Evolution of Energy Systems Research: Analysis of Documents Co-citation Network

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***Abstract*— The bibliometric overview investigates the evolution in the field of energy systems research over scientific publications in the Scopus database during the last two decades - 2001-2021. The study reveals the underlying topic structures derived from research document co-citation network using clustering algorithm of CiteSpace software. The representation of the research front with identified key topics is the result of visual and topological analysis of the network. The topics discovered correspond to the emerging trends such as multidimensional integration of energy systems, including hybrid renewable systems and sector coupling, cybersecurity and resilience issues, and various technologies related to machine learning, energy storage, DC microgrids, and others.**

***Index Terms*—energy systems, power systems, innovation development, research trends, research agenda, bibliometric analysis, scientometric analysis, visual analysis, CiteSpace.**

I. Introduction

Global socioeconomic development has a significant impact on energy systems, on their control and management [1]. The transformation of energy systems at the beginning of the 21st century leads to a significant technological shift and expansion of new energy technologies for production, transport, accumulation, distribution, and consumption. First of all, the use of renewable energy sources and improved efficiency are crucial topics to provide cleaner energy for a sustainable future [2]. There is an increase in the complexity of the energy infrastructures operating the flows of energy, the coverage of horizontal connections, the combination of territorial-technological and temporary management [3]. The active use of information and communication technologies fundamentally changes the root properties of energy systems. The systems become human-machine (cyber-physical) systems, interacting with the width of the network of power facilities, distributed over a large area, and functioning with a single connection of reliable and affordable power supply [4]. Understanding the future envision of the energy systems through strategic forecasting of the innovative development of the economy is a difficult and complex challenge.

On the other hand, it is possible to use intelligent and computational tools based on big data analysis to support research and respective managerial activities. One of such promising approaches is a bibliometric analysis of the documents as codified knowledge (research articles, technology patents, analytical reports, etc.) related to the R&D sector. There are a lot of publications that implement scientometric approaches to review the issues of wide-range energy systems.

Many systematic bibliometric reviews in recent decades show strong interest in energy systems. A bibliometric analysis of development knowledge on multienergy systems, microgrids and Smart Grids, based on more than 20,000 articles from the Web of Science [5]. The paper [6] provides a comprehensive overview of the results of two decades of research and enables interested readers to obtain a comprehensive overview of the key trends in the energy systems analysis (ESA).

Several reviews analise energy research focusing on certain countries at the national level such as renewable energy in Turkey [7], energy sector in Spain [8].

This article continues the bibliometric research on the development of energy systems, started in the previous work [9]. The key contributions of this paper in the field of energy systems are a representation of state-of-the-art technology and visualization of the topics of research front over the document co-citation network. This paper

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http://dx.doi.org/10.38028/esr.2022.03.0008
Received June 28, 2022. Reviewed August 8, 2022. Revised September 12, 2022. Accepted October 18, 2022.

considers a holistic perspective rather than focusing on a specific issue or area.

The approach used in the paper is one of the critical components of an intelligent decision support system in the field of strategic and innovative development of the energy sector, including understanding the interrelationships of the main thematic areas and predicting future research directions.

II. Methodology and tools

The basis of the methodology in this article is the statistical and textual analysis of bibliometric data (metadata) of an array of scientific publications in line with the concept of "big data".

The general workflow of this analysis includes several sequential steps:

1. Retrieval of publications data related to a specific problem or knowledge area.
2. Data cleaning manually or automatically to remove irrelevant publications.
3. Scientometric quantitative analysis applying various metrics like betweenness centrality to construct different co-occurrence networks. Network examples are co-authorship networks, co-word networks, co-terms networks, co-citations networks, and others. Further clustering analysis of constructed networks is also an important part of the scientometric approach.
4. Visualization of the knowledge domain and in-depth analysis to obtain the status quo of research, discover emerging trends, hidden interrelations, and other valuable outputs.

In this article, we use CiteSpace, a Java-based scientometric software package developed by Chaomei Chen, to create and visualize bibliographic record networks [10]. CiteSpace is intended for a systematic review of the scientific literature and is widely used in scientometric studies [11, 12]. CiteSpace supports a complete analytical process for visualizing and analyzing research trends and patterns in the scientific literature [13, 14].

The structure and dynamics of the literature can be analyzed in terms of a co-citation network derived from citations generated by citing articles [15]. CiteSpace uses both base documents imported from Scopus and documents obtained from the bibliographic lists of these documents to construct a network. Additionally, the document co-citation network can be decomposed into different clusters of closely related links to represent research topics [16]. These clusters can then be labeled a set of the terms extracted from the titles of the most representative citing articles for each cluster. Each cluster found within the co-citation network weighted on a time scale, represents a common research topic that is relevant in a certain period. In this way, the evolution of the key topics in the certain field can be investigated to identify the global research trends.

