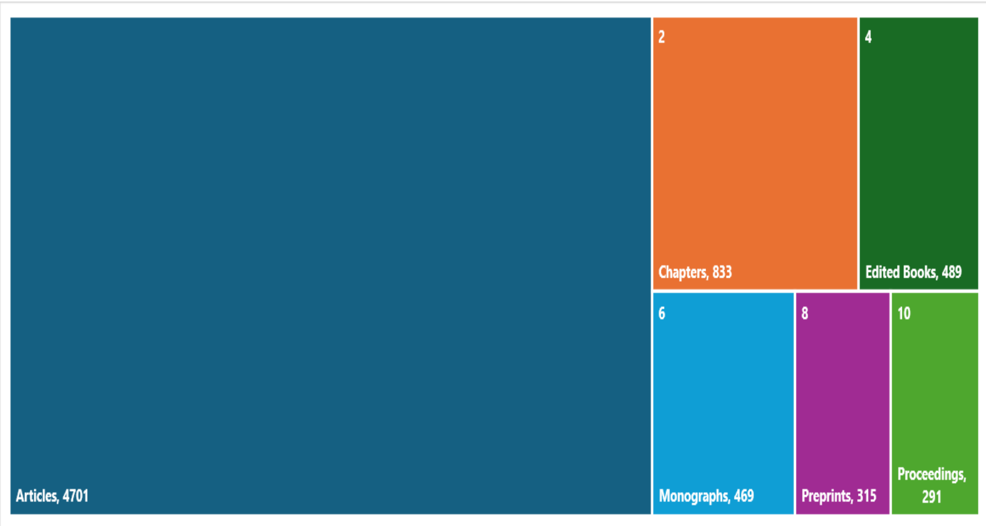

Figure 2. Selected types of publications for decarbonised electricity (Source: processed from the query performed on Dimensions database)

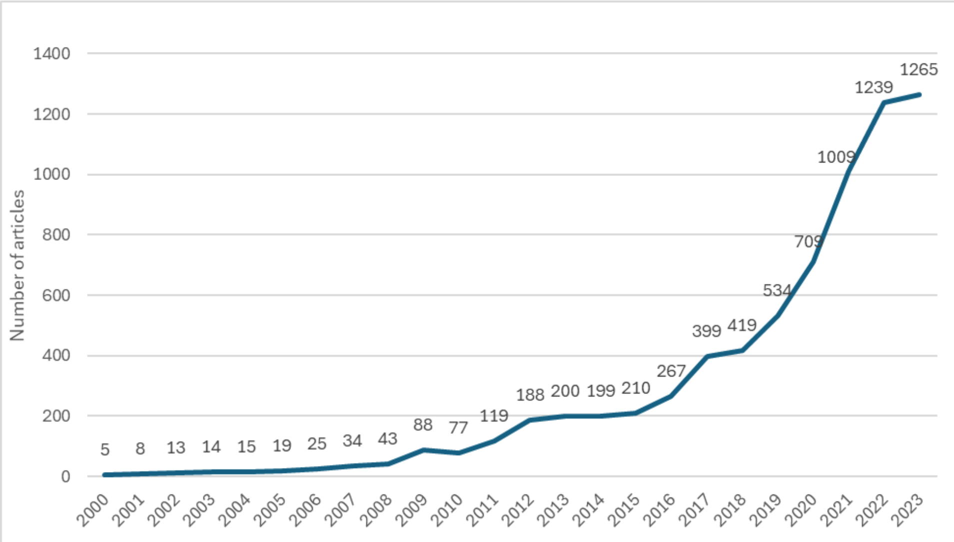

Figure 3. The evolution of the number of publications for decarbonised electricity (Source: processed from the query performed on Dimensions database)

