Qualitative assessment and global mapping of research trends in supercritical CO_2 power cycle technology

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Abstract

Worldwide attempts are being made to harness wasted heat or optimize the power systems by achieving the theoretical efficiency of supercritical carbon dioxide (S-CO_2) power cycle. The heterogeneity and variable quality of scholarly data may challenge researchers of the field (S-CO_2 power cycle) to survey all of the available information. This study is focused on scientometric analysis provide deep insights into global research performance and the collaborative architectonical structure. It reveals the progressive research trend (2000-2019) of Supercritical Carbon dioxide (S-CO2) power cycle and hotspot areas by considering various quantitative measures. The sophisticated altimetric model was employed to analyze scientific researches that originated from Scopus Elsevier and Web of Science. Quantitative measures include the contribution of countries, organizations, authors, funding agencies, and journals were investigated and ranked. Moreover, a scientific mapping approach is applied to identifying the cross-connections of each quantitative measure. It is indicated that the S-CO_2 power cycle focused research increased exponentially from 2010. National Natural Science Foundation of China, USA Department of Energy, and Fundamental Research Funds for the Central Universities are leading sponsor agencies. USA Department of Energy, Xian Jiao Tong University, and Korea Advance Institute of Science and Technology are the most productive organizations. Similarly, Energy, Applied Thermal Engineering, and Energy Conversion and Management are top productive journals. At the same time, the USA, China, and South Korea are leading countries, and Lee, Jeong Ik Dai, Yiping Lee, and Jekyoung are the most dominating Authors in the S-CO_2 power cycle technology developmental contributions. The core study areas include layout configuration with other power cycles, especially the Brayton cycle, optimization of operating conditions, and design of heat exchangers. S-CO_2 higher condensation temperature and need of cooling media below ambient conditions is the big challenge in hot geographic regions. Dynamic modeling with integrated optimization, the study on compactness, simplicity of the S-CO_2 power configuration as well as improving condensation temperature could be more hotspot areas in future research.

Keywords: S-CO_2 power cycle; Scientometric; Scientific mapping; waste heat recovery; Energy Efficiency

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1. Introduction

A rapidly growing concern to harness renewable resources and clean energy, especially thermal conversion and power generation, has accelerated the research intentions for waste heat recovery with improved efficiencies [1]. It is estimated that more than 50% energy is wasted in industries and power sector [2]. A variety of eco-friendly technologies have been proposed in the current era for thermal conversions and to reduce greenhouse emissions effectively [3-4]. Utilization of low-grade heat from industrial waste, solar plants, geothermal energy, municipal solid waste into energy or other thermodynamic cycles is well-known and most promising ideas to increase the system performance [5-6]. The power cycle employed at supercritical temperature and pressure (S-CO_2 power cycle) is gaining more interest in scientists as modern technology with versatile applications [7-8].

In the last two decades, a series of different projects and experimental loops on the S-CO_2 power cycle are being investigated and still under development to explore more fundamental aspects. Since 2007, "The S-CO_2 Power Cycles Symposium" takes place every two years and regular activity in the ASME Turbo Expo conference. Recently, several conferences are being organized in Europe (1st European Seminar on Supercritical CO_2 Power Systems and 1st International Seminar on Non-Ideal Compressible-Fluid Dynamics for Propulsion & Power) [9].

The exponential increase in the number of publications since the start of the current century also indicated the worth of S-CO_2 power cycle employment. There are vast applications in industries specifically the processes include heat exchange phenomena including Concentrating Solar Power, Turbomachinery, Fossil Energy and Nuclear energy conversion units and most but not least waste heat recovery applications in all power cycles [10–18]. Over the past two decades, the published papers related to the S-CO_2 power cycle covered many aspects, including configuration, heat source categorization and application, standalone/combined cycles, locus, and particular embodiments [19]. Crespi et al. [1] published the most recent review article with a summary of the S-CO_2 power cycle, inline studies, and discussed the definite work of different authors in the field. However, no attempts have been made on the perspective of the developmental and research trend of the S-CO_2 power cycle research publications, which can quantitatively evaluate the significance of the field in the knowledge advancement and identify major research themes to set future goals and collaborative studies. Many of the research publications based on scientometric has been highlighted by Imran et al. [4] in their recent work. To analyze the global impact and importance of scientometric, several studies in different domains are reported every year; the research in the energy field is presented in Table 1.

Table 1

Recent scientometric and bibliometric studies in the field of energy.

Reference	Descriptive content	Data time span
[20]	Where is Thermal Energy Storage (TES) research going on?	1998-2017
[21]	Research on biomass energy and environment from the past to the future	1998-2017
[22]	A retrospective analysis with bibliometric of energy security	2000-2017
[23]	A review of research on embodied energy of buildings	1996-2015
[24]	Renewable energy source integration into power networks, research trends and policy implications	2000-2016
[25]	Heterogeneity of industrial development and evolution of cleaner production	2002-2017
[26]	Characteristics and trends of research on waste-to-energy incineration	1999-2015
[27]	Past, current and future of biomass energy research	1998-2013
[28]	Way forward to alternative energy research	1994-2013
[29]	Bibliometric and visualized analysis of China's coal research	2000-2015
[30]	Chinese energy and fuels research priorities and trend	1993-2012
[31]	Assessment on the research trend of low-carbon energy technology investment	1985-2013
[32]	A scientometric analysis and visualization of global green building research	1974-2013
[33]	A scientometric study of heat transfer journal literature	1900-2017
[34]	Scientometric review of global research trends on green buildings in construction journals	1992-2018
[35]	The research on energy in Spain	1957-2012
[4]	Recent research trends in organic Rankine cycle technology	2000-2016
[36]	Mapping renewable energy subsidy policy research published from 1997 to 2018: A scientometric review	1997-2018

There has been an increasing interest in the low temperature and waste heat to power conversion technologies in recent years. The literature related to the S-CO2 power cycle field has grown substantially. Therefore, it is of crucial importance to identify the core research themes, contribution of authors and institutes, and qualitatively assess the publications. None of the previous work on the S-CO2 power cycle addresses these aspects. The heterogeneity and variable quality of scholarly data may challenge researchers of the field (S-CO2 power cycle) to survey all of the available information. This study is focused on scientometric analysis provide deep insights into global research performance and the collaborative architectonical structure. It reveals the progressive research trend (2000-2019) of Supercritical Carbon dioxide (S-CO2) power cycle and hotspot areas by considering various quantitative measures. The sophisticated altimetric model was employed to analyze scientific researches that originated from Scopus Elsevier and Web of Science. Quantitative measures include the contribution of countries, organizations, authors, funding agencies, and journals were investigated and ranked. Moreover, a scientific mapping approach is applied to identifying the cross-connections of each quantitative measure.

The objective of this work to qualitative analysis and developmental trends of the S-CO_2 power cycle research cluster and identify the ignored areas to reveal internal structures and hidden inferences for technology advancement. In this way, the number of quantitative measures is investigated, including but not limited to highly productive and influential authors, most contributing countries, top institutions, and collaborating authors. This study can provide an in-depth understanding and guidance for researchers and to systematically reveal the gap between lab research and commercialization with industry adoptability impact and core areas that required more attention.

2. Research Methodology

In this analysis, the Scopus and Web of Science Core Collection (Thompson Reuters Corporation) with altimetric evaluation is employed to retrieve the bibliographic study on S-CO_2 power cycle-based publications. It has been witnessed that Web of Science and Scopus has wider coverage on scientific publications [37][4]. The number of science mapping tools are available for analyzing and visualizing structural, dynamic, and temporal patterns and trends in the scientific literature. Based on the specific analysis, every science mapping tool has its own weak and strong core points. Therefore, to improve the quality of science mapping research and core analysis, appropriate use of different tools according to the study domain is necessary. After analyzing different science mapping methods, VOSviewer, SciVal, and CiteSpace were selected.

Supercritical carbon dioxide is also used as a fluid and reacting element in different chemical productions and as catalysts. However, only the application as heat transfer or employment in the power cycle was considered during database investigation. The research database was filtered using all possible abbreviations and words "S-CO_2 power cycle, supercritical CO_2 power cycle, Supercritical carbon dioxide power cycle, S-CO_2 power cycle" in article title, abstract and keywords of the database. Another filter was applied by just considering the era of the 21st century's progress (2000-2019) to find the growth and prospect of presently growing organizations and scientists in the S-CO_2 power cycle field. Finally, a total of 1159 articles on the S-CO_2 power cycle from 2000 to 2019 were considered for the scientometric study.