III. Data

The study was based on a set of scientific documents related to the field of energy systems. The Scopus International Science Citation Index database was used as a source of bibliographic metadata as in [9]. The Scopus database contains a large number of documents and has a convenient interface and API to export necessary metadata in Scopus CSV format. A search was carried out in the database using the phrases “energy system” and “power system”. The Scopus search engine automatically merges both the single and plural forms of the ‘system’ noun.

The constructed query selects research publications of document type as “Article” and “Review” from reviewed and trusted journals. Documents of type “Review” were chosen to build more consistent co-citation network. The main language of the documents is English only. Documents within the period 2001–2021 were considered since the observed growth of scientific publications.

To avoid including irrelevant documents, for example, from medical science, the search results were filtered to remove the subject areas far from “Energy” like “Medicine”, “Nursery”, “Computer Science”, “Arts and Humanities”, etc. On the other hand, since “energy” is a multidisciplinary topic, subject categories such as “Engineering”, “Chemistry”, “Environmental Science”, “Social Science”, “Material Science”, etc. remain under consideration.

The exact query text of advanced document search in Scopus is as follows:

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TITLE-ABS-KEY ( "energy system*" OR "power system*" ) AND PUBYEAR > 2000 AND PUBYEAR < 2022 AND ( EXCLUDE ( SUBJAREA,"BIOC" ) OR EXCLUDE ( SUBJAREA,"MEDI" ) OR EXCLUDE ( SUBJAREA,"ARTS" ) OR EXCLUDE ( SUBJAREA,"HEAL" ) OR EXCLUDE ( SUBJAREA,"PSYC" ) OR EXCLUDE ( SUBJAREA,"NEUR" ) OR EXCLUDE ( SUBJAREA,"PHAR" ) OR EXCLUDE ( SUBJAREA,"NURS" ) OR EXCLUDE ( SUBJAREA,"IMMU" ) OR EXCLUDE ( SUBJAREA,"VETE" ) OR EXCLUDE ( SUBJAREA,"DENT" ) OR EXCLUDE ( SUBJAREA,"Undefined" ) ) AND ( LIMIT-TO ( LANGUAGE,"English" ) ) AND ( LIMIT-TO ( DOCTYPE,"ar" ) OR LIMIT-TO ( DOCTYPE,"re" ) )
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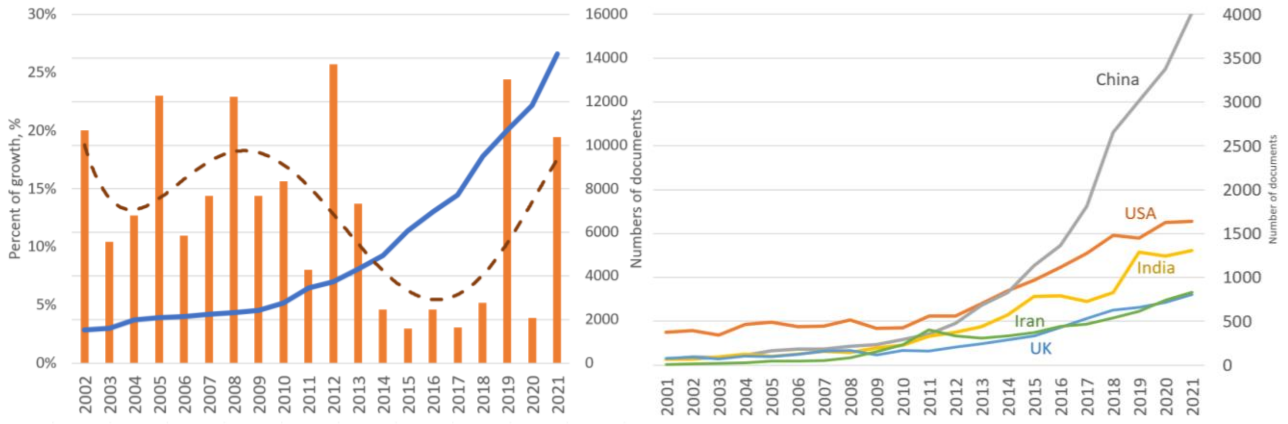
The query search on November 26, 2021, gives a quite large dataset of 103,858 documents including 98,097 research articles and 5,830 reviews. The documents were successfully imported automatically through the CiteSpace. The dataset contains:

- 3,510,634 total references,
- 3,378,143 (96.0%) valid references,
- 251,217 unique keywords.