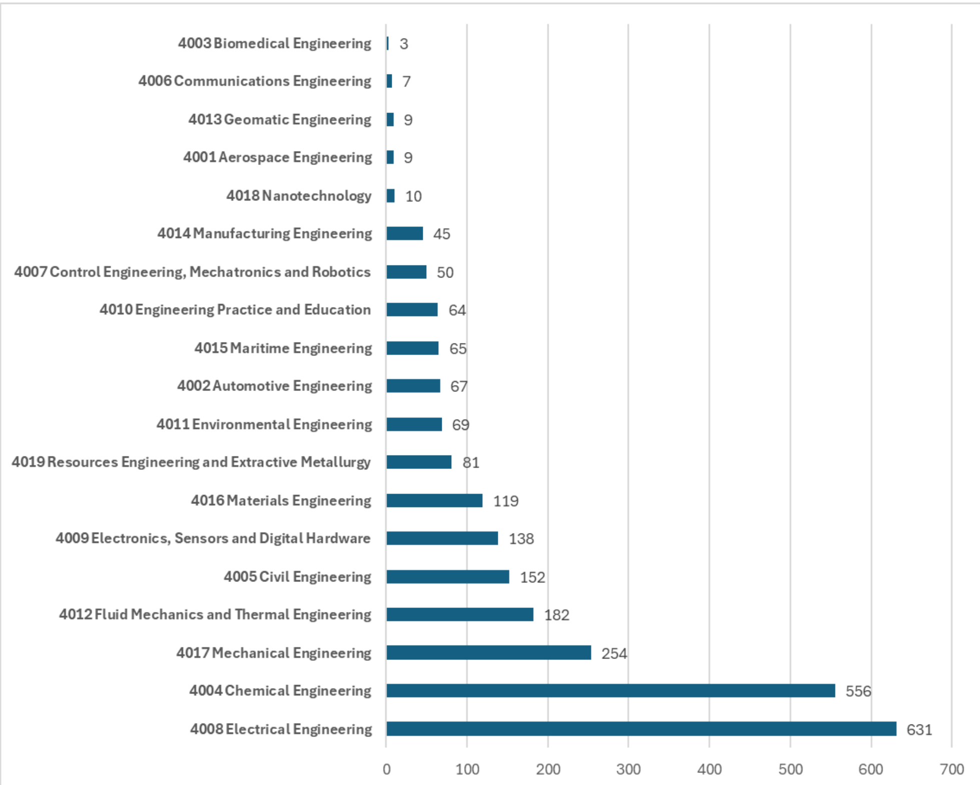

Figure 4. The number of publications by field of research in engineering (code 40-ANZSCR 2020) (Source: processed from the query performed on Dimensions database)

3.2 Semantic map

The co-occurrence map term analysis was performed on VOSviewer to reflect the content of research inside the decarbonised electricity boundaries. The term co-occurrence was used to create a network based on text data imported from Dimensions, title and abstract fields. The result is a map based on distance-based nodes; the node size indicates the number of publications containing a particular term (the larger the node, the greater the number of publications), while the distance between nodes indicates the strength of the relationship between the keywords (the shortest the distance, the more robust the relationship). VOSviewer provides a grouping technique of clustering the related keywords in the same group by using the same colour for each group. The most relevant terms were considered (full counting, min. occurrence of a term: 20, relevance score > 70%, normalization method: association strength), resulting 107 terms, that were grouped in 5 relevant clusters of different colours, with 3720 links. As shown in figure 5, the top 5 most frequent words in the field of decarbonised electricity were hydrogen, followed by energy storage, power systems, energy transition and climate change, highlighting the most important ways that lead to decarbonised electricity, but also their effect on the environment (hotspots for inputs and outputs).