3. Results and discussion

The publication cluster extracted from Web of Science and Scopus database evaluated with already briefed quantitative parameters, subfield categories, sequential publication rate by year, organization growth, countries growth based on research productivity analysis, and top authors of the field is presented and discussed. However, the significance of each work may vary from article to article. The citation of the publication could be a good indicator of the importance of each work. Moreover, the mapping trends and nodes with different strength categories are also presented with the employment of the VOSviewer mapping tool. The mapping is the network visualization, and all items presented by circles. The thickness of the circle presents the strength and productivity of the item, and the curve lines and curve thickness between items showed the connectivity/collaboration/keyword occurrence of the publications.

3.1. Publication trend

There were 976 articles published from 2000-2019, as shown in Figure 1. The number of publications on S-CO_2 power cycle employment is increasing exponentially from the year 2010. The growing trends of environmental impacts due to thermal systems and rated concern of energy-efficient technologies and worldly intentions' by G8 and G20 meetings might follow a rapid increase in publication trend from 2009 to date. The S-CO_2 power cycle versatile applications of already existing systems, like thermal power plants, CSP technologies, and marine engines, make it more popular in the current decade. The abrupt yearly increase in the publication shows the high interest of researchers towards energy-saving technologies and waste heat recovery-based interests and the adaptability of the S-CO_2 power cycle.

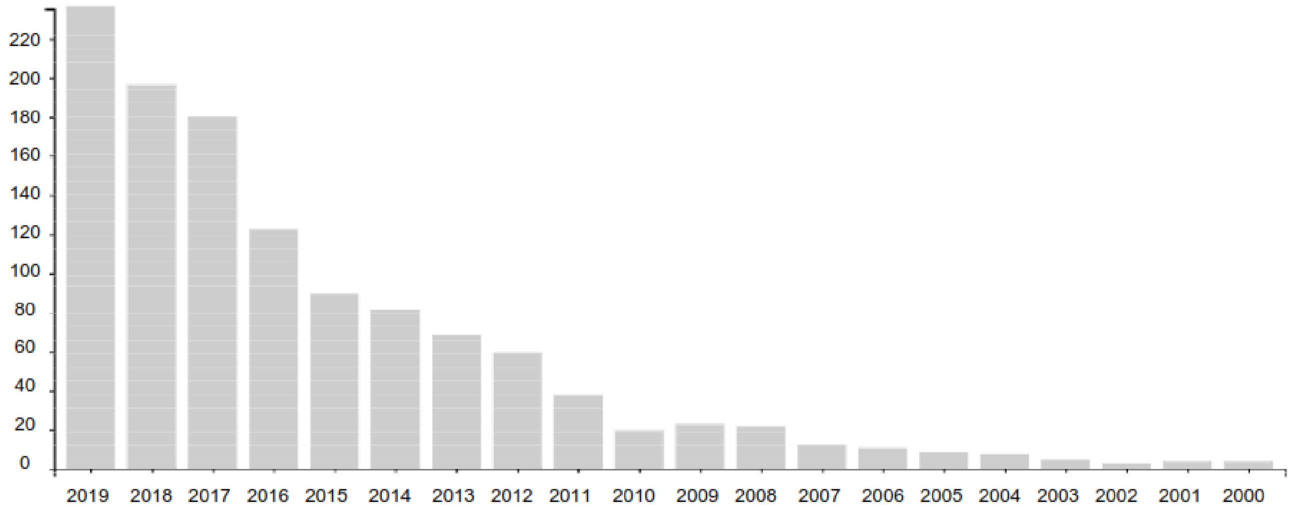

Figure 1: Yearly growth trend of S-CO_2 power cycle publications

3.2. Study divergence

The worldwide contribution to the S-CO_2 power cycle is mostly based on consistently organized annual meetings, which covers more than 50% of the total publications, as shown in Figure 2. There are various organizations scheduled meetings, i.e., "the Supercritical CO_2 Power Cycles Symposium" takes place since 2007 with the interval of every two years in the United States, another committee was established by the International Gas Turbine Institute in 2012, which is now developing regular activity in the ASME Turbo Expo conference. Recently, a series of short meetings have also been organized in Europe (1st European Seminar on Supercritical CO_2 (SCO_2) Power Systems and 1st International Seminar on Non-Ideal Compressible-Fluid Dynamics for Propulsion & Power).

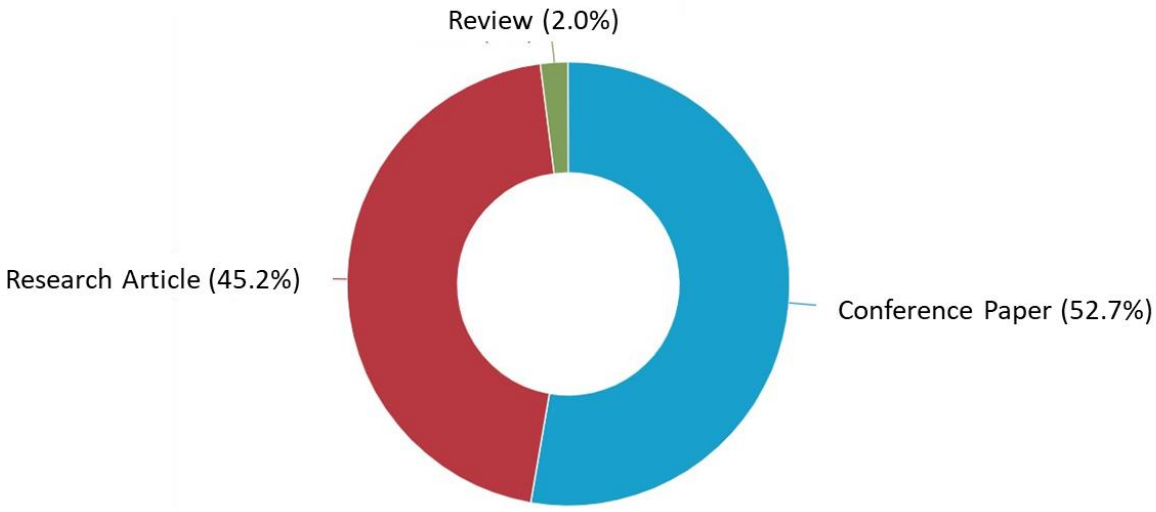

Figure 2: Article types

The conditional distribution of S-CO_2 power cycle research studies retrieved from Scopus and WoS database is shown in Figure 3. More than 50% of published work covered the subject area of the Energy and Engineering domain. This distribution is also supporting evidence of the above-cited mapping trend, which also highlighted the similar behavior of the S-CO_2 power cycle, mostly in the Energy sector.