Fig. 1 (a) presents the publishing statistics over the retrieved documents by years. The diagram shows the exponential growth in publishing activity (blue curve). The orange columns together with the calculated polynomial trending brown line are the percentages of growth from year to year. Fig. 1 (b) shows the annual publishing



a) b)

Fig. 1. Publishing growth on the field of energy systems research in the Scopus database in 2001-2021: (a) total number of documents by year (blue line) and annual growth (orange bars and dashed trend line); (b) publication activity of the top 5 countries by year.

activity of the five productive countries. The diagram represents a typical scientific publishing boom that started from the beginning of the 2010s in the world and especially in China. We see that the total annual contribution from China surpasses that of the USA and contributors from other countries since 2015.

IV. Analysis of the Document co-citation network

A weighted document co-citation network was built using CiteSpace software to analyze the evolution of research in the energy/power system field. CiteSpace's criterion for the selection to build the network is a general threshold based on the value of the g-index with expanding coefficient $k = 25$ (for more details, see [14]). This criterion delivers 2476 nodes representing research papers, and 10925 edges - citing links between them. Figure 2 represents the visualization of the network. Color indicates the year of publication relative to the timeline from 2001 up to 2021, and the size of the node depends on the number of citations. Due to significant growth of research activity, scientific publication, and citing practices as shown on Fig. 1 the density of the network is much higher for period 2011-2021.

Cluster analysis, applied to the constructed network, detects the main topics (clusters) to which the researchers was drawn. Each topic is characterized by a keyword profile, which is a set of specific terms obtained from the text information of documents (title, keywords, abstract) related to a specific cluster. All clusters are numbered in descending order of their sizes. Cluster labels are obtained from the titles of the papers using a log-likelihood ratio (LLR) weighting algorithm. The LLR algorithm is used to calculate and define a set of terms or keyword's profiles that represent the basic theme of each cluster of co-cited documents. On figure 2 only top terms of cluster keyword's profile are shown. In some cases, they could not reflect the actual topic of a particular cluster. Table 1 contains list of most frequent terms for each cluster. In general, these terms describe the topic together.

Based on the results of the cluster analysis of the co-citation network, the "hottest" topics of energy / power system research are observed. The two main branches are detected visually.

First, the strongest topic #0 "hybrid renewable energy system" represents the main research efforts of the last few years focused on effective solutions to implement renewable energy sources into conventional energy systems. Of course, topic #0 is very close to relating topics such as #12 "energy storage system" and #3 "integrated energy system". The stochastic nature of renewable energy sources requires the development of energy storage technologies to provide a reliable energy supply. "Integrated energy systems" is another promising concept for the flexible use of different energy sources and technologies. The next important topic in the research branch is #1 "sector coupling", which means combining energy-consuming sectors (buildings heating and cooling, transport and industry) with power generation. Sector coupling plays the important role in the context of decarbonization. The topics mentioned above have the ancestor topic #2 "heat roadmap Europe", which has a more informative label as "smart energy system" of the same weight. This topic began to be actively discussed in the late 2000s. The next topic #13 "energy justice" collects papers addressing to the socioeconomic issues and new market regulations that follow with the technological transformation of energy systems.

Second main research branch in Figure 2 is formed by four clusters: #5 "robust unit commitment", #7 "dc microgrid", #8 "electric vehicle", #11 "false data injection attack".