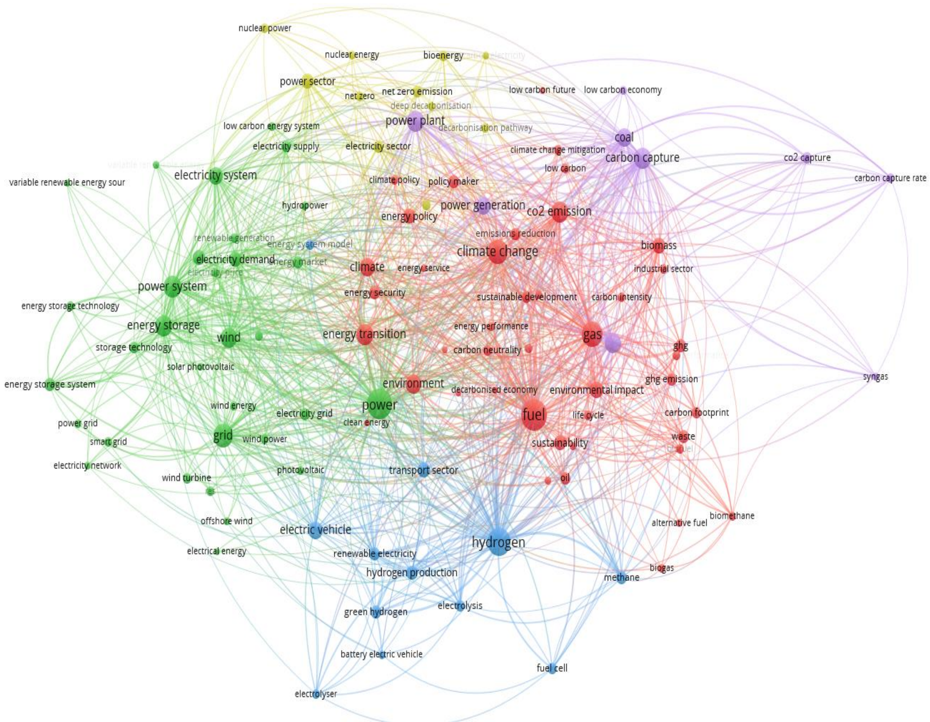

Figure 5. Co-occurrence map term analysis (Source: data retrieved from VOSviewer).

3.3. Citation and co-citation analyses

For the citation analysis, two factors were considered crucially important: the sources of publication and the cited references. The first unit selected was referring to the sources (publications) for which was set a minimum number of citations of 10 and a minimum occurrence at the source of 5, resulting 70 items, grouped in 18 clusters, with 407 links (see figure 6). Top 5 most influential journals in the field are: Energies (MDPI), Energy Policy (Elsevier), Energy (Elsevier), Applied Energy (Elsevier) and Renewable and Sustainable Energy Reviews (Elsevier).