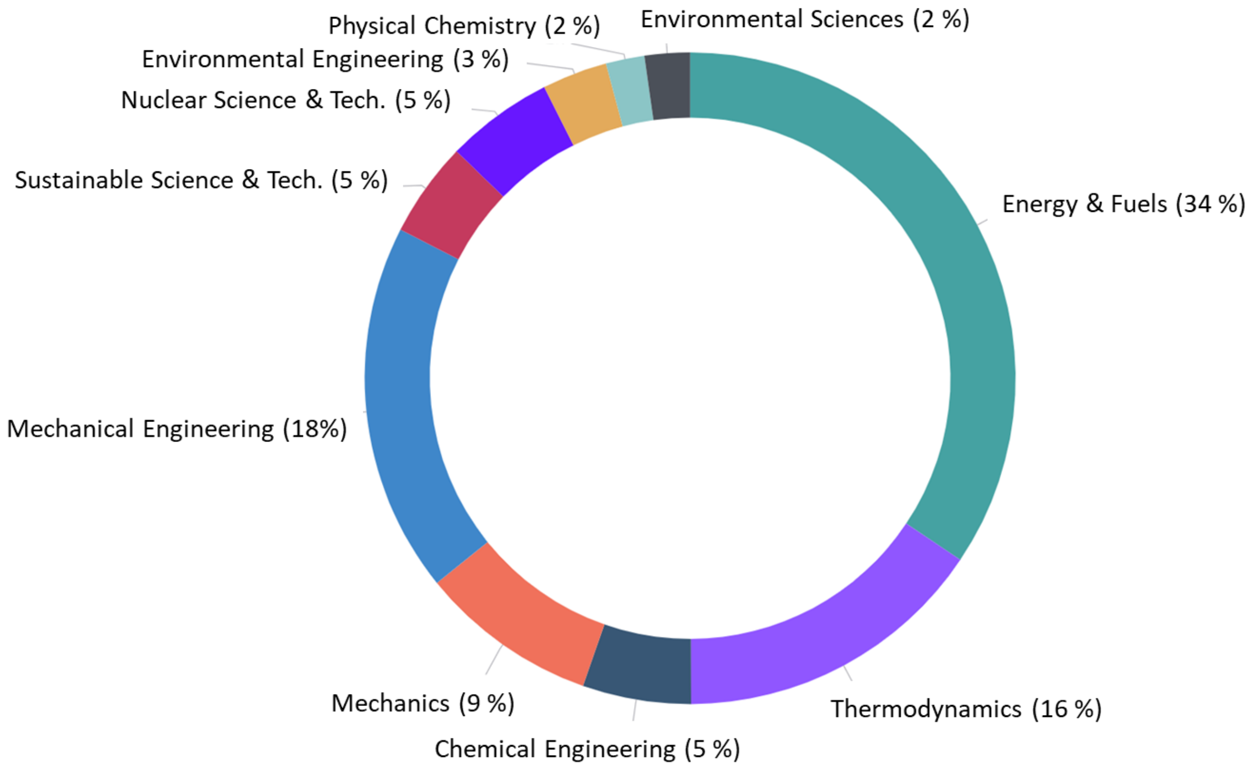

Figure 3: Categorical distribution

It is worth mentioning that the employment of the S-CO_2 power cycle is getting a significant role in the power industry and application of waste heat recovery in other energy systems. A categorical analysis based on the occurrence and frequency of keywords in relevant publications annually and based on fractional counting methodology is shown in Fig. 4 and Fig. 5. The interest of the S-CO2 power cycle initially drawn by nuclear technology-based systems and then conventional power plants. In recent years the more S-CO2 study has been undertaken on the system development with optimization of CSP and other renewable energy systems. The heat exchanger recuperates, and various flexible configuration options of the S-CO2 power cycle are the hotspot areas in recent days.

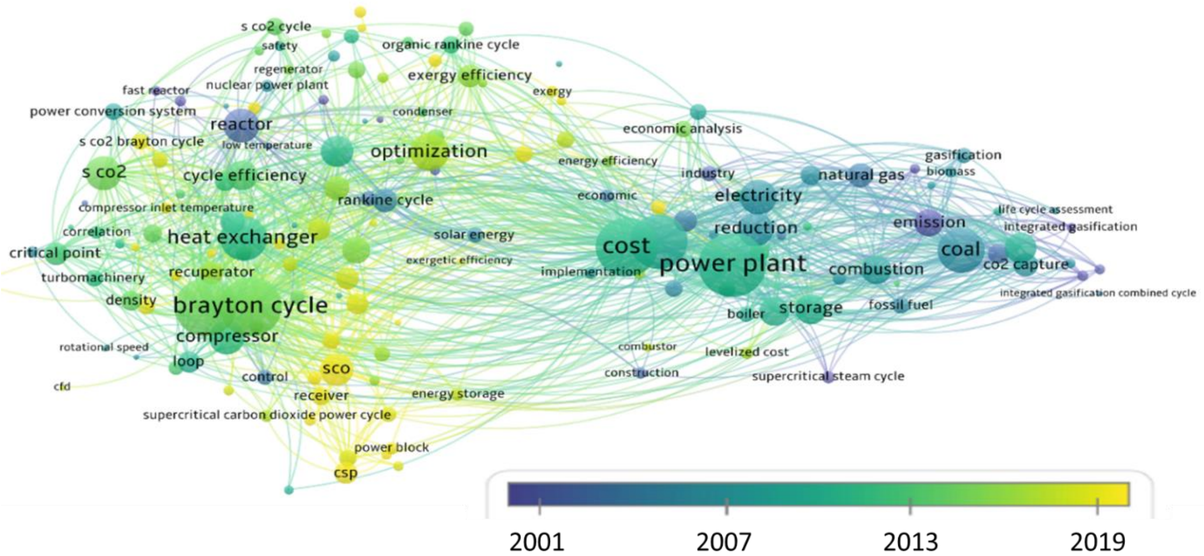

Figure 4: Keywords scientific mapping and field trend

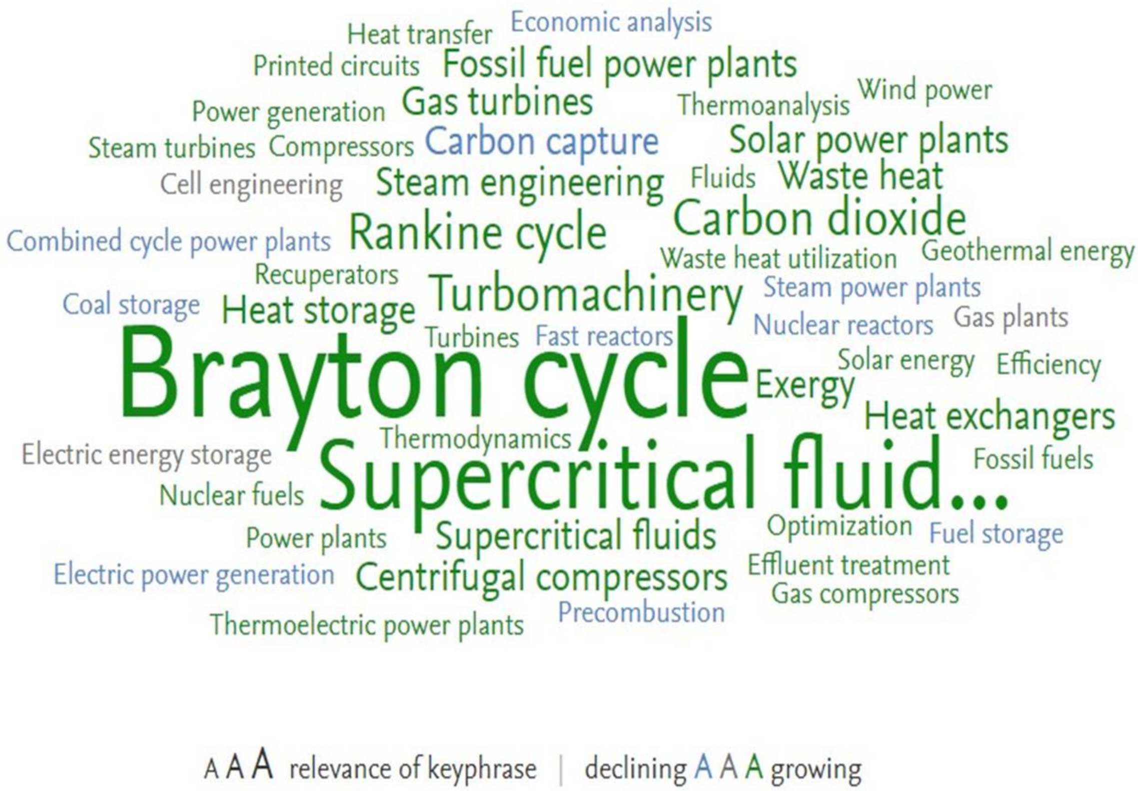

Figure 5: Recent growing interest based on keywords analysis

3.3. Productive journals in the field

The source was analyzed for each publication based on S-CO2 power cycle employed systems to identify the top 10 most productive journals in the field. It is found that Energy has the largest share and top in the list with 1886 times cited and 85 documents. The year timeline with publishing growth of SCO_2 field documents is shown in Figure 6. Applied Thermal Engineering, Energy Conversion, and Management applied Energy and Proceedings of the ASME Turbo Expo are placed order inline share of subject study by number and citations. In terms of Citation impact and their cross citation, a trigonometry mapping is shown in Figure 7. The thickness of the curve lines shows the strength of cross citations in the field, and change in color space depicts the recent publishing trend on annual bases.