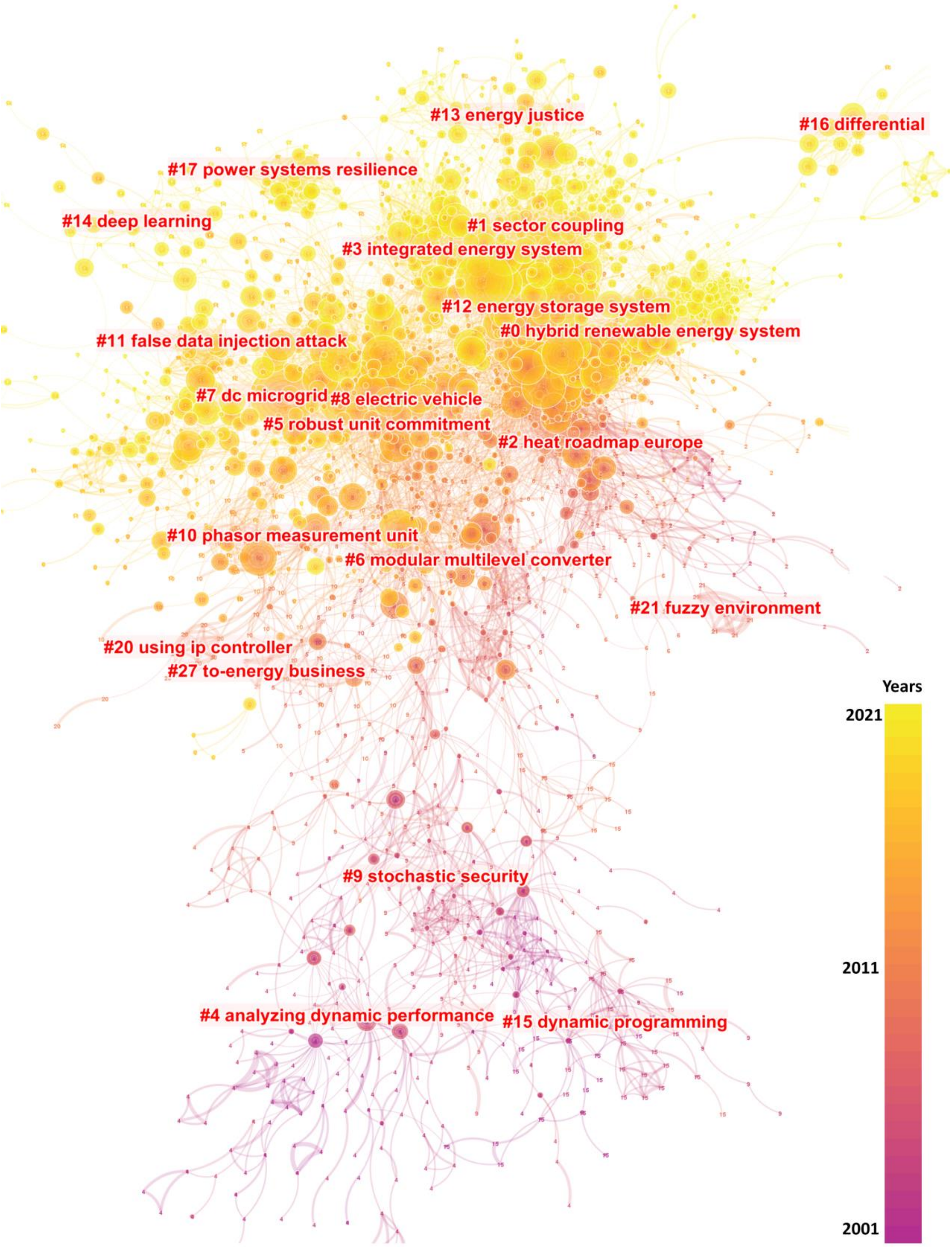


Fig. 2. Clusters with topic labels found on the document co-citation network.

Table 1. Cluster keyword profiles identified from document co-citation network in 2001 - 2021.