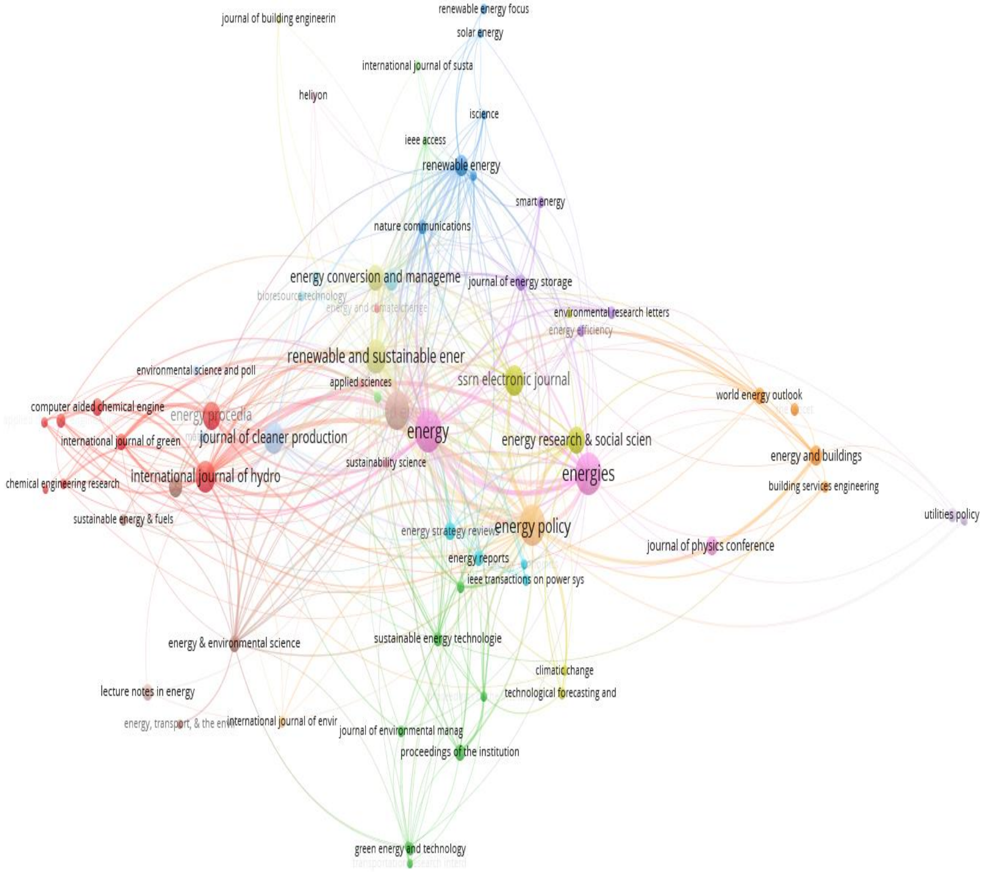

Figure 6. Citation analysis by sources (Source: data retrieved from VOSviewer)

The second unit selected was referring to the actual cited references for which was set a minimum number of citations of 20 (h index=20), resulting 58 items, grouped in 6 clusters, with 805 links (see figure 7). Top 5 most cited publications were authored by Tom Brown (Brown et al., 2018), Brian Vad Mathiesen (Mathiesen et al., 2015), Frank W. Geels (Geels, 2002), Manuel Götz (Götz at al., 2016) and Henrik Lund (Lund et al., 2017). In these papers the electricity sector is tackled, and methods of decarbonising are shown as international grid integration, smart energy systems, smart electricity grids, possibilities of transition to 100% renewable energy sources, deployment of hydrogen, and net zero buildings. Moreover, the importance of policies is highlighted to reach the decarbonisation objective of 2050.

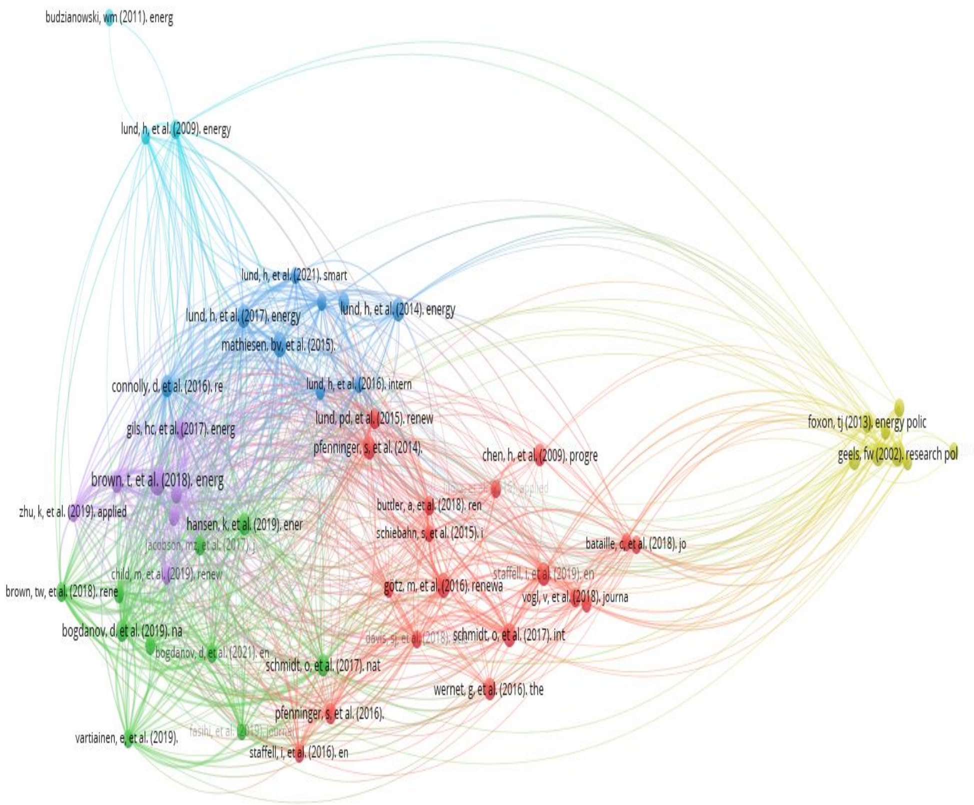

Figure 7. Citation analysis by cited reference (Source: data retrieved from VOSviewer)