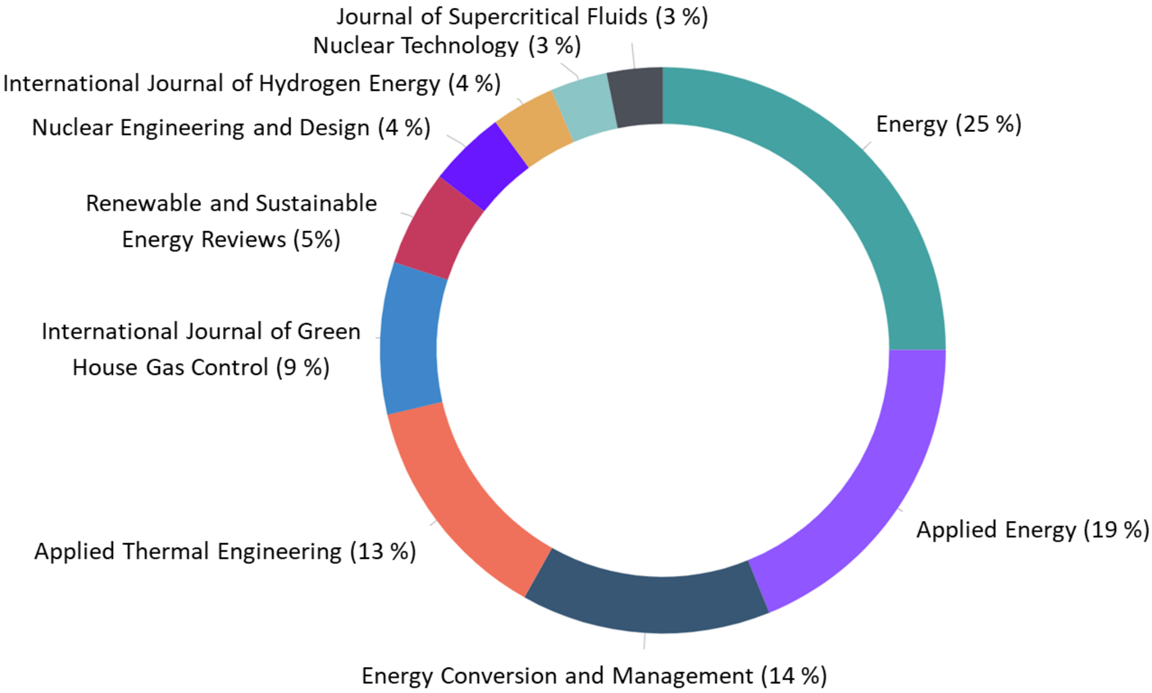

Figure 6: Annual trend analysis of most productive sources in the field (2000-2019)

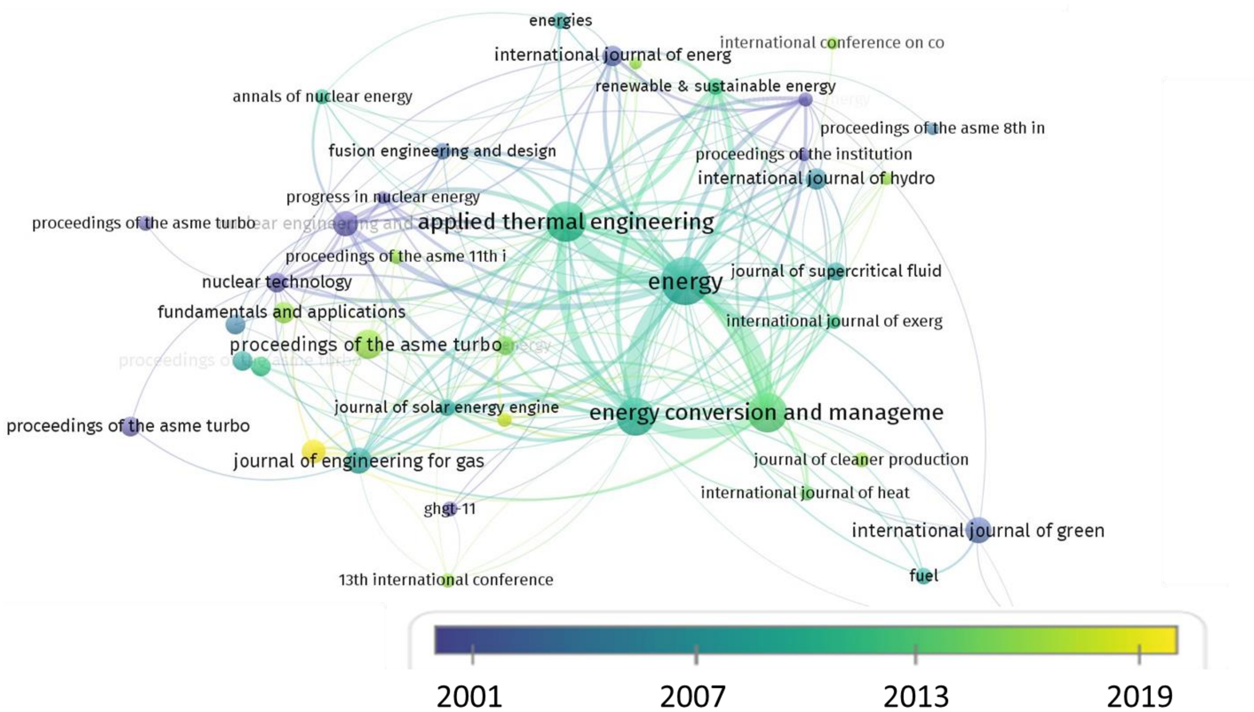

Figure 7: Degree of citation mapping and the recent trend of most productive sources in the field

3.4. Authorship pattern

The database investigation in terms of authorship trend has shown 976 published articles by 160 authors from 49 countries. The top 10 most productive authors in the context of scholarly output and citations are shown in Figure 8, and their affiliation with other detailed impact is shown in Table 2. Lee Jeong (h-Index 11) is the leading author with 33 papers in SCO_2 power cycle employment and 400 times citations.

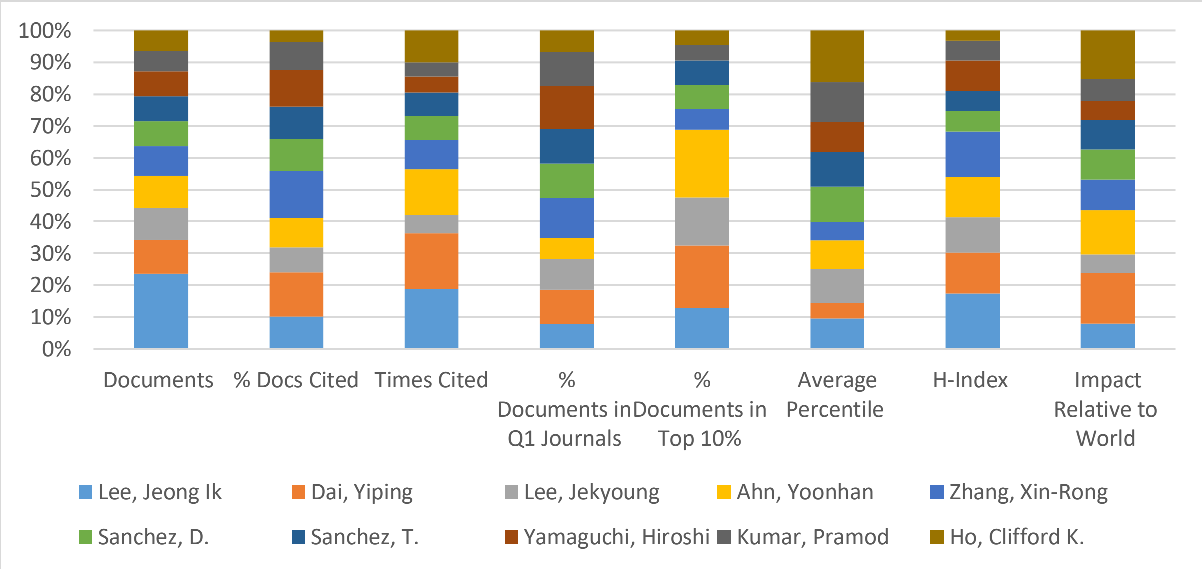

Figure 8: Top 10 productive Authors in SCO_2 cycle technology field

Table 2

Top 10 productive Authors and their affiliations in SCO_2 cycle technology field

Name	Affiliation	Doc.	% Docs Cited	% Documents in Q1 Journals	% Documents in Top 10%	Average Percentile	H-Index
Lee, Jeong Ik	Korea Advanced Institute of Science & Technology (KAIST)	33	63.64%	57.89%	30.30%	49.26	11
Dai, Yiping	Xi'an Jiaotong University	15	86.67%	80%	46.67%	24.62	8
Lee, Jekyoung	Korea Advanced Institute of Science & Technology (KAIST)	14	50%	71.43%	35.71%	54.55	7
Ahn, Yoonhan	Korea Advanced Institute of Science & Technology (KAIST)	14	57.14%	50%	50%	46.75	8
Zhang, Xin-Rong	Peking University	13	92.31%	92.31%	15.38%	29.96	9
Sanchez, D.	University of Sevilla	11	63.64%	80%	18.18%	56.45	4
Sanchez, T.	University of Sevilla	11	63.64%	80%	18.18%	56.45	4
Yamaguchi, Hiroshi	Doshisha University	11	72.73%	100%	0%	47.78	6
Kumar, Pramod	Indian Institute of Science (IISC) - Bangalore	9	55.56%	80%	11.11%	64.57	4
Ho, Clifford K.	Sandia National Laboratory	9	22.22%	50%	11.11%	83.69	2

To analyze the article growth and significance of specific study, ten most cited articles are presented in Table 3. There are mainly four research categories involved in the highly cited papers, including application-oriented study, cycle performance analysis, configuration scalability, and key component analysis.