Cluster ID	Size	Silhouette	Mean year	Label (LLR)
0	200	0.919	2013	hybrid renewable energy system (66479.66, 1.0E-4); hybrid energy system (52691.74, 1.0E-4); case study (25715.16, 1.0E-4); renewable energy system (20119.44, 1.0E-4); techno-economic analysis (20020.19, 1.0E-4)
1	183	0.851	2015	sector coupling (21530.39, 1.0E-4); high share (15783.33, 1.0E-4); power sector (13901.89, 1.0E-4); energy system model (13493.96, 1.0E-4); hydrogen production (13243.51, 1.0E-4)
2	181	0.865	2007	heat roadmap Europe (7019.11, 1.0E-4); smart energy system (7019.11, 1.0E-4); large-scale integration (6854.62, 1.0E-4); energy system analysis (5501.04, 1.0E-4); life cycle (5434.42, 1.0E-4)
3	176	0.873	2014	integrated energy system (56565.28, 1.0E-4); multi-energy system (38993, 1.0E-4); energy hub (29611.42, 1.0E-4); energy system (23101.55, 1.0E-4); integrated electricity (20500.39, 1.0E-4)
4	173	0.995	1998	analyzing dynamic performance (4445.52, 1.0E-4); vector field (4445.52, 1.0E-4); parameter space (4445.52, 1.0E-4); controller design (3908.49, 1.0E-4); using normal form (3201.91, 1.0E-4)
5	158	0.873	2009	robust unit commitment (16387.49, 1.0E-4); unit commitment (15905.79, 1.0E-4); stochastic unit commitment (13278.1, 1.0E-4); wind uncertainty (10865.33, 1.0E-4); wind power generation (8874.34, 1.0E-4)
6	153	0.899	2007	modular multilevel converter (10225.39, 1.0E-4); wind energy conversion system (8300.53, 1.0E-4); grid integration (8026.56, 1.0E-4); reactive power control (7156.72, 1.0E-4); dc-dc converter (6702.55, 1.0E-4)
7	147	0.88	2013	dc microgrid (39370.32, 1.0E-4); virtual synchronous generator (31684.68, 1.0E-4); islanded microgrid (16861.55, 1.0E-4); weak grid (16559.39, 1.0E-4); stability analysis (13693.78, 1.0E-4)
8	128	0.808	2011	electric vehicle (41492.13, 1.0E-4); plug-in electric vehicle (21378.23, 1.0E-4); load frequency control (20115.16, 1.0E-4); smart grid (13442.44, 1.0E-4); quasi-oppositional harmony search algorithm (12717.23, 1.0E-4)
9	115	0.958	2001	stochastic security (2423.06, 1.0E-4); competitive electricity market (1835.85, 1.0E-4); ac constraint (1719.57, 1.0E-4); transmission system (1530.28, 1.0E-4); power systems operation (1215.97, 1.0E-4)
10	99	0.93	2008	phasor measurement unit (13746.54, 1.0E-4); gravitational search algorithm (9657.52, 1.0E-4); economic load (5584.26, 1.0E-4); artificial bee colony algorithm (4953.39, 1.0E-4); considering measurement redundancy (4558.35, 1.0E-4)
11	84	0.914	2013	false data injection attack (58164.37, 1.0E-4); smart grid (39959, 1.0E-4); cyber attack (22401.6, 1.0E-4); power grid (8392.18, 1.0E-4); data integrity attack (8116.37, 1.0E-4)
12	71	0.883	2013	energy storage system (19599.3, 1.0E-4); energy storage (18119.66, 1.0E-4); hybrid energy storage system (13705.2, 1.0E-4); energy storage technologies (11584.05, 1.0E-4); air energy storage system (11029.82, 1.0E-4)
13	60	0.956	2015	energy justice (9966.24, 1.0E-4); to-peer energy trading (9261.4, 1.0E-4); energy transition (9064.67, 1.0E-4); power system (3914, 1.0E-4); local electricity market (3531.15, 1.0E-4)
14	58	0.977	2016	deep learning (14204.23, 1.0E-4); machine learning (8584.87, 1.0E-4); deep learning model (6963.23, 1.0E-4); reinforcement learning (5034.53, 1.0E-4); deep reinforcement learning (4434.68, 1.0E-4)
15	55	0.976	2000	dynamic programming (774.48, 1.0E-4); traditional structure (689.64, 1.0E-4); enhanced adaptive lagrangian relaxation (647.56, 1.0E-4); economic load (633.93, 1.0E-4); generator planning (633.53, 1.0E-4)
16	32	1	2016	differential evolution (2623.51, 1.0E-4); incorporating stochastic wind (2472.89, 1.0E-4); solar generation (2472.89, 1.0E-4); facts device (2183.14, 1.0E-4); phosphoric acid fuel cell (2144.65, 1.0E-4)
17	29	0.997	2016	power systems resilience (2553.7, 1.0E-4); extreme weather event (2458.55, 1.0E-4); energy system resilience (1697.81, 1.0E-4); power system resilience (1678.57, 1.0E-4); resilience assessment (1613.58, 1.0E-4)
19	19	1	2012	wireless power transfer system (5914.99, 1.0E-4); inductive power transfer system (4391.08, 1.0E-4); wireless power transfer (1865.97, 1.0E-4); resonant converter (912.41, 1.0E-4); three-coil wireless power transfer system (796.6, 1.0E-4)
20	11	1	2006	using ip controller (372.53, 1.0E-4); two-area load frequency control (195.65, 1.0E-4); multi-area load frequency control (173.83, 1.0E-4); harmony search (129.97, 1.0E-4); PID controller adjustment (64.98, 1.0E-4)
21	7	0.999	2005	fuzzy environment (74.88, 1.0E-4); community-scale renewable energy system (49.51, 1.0E-4); uncertainty-an interval chance-constrained programming approach (49.51, 1.0E-4); regional energy system (32.59, 1.0E-4); multiple uncertainties (24.66, 1.0E-4)
27	4	1	2010	to-energy business (54.78, 1.0E-4); considering environmental constraint (27.05, 1.0E-4); power system (2.12, 0.5); smart grid (0.22, 1.0); case study (0.19, 1.0)