For the co-citation analysis the unit selected was referring to the cited authors for which was set a minim number of citations of 20, most relevant 70%, and publications considered are those with up to 20 authors, resulting 45 researchers, grouped in 5 clusters represented by different colours, with 429 links (see figure 8). The connection of researchers is established on the basis of the number of times they cite each other. The node size is referring to the researcher's co-citation frequency, while the connections reflect the number of citations.

The top 5 most co-cited authors which have strong co-citation networks are (only one researcher selected by university): Breyer Christian (Lappeenranta University of Technology, Finland), Lund Henrik (Aalborg University, Denmark), Goran Strbac (Imperial College London, United Kingdom), Benjamin Kenneth Sovacool (Boston University, United States) and Geoffrey Paul Hammond (University of Bath, United Kingdom).

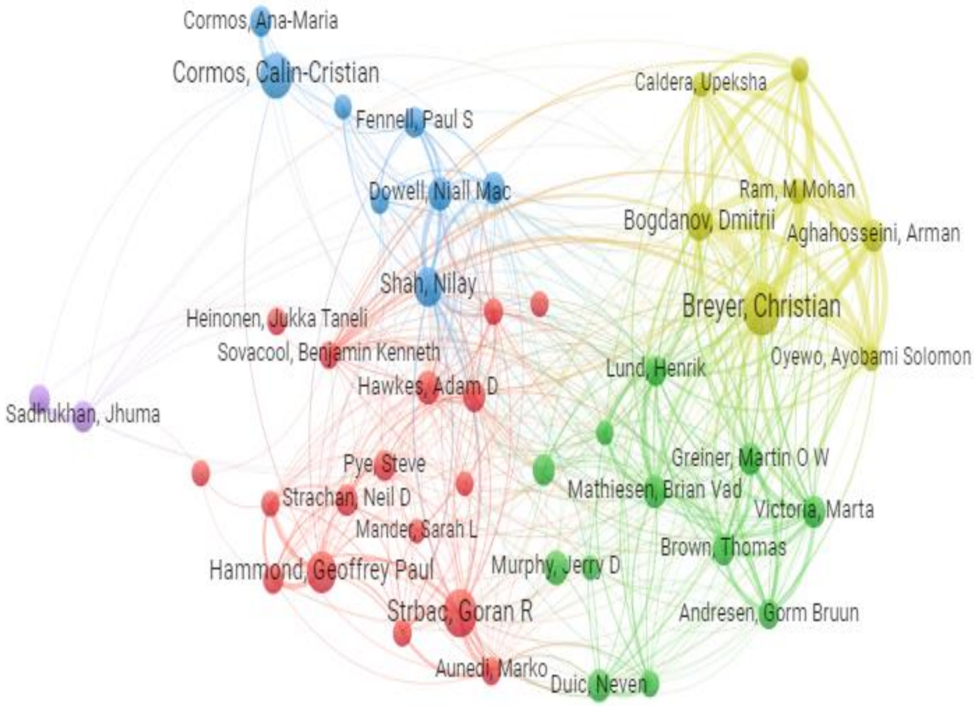

Figure 8. Co-citation network (Source: data retrieved from VOSviewer).

A challenge of this research was to retrieve data in consistent format, with no-duplications. To this end, Dimensions database was selected, as other data bases have no totally harmonized cited references, and a thesaurus file was created to remove all possible double counting. Another challenge was related to the employment of English, British and American, but after an initial screening of several writing styles and numerous keywords and logical sequences, the most appropriate string was employed in this study, which was considered to best serve its purpose.