Table 3

Top 10 most cited papers in SCO_2 cycle technology field

Author	Year	Document Citation	Journal
Ho, C.K., Iverson, B.D. [38]	2014	254	Renewable and Sustainable Energy Reviews
Yildiz, B., Kazimi, M.S. [39]	2006	231	International Journal of Hydrogen Energy
Iverson, B.D [40]	2013	190	Applied Energy
Yamaguchi, H. [41]	2006	187	Applied Thermal Engineering
Ahn, Y. [42]	2015	181	Nuclear Engineering and Technology
Rubin, E.S [43]	2015	160	International Journal of Greenhouse Gas Control
Wang, J. [44]	2010	140	Applied Energy
Zhang, X.R. [41]	2006	140	Renewable Energy
Chacartegui, R.[45]	2011	123	Applied Thermal Engineering
Kim, Y.M. [46]	2012	107	Energy

3.5. Institutions

The most contributing organizations in the field of SCO_2 power cycle development and employment are shown in Figure 9. The type of analysis was "co-authorship"; the unit of analysis was "organizations," and the counting method was "fractional counting." United States Department of Energy (DOE) is top in the list in the SCO_2 cycle technology. The annual growing trend of Xian Jiaotong University is growing very rapidly in recent years in this technology research. The collaborative structure and yearly switching interest between these organizations are presented in Figure 10.

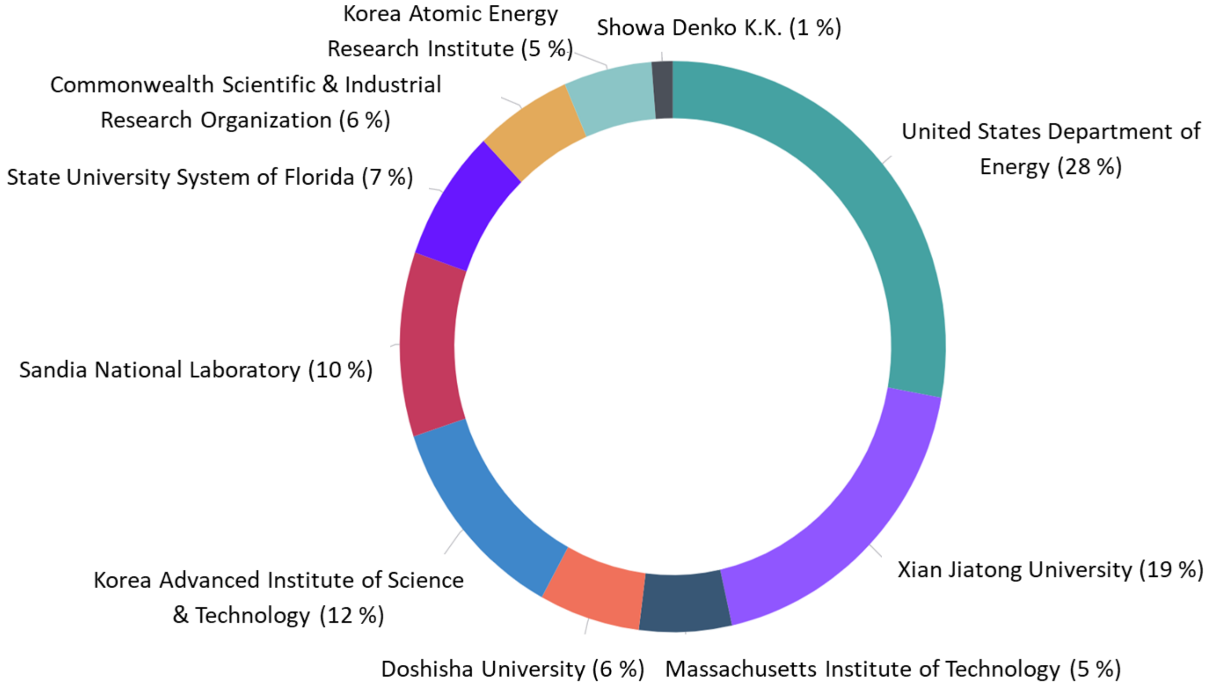

Figure 9: Annual trend analysis of Most productive organizations in SCO_2 cycle technology (2000-2019)

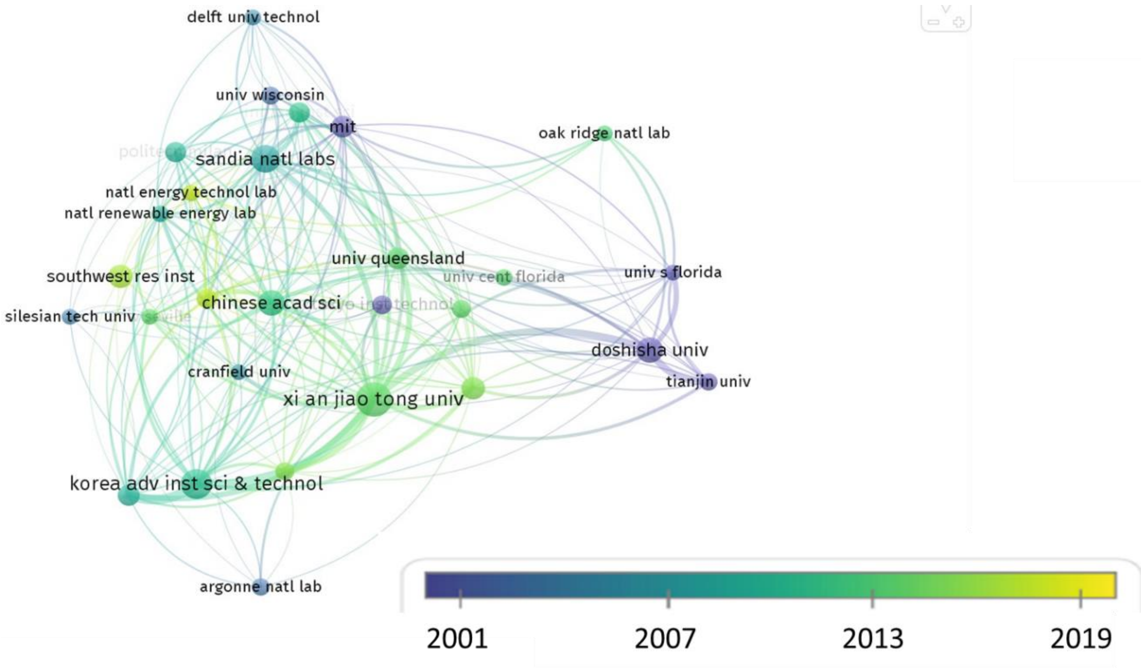

Figure 10: Degree of citation mapping and the recent trend of most productive organizations

3.6. Countries

Scientific collaborative work and the number of affiliations in a region represents the activeness of that country in the respective field. To investigate the productive region in SCO_2 cycle technology, the database was utilized in InCites, and top active regions are identified as shown in Figure 11. USA and China are the most productive countries with 261, 195 documents and 3049, 2308 citations, respectively, in SCO_2 cycle technology-based research, as shown in Table 3. The annual trend in Figure 12 also presents a competition and strength of the collaborative work environment between both countries, especially after 2010. It may be due to the growing trend in clean and efficient energy-based technologies, especially in the power sector. Japan, Spain, South Korea, and Australia are in the second cluster of collaborative work with the USA and China, as shown in Figure 13.