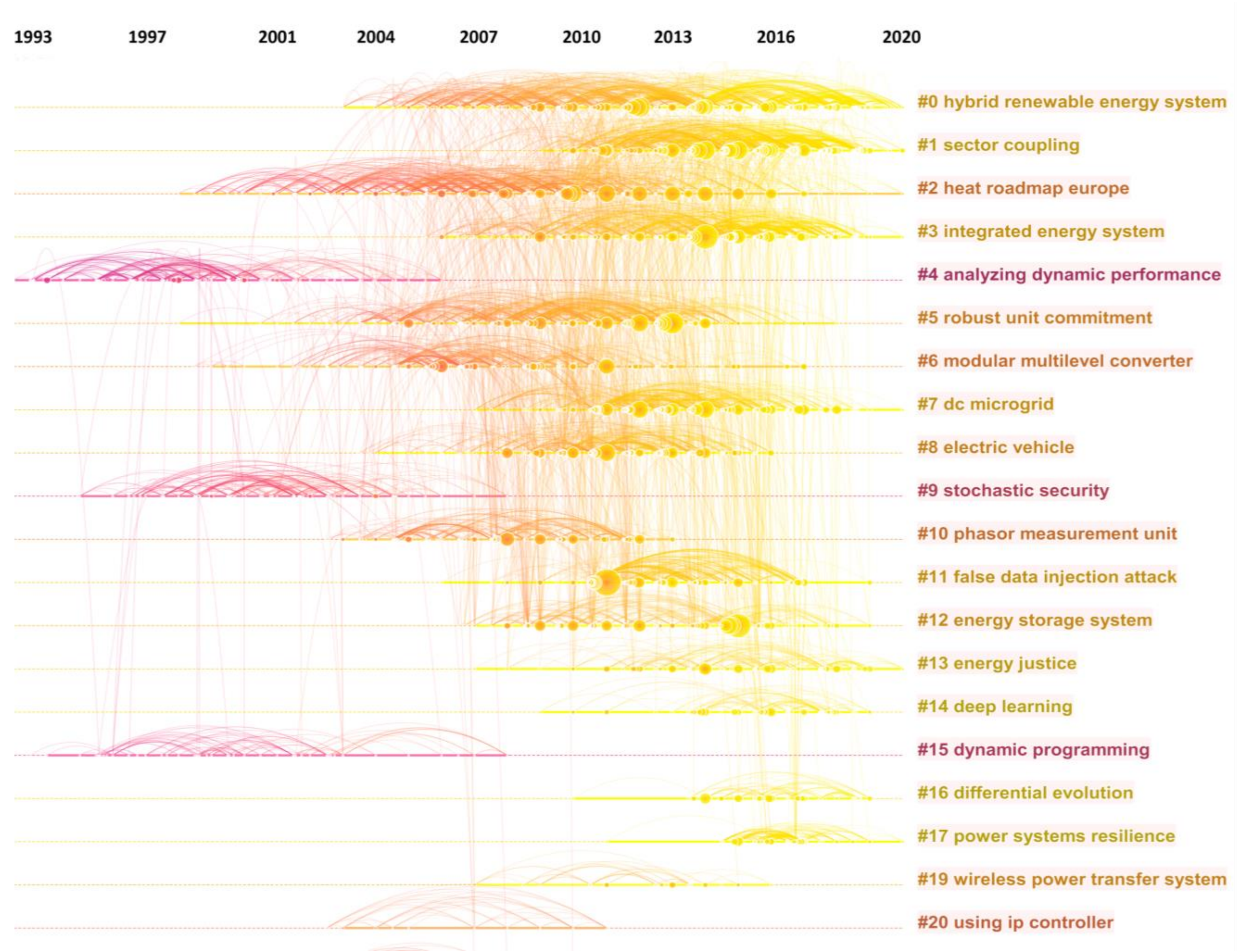


Fig. 3. Distribution of the topic clusters of the document co-citation network in the field of energy systems on the timeline.

In comparison with the first branch, these topics relate to the various advanced aspects of flexible and intelligent operation control in energy systems rather than development issues.

In addition, at the top of the network there are several separate topic clusters. These topics are more recent and, therefore, they have less citation impact. Cluster #14 "deep learning" reflects the relevance of using machine learning methods for adaptive intelligent control and management of electric power systems. #17 "power system resilience" is another important topic that highlights the increasing attention to the issue of system resilience during recent years.