The main contributions of this paper are as follows:

- The general analysis of the evolution of publications in the field of decarbonised electricity.
- The identification of main terms used to advance in the research direction of decarbonised electricity.
- The identification of the most influential publications, papers and authors (researchers) by applying citation and co-citation analyses.

By mapping the existing literature in the field of decarbonised electricity the paper meets its objectives. RQ1 referred to analysing the literature streams over the last 24 years and the present research showed a sharp increase in the number of publications, mostly scientific articles, mostly belonging to engineering fields. The answer for RQ2 led to the identification of the most popular keywords within the boundaries of the decarbonised electricity revealing both input and output terms. The answer to RQ3 revealed the most influential researchers, papers and journals. From countries and institutions perspectives, the UK scientists dominate the research in this field while from the publishers' perspective, the most influential production belongs to Elsevier publishing house.

The main limitations of this research lay on restricting the coverage to Dimensions database and only to articles, books and communications. It would be exciting to extend the content to patents and policies. However, these are not currently freely available for all the researchers. Another limitation may be related with the selection of the keywords, which is perfectible, but which serves the purpose of the present research. The selection of keywords aims to offer a comprehensive analysis, and the logical scheme was tested to offer the best results, based on a personal view. In such a way, this research provides a picture of decarbonised power systems and highlights its importance and the need to further study the identified hotspots. The research uncovers important issues for future research, but also identifies problems with data bases constraints as reporting and extracting valuable information, arguing for the need for a more transparent patent and policies retrieval.

4. Conclusions

Decarbonising electricity is a key issue to advance on the road towards climate neutrality. The challenges to reach the decarbonisation objective of 2050 are high considering the ongoing crises, political tensions, technological hurdles and political will.

The humanity needs a fundamental restructuring on all sustainable development pillars: economy, society and environment. The long-term ambition of climate neutrality may be achieved by decarbonizing global economy and this may be done by the states' governance capabilities to create proper comprehensive frameworks to address the climate crisis. This is a very ambitious goal, which comes at a cost for every nation, considering that fossil-fuels are still mainly deployed to secure the power needed by present living standards and, despite calls to international cooperation, every national economy is concerned with its own growth and competitiveness. Moreover, the decarbonisation must be performed in a rational and safe way, as other problems may emerge, because trying to solve one problem may lead to another. For instance, the development of some types of renewable energy (wind, solar, electric vehicles, batteries) and the development of new electricity grids which have high critical mineral intensity, will determine a major increase in demand for critical minerals as copper, cobalt, nickel, lithium, aluminium, zinc (International Energy Agency, 2022). Therefore, major challenges appear linked with investment in mining, responsible mining to avoid problems with the environment and depleting sites. Many hurdles may hinder the progress towards the climate neutrality as several problems may put supplemental strain on energy systems, as security of supply and natural endowment of a country, concern about economic growth and the structure of the national economy, social justice and democracy, trade relations and energy crisis as that linked with the current conflicts. The myriad effects on multiple dimensions and unpredictability of economic instabilities point to the need of bold transformative policies that must carve the way towards an authentic safe and rational climate neutrality. But these policies must come along with fundamental changes for restructuring of national economies and dismantling unstainable practices.

By answering the three research questions the paper systematises the knowledge in the field of decarbonised electricity, having theoretical and practical implications for researchers, scientific organizations and policy makers. The findings of this paper may assist scholars to better understand the decarbonized electricity field and to manage their research by pointing out the most relevant publications that will serve as a base for proposing new research directions. Moreover, the results of this study can be used for informing science and energy policies and research institutions and universities to better fund and evaluate scientific outputs.

The present research opens the way to address the practical challenges in deploying decarbonisation technologies by presenting also studies that are focused on real-world applications. However, the need for more practical applications remains and is a must condition for future as this may better bridge the gap between industry and academic research.

This research is part of a larger study and will continue with a comprehensive systematic review of the highly cited papers which were collected during this analysis.

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