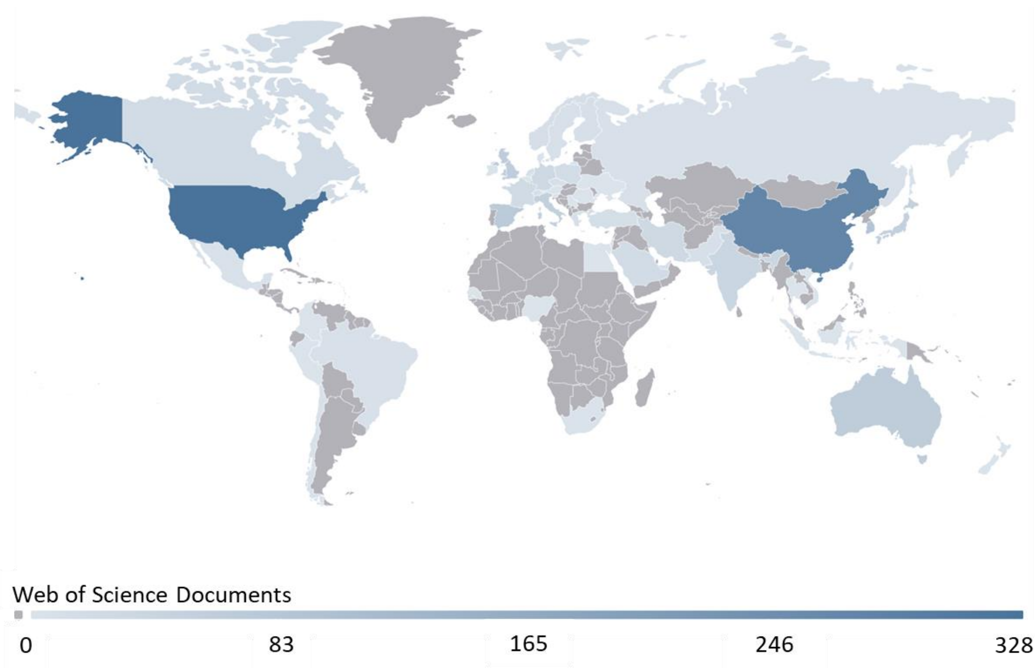

Figure 11: World geographical distribution of most productive regions in the field

Table 3

Top 10 productive countries and their strength factors in SCO_2 cycle technology

Name	Documents	Times Cited	% Docs Cited	% Documents in Top 10%	Average Percentile
USA	261	3,049	51.34%	14.94%	64.45
CHINA MAINLAND	195	2,308	72.82%	25.13%	43.82
SPAIN	65	1,059	83.08%	24.62%	38.9
SOUTH KOREA	64	759	68.75%	28.13%	47.71
JAPAN	56	1,081	73.21%	32.14%	43.15
AUSTRALIA	52	507	73.08%	23.08%	42.2
UNITED KINGDOM	47	655	78.72%	21.28%	41.22
ENGLAND	44	601	79.55%	20.45%	40.95
ITALY	43	643	76.74%	30.23%	39.37
INDIA	39	320	71.79%	12.82%	55.42

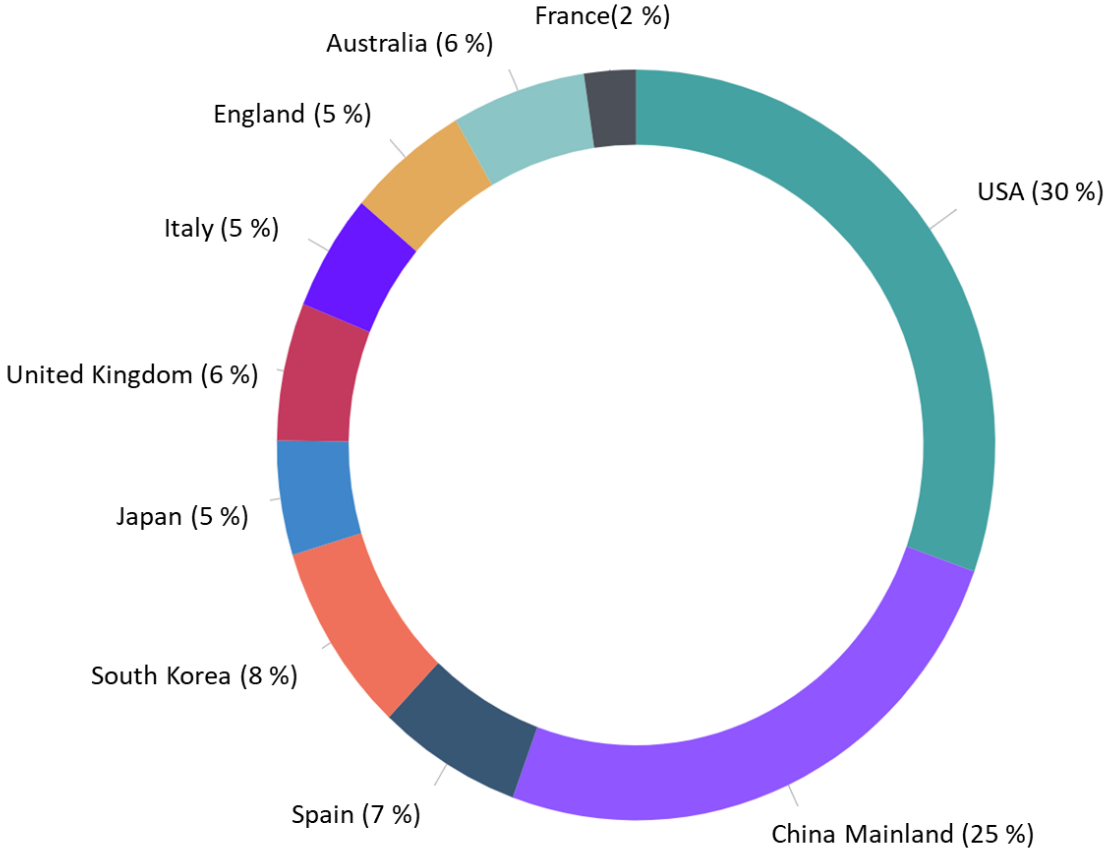

Figure 12: Annual trend analysis of Most productive countries in SCO_2 cycle technology (2000-2019)

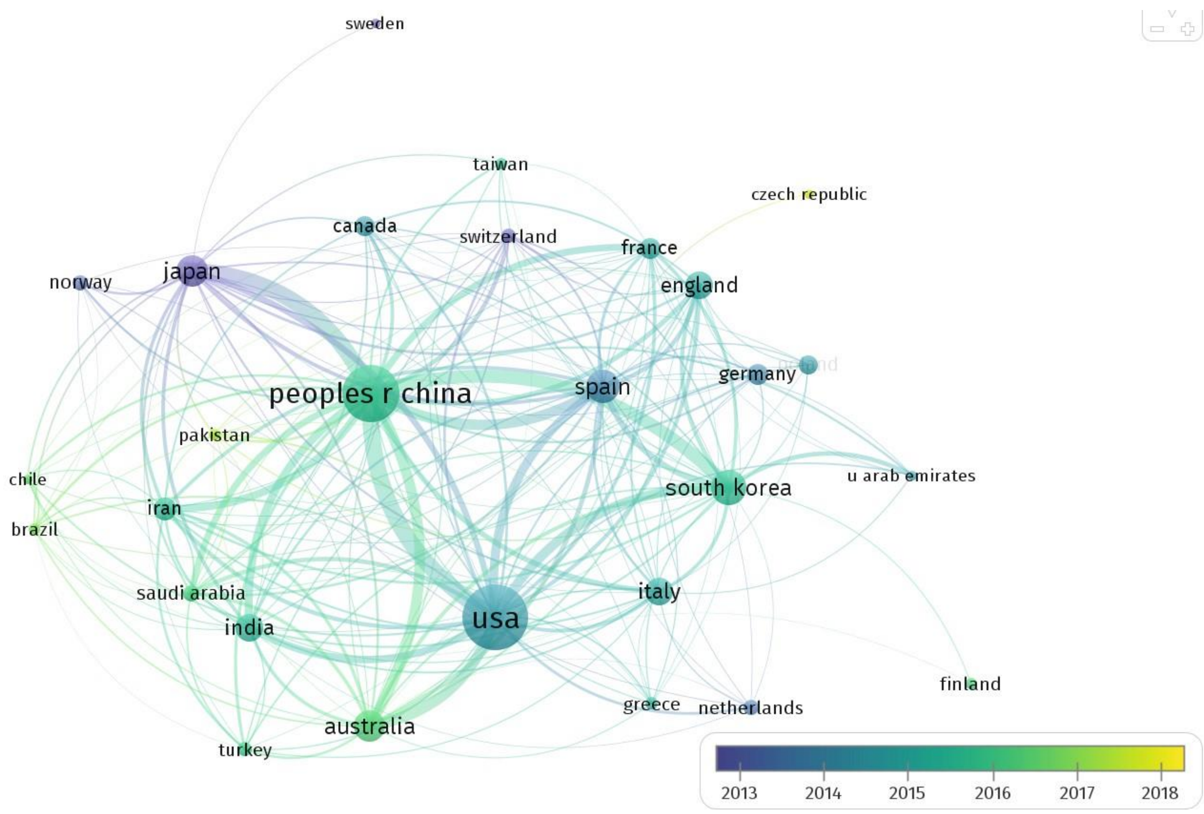

Figure 13: Degree of citation mapping and recent trend and collaboration of most productive countries in the field

3.7. Funding Agency

There are many organizations worldwide that are sponsoring research projects for innovative technology development and commercialization. A comparative investigation was also performed to identify the top shareholder agency in SCO_2 power cycle-based research projects. National Natural Science Foundation of China is ranked top in the list with 47% of shares all over the world. If it includes Chinese based other funding agencies as in Figure 14 and Table 4, China becomes more than 50% funds shareholder comparing to other top 10 countries list.