The research frontier is clearly observed on the document co-citation network (Fig. 3). The frontier topics are colored yellow according to the colormap used.

Figure 3 summarizes the distribution of the detected topic clusters of the document co-citation network over the period considered. The timeline view of the revealed clusters represents the evolution roadmap of energy / power systems research. The sizes of the circles correspond to a number of future citations. The curves along and between the main cluster lines are inner citations and cross-topic citations.

It is important to investigate the majority of publications cited in the built document co-citation network as having the highest impact on the scientific community. These documents have citation bursts that reflect changes in trending topics. A citation burst indicates that the citations of an article increase rapidly over a period of time. Table 2 reports the 50 references with the strongest citation burstiness. References are ordered by the start year of the burst to track the evolution of research focus. In Table 2, the column "Year" refers to the year of publication. The values of the column "Strength" are calculated by the default Kleinberg algorithm of CiteSpace. "Begin" refers to the year in which the citation of a publication begins to burst. The "End" column contains the last year of a burst. The red zone on the line in the last column shows the placement of the citation burst over time period 2001-2021. The average duration between publication year and mean year of the citation burst is about 5,25 years. The average duration of the burst period is about 2,5 years.

Table 2. List of top 50 documents with the strongest citation bursts in 2001-2021.

References	Year	Strength	Begin	End	2001 - 2021
[17] Kundur P, 1994, Power System Stability and Control	1994	34.15	**2001**	2002	
[18] Sauer PW, 1998, Power System Dynamics and Stability	1998	34.06	**2001**	2006	
Hingorani NG, 2000, Understanding FACTS	2000	30.7	**2002**	2008	
Abur A, 2004, Power System State Estimation	2004	32.28	**2005**	2012	
[20] Ackermann T, 2005, Wind Power in Power Systems	2005	49.62	**2007**	2013	
[21] Lund H, 2005, Large-scale integration of wind power into different energy systems @ Energy, V30, P2402-2412	2005	34.77	**2007**	2013	
[19] Kundur P, 2004, Definition and classification of power system stability @ IEEE Trans Power Syst, V19, P1387-1401	2004	27.65	**2007**	2012	
[25] Blaabjerg F, 2006, Overview of control and grid synchronization for distributed power generation systems @ IEEE Trans Ind Electron, V53, P1398-1409	2006	26.46	**2007**	2014	
Bollen MHJ, 2006, Signal Processing of Power Quality Disturbances	2006	25.93	**2007**	2014	
[22] Carrasco JM, 2006, Power-electronic systems for the grid integration of renewable energy sources, V53, P1002-1016	2006	55.33	**2008**	2014	
[26] Pepermans G, 2005, Distributed generation, V33, P787-798	2005	28.27	**2008**	2013	
Akagi H, 2007, Instantaneous Power Theory and Applications to Power Conditioning	2007	28.2	**2008**	2015	
[24] Lund H, 2007, Renewable energy strategies for sustainable development @ Energy, V32, P912-919	2007	38.3	**2009**	2015	
Phadke AG, 2008, Synchronized Phasor Measurements and Their Applications	2008	49.59	**2010**	2016	
[23] Lund H, 2008, Integration of renewable energy into the transport and electricity sectors through V2G @ Energy Policy, V36, P3578-3587	2008	43.97	**2010**	2016	
[27] Chicco G, 2009, Distributed multi-generation, V13, P535-551	2009	34.26	**2010**	2017	
Shayeghi H, 2009, Load frequency control strategies, V50, P344-353	2009	31.9	**2010**	2017	
[35] Kempton W, 2005, Vehicle-to-grid power implementation, V144, P280-294	2005	28.38	**2010**	2013	
[28] Pal B, 2005, Robust Control in Power Systems	2005	25.36	**2010**	2013	
[30] Strbac G, 2008, Demand side management, V36, P4419-4426	2008	48.46	**2011**	2016	
[32] Tuohy A, 2009, Unit commitment for systems with significant wind penetration @ IEEE Trans Power Syst, V24, P592-601	2009	38.43	**2011**	2017	
Lund H, 2010, The role of district heating in future renewable energy systems @ Energy, V35, P1381-1390	2010	28.72	**2011**	2017	
Flourentzou N, 2009, VSC-based HVDC power transmission systems, V24, P592-602	2009	26.53	**2011**	2017	
[41] Rashedi E, 2009, GSA, V179, P2232-2248	2009	38.15	**2012**	2017	
Wang J, 2008, Security-constrained unit commitment with volatile wind power generation @ IEEE Trans Power Syst, V23, P1319-1327	2008	33.03	**2012**	2016	
[33] Zhou W, 2010, Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems @ Appl Energy, V87, P380-389	2010	26.8	**2012**	2016	
[29] Bevrani H, 2009, Robust Power System Frequency Control	2009	26.65	**2012**	2017	
[37] Chen H, 2009, Progress in electrical energy storage system, V19, P291-312	2009	44.61	**2013**	2017	
[36] Clement-Nyns K, 2010, The impact of charging plug-in hybrid electric vehicles on a residential distribution grid @ IEEE Trans Power Syst, V25, P371-380	2010	28.92	**2013**	2018	
Farhangi H, 2010, The path of the smart grid @ IEEE Power Energy Mag, V8, P18-28	2010	28.65	**2013**	2018	
[38] Beaudin M, 2010, Energy storage for mitigating the variability of renewable electricity sources, V14, P302-314	2010	28.16	**2013**	2017	
[34] Morales JM, 2009, Economic valuation of reserves in power systems with high penetration of wind power @ IEEE Trans Power Syst, V24, P900-910	2009	27.21	**2013**	2017	
[31] Palensky P, 2011, Demand side management, V7, P381-388	2011	25.87	**2013**	2019	
[40] Connolly D, 2010, A review of computer tools for analyzing the integration of renewable energy into various energy systems @ Appl Energy, V87, P1059-1082	2010	56.21	**2014**	2018	
Zimmerman RD, 2011, MATPOWER, V26, P12-19	2011	59.72	**2016**	2019	
Sun J, 2011, Impedance-based stability criterion for grid-connected inverters @ IEEE Trans Power Electron, V26, P3075-3078	2011	28.52	**2017**	2019	
[39] Hirsch A, 2018, Microgrids, V90, P402-411	2018	29.62	**2019**	2021	

In the beginning of the period the power system stability, dynamics and control were more attractive topics [17-19]. From the middle of the first decade the focus was shifted to renewable energy sources, especially wind power generation [20, 21]. The two main issues at this time are:

(1) Integration of renewable sources into electric power systems [21-23] to provide sustainable economic development [24];

(2) Coordination of distributed generation, including renewable sources, with operating conditions of the electrical power grid [25, 26]. The “distributed generation” remained a highly cited topic in the next decade [27].

In the 2010s, we can see several important topics from highly cited publications. On the one hand, there has been an increase in attention to robust electric power system control [28, 29], and on the other hand to the demand side management for effective electricity supply [30, 31].

Research efforts aimed at optimal implementation of renewable and alternative energy sources in electric power systems [32-34], including in connection with the future spread of electric vehicles [35, 36]. Progress in the use of energy storage systems becomes important for effective management to compensate volatile electricity production from stochastic renewable sources [37, 38]. At the end of the review period, the development and operating becomes an unexpectedly popular topic [39]. The general trend of the second period is also that researchers are interested in the appropriate approaches and tools for modeling and optimizing transforming energy systems [40, 41].

V. Conclusions

This work presents a scientometric review of energy systems research for the last two decades 2001-2021 through an exhaustive analysis of research literature retrieved from the Scopus database. In opposite to the other bibliometric studies in the energy field, this analysis mainly focuses on the topic structures and its and temporal evolution. The document co-citation network was built on the basis of more than 100,000 publications. In addition, the top 50 publications with strong citation bursts were analyzed. Thus, the general topics hotspots and development trends in the research of energy systems were evaluated and visualized.

This study has several limitations. First, it should be noted that the semantic meaning of the basic terms of the study concerns mainly electric power systems, but not energy systems in general. In the study, energy systems related to heat supply and different types of perspective fuel supply (natural gas, hydrogen, methanol, etc.) were poorly considered.

Another limitation is the nonuniform temporal resolution at the construction of the document co-citation network. It is difficult to identify representative clusters in earlier periods, as there was increased publication activity and abundant citations from the middle of the 2010s. This drawback can be overcome in future research through the use of a dynamic thresholding g-index value.

The study represents the dynamics in the most common topics in the knowledge domain, but deeper semantic structures and their interrelations remained outside of the consideration. The quantification and classification of the multidisciplinary and complex field of energy systems is not simple. Future work implies the use of a predesigned hierarchical ontology to overcome existing gaps and to build an adaptive semantic model of developing the knowledge domain of energy systems.

The preliminary results of the study were presented and discussed at the conference “Information and Mathematical Technologies in Science and Management”, June 29 - July 8, 2021, Irkutsk, Russia.

Acknowledgments

The research is funded by the Russian Foundation for Basic Research (project No. 20-07-00994).

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