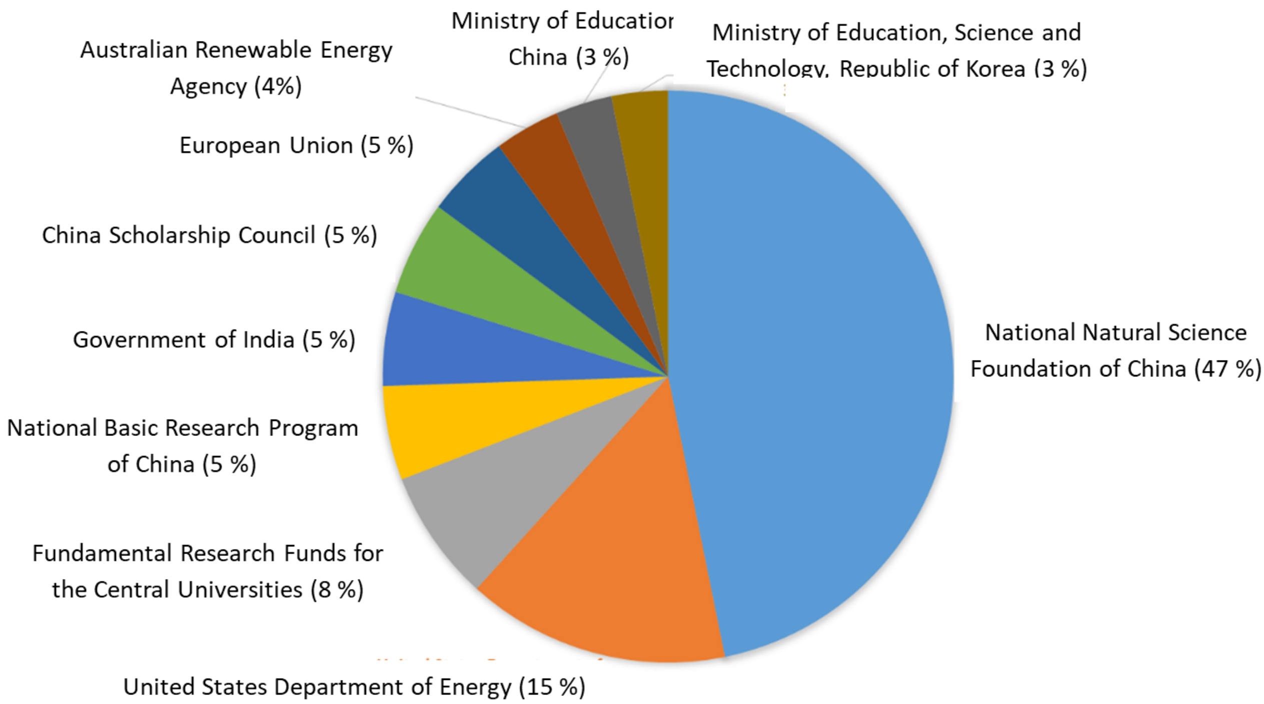

Figure 14: Major funding agencies for the development and employment of the S-CO_2 cycle technology

Table 4

Major funding agencies and their time citation impact relative to the world in SCO_2 cycle technology field

Name	Documents	Times Cited	% Docs Cited	% Documents Journals	% Doc. in the Top 10%	Average Percentile	H-Index	Impact Relative to World
National Natural Science Foundation of China	88	1,045	79.55%	73.58%	30.68%	39.51	18	0.96
United States Department of Energy (DOE)	28	390	60.71%	68.75%	10.71%	61.03	8	1.12
Fundamental Research Funds for the Central Universities	14	155	78.57%	71.43%	28.57%	45.57	5	0.89
National Basic Research Program of China	10	208	100%	66.67%	40%	20.92	7	1.67
Government of India	10	125	90%	77.78%	20%	42.24	6	1.01
China Scholarship Council	10	73	90%	100%	20%	29.16	4	0.59
European Union (EU)	9	155	77.78%	75%	22.22%	35.51	3	1.39
Australian Renewable Energy Agency (ARENA)	7	158	100%	85.71%	71.43%	11.38	6	1.82
Ministry of Education, China - 111 Project	6	58	66.67%	100%	16.67%	50.96	2	0.78

Ministry of Education, Science and Technology, Republic of Korea	6	134	100%	16.67%	50%	23.02	5	1.8

4. Conclusion

To improve the use of energy-efficient technologies wasted heat recovery, and reduce environmental pollution, employment, and development in the S-CO_2 power cycle study is very important. It has been grown in the last decade. It predicted that the S-CO_2 power cycle got great attention from the energy industry in the power generation sector. Its versatility and performance at a moderate temperature set apart from other existing technologies in the field.

This paper widely presented the outcomes in terms of qualitative analysis with quantitative and inclusive scientific mapping approaches for the last two decades (2000-2019) by using the database of Scopus and Web of Science Core Collection (Thompson Reuters Corporation), 1159 articles were published by 160 authors from 49 countries. This paper provided a clear presentation and statistical growth of top authors, organizations, countries, funding agencies, collaborations, and dynamics of research direction in the field of S-CO_2 power cycle technology. Moreover, this research presented a productive trend and collaborative network behavior to set future research directions and hotspot areas in the field. USA and United States Department of Energy (DOE) are top in the country and institutes list with 261 and 92 articles share, respectively. Energy is the most productive journal and leading in the list with 1886 times cited with 85 documents. In contrast, Lee Jeong (h-Index 11) from South Korea is the dominating author with 33 papers in S-CO_2 power cycle employment, and the National Natural Science Foundation of China is ranked as the top funding agency with 47% shares. The most recent trend includes heat exchangers, recuperators, whole cycle configuration, optimization, and applications for waste heat recovery in thermal systems. There is a lack of study in the layout configuration with a wide variety analysis of operating conditions for more diverse use and integration, specially compactness of the S-CO_2 power cycle for mobile power applications with energy systems. Advanced modeling approaches still required to investigate the system simplicity and compactness for mobile applications in small systems as well. Moreover, the adaptability in tropical and arid regions is also challenging because S-CO_2 condensation temperature is lower than ambient conditions.

5. Acknowledgment

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6. References

[1] F. Crespi, G. Gavagnin, D. Sánchez, and G. S. Martínez, “Supercritical carbon dioxide cycles for power generation: A review,” *Appl. Energy*, vol. 195, pp. 152–183, Jun. 2017.

[2] E. Woolley, Y. Luo, and A. Simeone, “Industrial waste heat recovery: A systematic approach,” *Sustain. Energy Technol. Assessments*, vol. 29, pp. 50–59, 2018.

[3] F. A. Al-Sulaiman and M. Atif, “Performance comparison of different supercritical carbon dioxide Brayton cycles integrated with a solar power tower,” *Energy*, vol. 82, pp. 61–71, Mar. 2015.

[4] M. Imran, F. Haglind, M. Asim, and J. Zeb Alvi, “Recent research trends in organic Rankine cycle technology: A bibliometric approach,” *Renew. Sustain. Energy Rev.*, vol. 81, pp. 552–562, Jan. 2018.

[5] A. Shahnazari, M. Rafiee, A. Rohani, B. Bhushan Nagar, M. A. Ebrahiminik, and M. H. Aghkhani, “Identification of effective factors to select energy recovery technologies from municipal solid waste using multi-criteria decision making (MCDM): A review of thermochemical technologies,” *Sustain. Energy Technol. Assessments*, vol. 40, p. 100737, 2020.

[6] T. Neises and C. Turchi, “A Comparison of Supercritical Carbon Dioxide Power Cycle Configurations with an Emphasis on CSP Applications,” *Energy Procedia*, vol. 49, pp. 1187–1196, Jan. 2014.

[7] P. Dutta and P. Kumar, “Supercritical Carbon Dioxide-Based Power Cycles,” *Encycl. Sustain. Technol.*, pp. 419–428, Jan. 2017.

[8] S. Park, J. Kim, M. Yoon, D. Rhim, and C. Yeom, “Thermodynamic and economic investigation of coal-fired power plant combined with various supercritical CO2 Brayton power cycle,” *Appl. Therm. Eng.*, vol. 130, pp. 611–623, Feb. 2018.

[9] T. Neises and C. Turchi, “Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650 °C,” *Sol. Energy*, vol. 181, pp. 27–36, Mar. 2019.

[10] J. Moore, “9 - Auxiliary equipment,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 245–253.

[11] D. Thimsen, R. A. Dennis, K. Brun, and B. A. Pint, “15 - Research and development: Essentials, efforts, and future trends,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 415–422.

[12] G. Musgrove, S. Sullivan, D. Shiferaw, P. Fourspring, and L. Chordia, “8 - Heat exchangers,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 217–244.

[13] T. C. Allison, J. Moore, R. Pelton, J. Wilkes, and B. Ertas, “7 - Turbomachinery,” in

Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 147–215.

[14] N. T. Weiland, R. A. Dennis, R. Ames, S. Lawson, and P. Strakey, “12 - Fossil energy,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 293–338.

[15] M. Poerner and A. Rimpel, “10 - Waste heat recovery,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 255–267.

[16] G. Musgrove and S. Wright, “1 - Introduction and background,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 1–22.

[17] C. S. Turchi, J. Stekli, and P. C. Bueno, “11 - Concentrating solar power,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 269–292.

[18] J. J. Sienicki and A. Moisseytsev, “13 - Nuclear power,” in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 339–391.

[19] A. A. Gkountas, A. M. Stamatelos, and A. I. Kalfas, “Recuperators investigation for high temperature supercritical carbon dioxide power generation cycles,” *Appl. Therm. Eng.*, vol. 125, pp. 1094–1102, Oct. 2017.

[20] A. Calderón, C. Barreneche, K. Hernández-Valle, E. Galindo, M. Segarra, and A. I. Fernández, “Where is Thermal Energy Storage (TES) research going? – A bibliometric analysis,” *Solar Energy*, Pergamon, Jan-2019.

[21] G. Mao, N. Huang, L. Chen, and H. Wang, “Research on biomass energy and environment from the past to the future: A bibliometric analysis,” *Sci. Total Environ.*, vol. 635, pp. 1081–1090, Sep. 2018.

[22] W. Zhou, A. Kou, J. Chen, and B. Ding, “A retrospective analysis with bibliometric of energy security in 2000–2017,” *Energy Reports*, vol. 4, pp. 724–732, Nov. 2018.

[23] R. Zeng and A. Chini, “A review of research on embodied energy of buildings using bibliometric analysis,” *Energy Build.*, vol. 155, pp. 172–184, Nov. 2017.

[24] E. Hache and A. Palle, “Renewable energy source integration into power networks, research trends and policy implications: A bibliometric and research actors survey analysis,” *Energy Policy*, vol. 124, pp. 23–35, Jan. 2019.

[25] W. Cong and L. Shi, “Heterogeneity of industrial development and evolution of cleaner production: Bibliometric analysis based on JCLP,” *J. Clean. Prod.*, vol. 212, pp. 822–836, Mar. 2019.

[26] Y. Wang, N. Lai, J. Zuo, G. Chen, and H. Du, “Characteristics and trends of research on waste-to-energy incineration: A bibliometric analysis, 1999-2015,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 95–104, 2016.

[27] G. Mao, H. Zou, G. Chen, H. Du, and J. Zuo, “Past, current and future of biomass energy research: A bibliometric analysis,” *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1823–1833, 2015.

[28] G. Mao, X. Liu, H. Du, J. Zuo, and L. Wang, “Way forward for alternative energy research: A bibliometric analysis during 1994-2013,” *Renew. Sustain. Energy Rev.*, vol. 48, pp. 276–286, 2015.

[29] B. Peng *et al.*, “Bibliometric and visualized analysis of China’s coal research 2000–2015,” *J. Clean. Prod.*, vol. 197, pp. 1177–1189, Oct. 2018.

[30] H. Q. Chen *et al.*, “Chinese energy and fuels research priorities and trend: A bibliometric analysis,” *Renew. Sustain. Energy Rev.*, vol. 58, pp. 966–975, 2016.

[31] H. Yu, Y.-M. Wei, B.-J. Tang, Z. Mi, and S.-Y. Pan, “Assessment on the research trend of low-carbon energy technology investment: A bibliometric analysis,” *Appl. Energy*, vol. 184, pp. 960–970, Dec. 2016.

[32] A. Darko, A. P. C. Chan, X. Huo, and D.-G. Owusu-Manu, “A scientometric analysis and visualization of global green building research,” *Build. Environ.*, vol. 149, pp. 501–511, Feb. 2019.

[33] M. Tsay and C. Lai, “A scientometric study of heat transfer journal literature from 1900 to 2017,” *Int. Commun. Heat Mass Transf.*, vol. 98, pp. 258–264, Nov. 2018.

[34] I. Y. Wuni, G. Q. P. Shen, and R. Osei-Kyei, “Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018,” *Energy Build.*, vol. 190, pp. 69–85, May 2019.

[35] F. G. Montoya, M. G. Montoya, J. Gómez, F. Manzano-Agugliaro, and E. Alameda-Hernández, “The research on energy in Spain: A scientometric approach,” *Renew. Sustain. Energy Rev.*, vol. 29, pp. 173–183, 2014.

[36] N. Shen, R. Deng, H. Liao, and O. Shevchuk, “Mapping renewable energy subsidy policy research published from 1997 to 2018: A scientometric review,” *Util. Policy*, vol. 64, p. 101055, 2020.

[37] F. G. Montoya, A. Alcayde, R. Baños, and F. Manzano-Agugliaro, “A fast method for identifying worldwide scientific collaborations using the Scopus database,” *Telemat.*

Informatics, vol. 35, no. 1, pp. 168–185, Apr. 2018.

[38] C. K. Ho and B. D. Iverson, “Review of high-temperature central receiver designs for concentrating solar power,” *Renew. Sustain. Energy Rev.*, vol. 29, pp. 835–846, Jan. 2014.

[39] B. Yildiz and M. S. Kazimi, “Efficiency of hydrogen production systems using alternative nuclear energy technologies,” *Int. J. Hydrogen Energy*, vol. 31, no. 1, pp. 77–92, Jan. 2006.

[40] B. D. Iverson, T. M. Conboy, J. J. Pasch, and A. M. Kruizenga, “Supercritical CO2 Brayton cycles for solar-thermal energy,” *Appl. Energy*, vol. 111, pp. 957–970, Nov. 2013.

[41] X. R. Zhang, H. Yamaguchi, D. Uneno, K. Fujima, M. Enomoto, and N. Sawada, “Analysis of a novel solar energy-powered Rankine cycle for combined power and heat generation using supercritical carbon dioxide,” *Renew. Energy*, vol. 31, no. 12, pp. 1839–1854, Oct. 2006.

[42] Y. Ahn *et al.*, “Review of supercritical CO2 power cycle technology and current status of research and development,” *Nucl. Eng. Technol.*, vol. 47, no. 6, pp. 647–661, Oct. 2015.

[43] E. S. Rubin, J. E. Davison, and H. J. Herzog, “The cost of CO2 capture and storage,” *Int. J. Greenh. Gas Control*, vol. 40, pp. 378–400, Sep. 2015.

[44] J. Wang, Z. Sun, Y. Dai, and S. Ma, “Parametric optimization design for supercritical CO2 power cycle using genetic algorithm and artificial neural network,” *Appl. Energy*, vol. 87, no. 4, pp. 1317–1324, Apr. 2010.

[45] R. Chacartegui, J. M. Muñoz de Escalona, D. Sánchez, B. Monje, and T. Sánchez, “Alternative cycles based on carbon dioxide for central receiver solar power plants,” *Appl. Therm. Eng.*, vol. 31, no. 5, pp. 872–879, Apr. 2011.

[46] Y. M. Kim, C. G. Kim, and D. Favrat, “Transcritical or supercritical CO2 cycles using both low- and high-temperature heat sources,” *Energy*, vol. 43, no. 1, pp. 402–415, Jul. 2012.