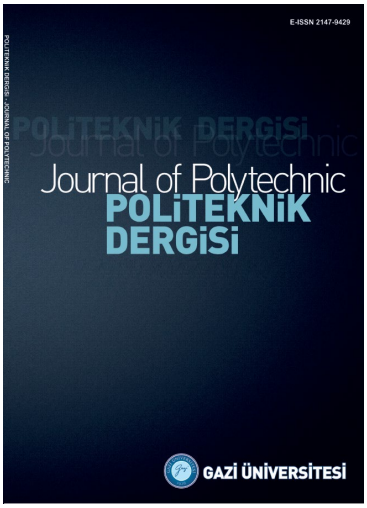

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A bibliometric analysis of geothermal energy utilization research

Jeotermal enerji kullanımı araştırmalarının bibliyometrik analizi

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A Bibliometric Analysis of Geothermal Energy Utilization Research

Highlights

- *A bibliometric analysis was used to examine academic productivity on the topic of Geothermal Energy Utilization*
- *A total of 7603 articles published between 1980 and 2023 in the WoS Core Collection were analyzed*
- *The most productive country, journal and author were "China", "Geothermics" and "Ibrahim Dincer" respectively*
- *Encanced Geothermal Systems and Hydrogen Technologies are emerging trends in scientific research*

Graphical Abstract

Geothermal energy, Geothermal Ground source heat pump, Renewable energy, Enhanced geothermal system, Heat pump, Organic Rankine cycle, Ground heat exchanger, Exergy and Optimization are the top ten keywords.

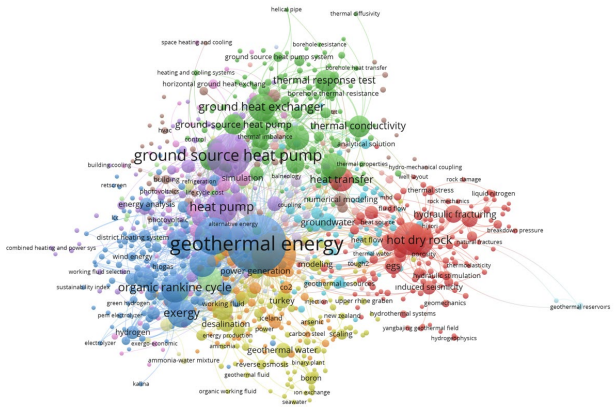

Figure. Keywords

Aim

The aim was to identify the focal points of scientific studies and highlight developmental trends.

Design & Methodology

Bibliometric analysis was conducted on the topic of Geothermal Energy Utilization using VOSviewer, Bibliometrix (R), and Citespace software.

Originality

This study is an original study that examines the field of Geothermal Energy Utilization using bibliometric methods.

Findings

The analysis revealed that geothermal energy systems are studied in terms of system analysis, design, and optimization. The two most productive countries in this field are China and the United States. The two most productive scientists in the field are İbrahim Dinçer and Arif Hepbaşlı.

Conclusion

This study provides a comprehensive review of the relevant literature, revealing the dynamics of this field over time. Innovations and research in geothermal energy will have a vital part in the expansion of this field.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

A Bibliometric Analysis of Geothermal Energy Utilization Research

Araştırma Makalesi / Research Article

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ABSTRACT

Energy use is a key factor in tackling the climate crisis and advancing climate goals. Besides technological advancements for the effective and efficient use of energy resources, it is very important for scientific studies to support evolving technologies. Geothermal energy is a renewable and natural energy source that can be used directly or in the electricity generation in many regions of the world. This study presents a bibliometric analysis within the scope of "Geothermal Energy Utilization" (GEU). By determining the scientific development and bibliometric evaluation of the researched field, this study aims to identify the focal points of scientific studies and highlight development trends. By using VOSviewer, Bibliometrix (R), and Citespace software, an analysis was conducted on 7603 publications extracted from the Web of Science (WoS) Core Collection. The publications filtered according to the research topic were evaluated within the scope of publication number, country analysis, journal analysis, author analysis, keyword analysis and most influential publications analysis. According to the study results, the most productive country, journal and author were "China", "Geothermics" and "Ibrahim Dincer" respectively. According to the results of the thematic map analysis, the keywords "Organic Rankine cycle", "exergy" and "optimization" fall under the "motor" theme group.

Keywords: Geothermal energy, bibliometric analysis, renewable energy.

Jeotermal Enerji Kullanımı Araştırmalarının Bibliyometrik Analizi

ÖZ

İklim kriziyle mücadele ve iklim hedeflerinin ileriye taşınabilmesinde enerji kullanımı kilit faktördür. Enerji kaynaklarının etkin ve verimli kullanımı için teknolojik gelişimin yanı sıra bilimsel çalışmaların gelişen teknolojiyi desteklemesi oldukça önemlidir. Jeotermal enerji dünyanın birçok bölgesinde bulunan, elektrik enerjisi üretimi ve doğrudan kullanılabilen yenilenebilir ve doğal bir enerji kaynağıdır. Bu çalışmada "jeotermal enerji kullanımı" kapsamında bir bibliyometrik analiz sunulmuştur. Araştırılan alanın bilimsel gelişimi ve bibliyometrik değerlendirmesi belirlenerek, bilimsel çalışmaların odaklandığı konuların ortaya konulması ve gelişim eğilimlerine dikkat çekilmesi hedeflenmektedir. VOSviewer, Bibliometrix (R) ve Citespace yazılımları kullanılarak Web of Science Core Collection'dan çıkarılan 7603 yayın üzerinde analiz gerçekleştirilmiştir. Araştırma konusuna göre filtrelenen yayınlar yayın sayısı, ülke analizi, dergi analizi, yazar analizi, anahtar kelime analizi ve en etkili yayınlar analizi kapsamında değerlendirilmiştir. Çalışma sonuçlarına göre, en verimli ülke, dergi ve yazar sırasıyla China, Geothermics ve Ibrahim Dinçer olmuştur. Tematik harita analizi sonuçlarına göre, "Organik Rankine çevrimi", "ekserji" ve "optimizasyon" anahtar kelimeleri "motor" tema grubunda yer almaktadır.

Anahtar Kelimeler: Jeotermal enerji, bibliyometrik analiz, yenilenebilir enerji.

1. INTRODUCTION

As the issues of limiting global warming, mitigating climate change and decarbonizing societies become more urgent each passing day, energy conservation, energy efficiency and renewable energy sources are increasingly being considered across the world. Power generation systems based on renewable resources are being developed and globalized to address these issues [1]. Many countries are focused on rapidly developing the share of renewable energy in the energy sector and introducing new policies. This focus has led to extensive research and scientific studies in renewable energy technologies [2]. Geothermal energy is a natural energy source with the potential to make a significant contribution to the global renewable energy sector. In recent years, geothermal technologies have made remarkable progress. Advances in drilling methods, improved heat exchange systems, and cutting-edge energy conversion techniques have expanded the accessibility and versatility of geothermal energy. Additionally, the increasing global need for sustainable energy solutions has driven greater investment in geothermal projects, boosting its prominence in energy markets. Studies on geothermal energy include those aiming to benefit from the ample and unlimited thermal energy of the Earth. It covers a wide scientific spectrum ranging from thermodynamics to heat transfer, geophysics to geology, environmental sciences to materials, and bioenergy to agricultural fields [3]. Recent studies have shown that utilizing geothermal energy as well as increasing the efficiency of existing geothermal

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systems is one of the options to overcome the climatic challenges facing the world.

Geothermal energy has limitations such as location dependence, exploration risks and high initial investment costs [3]. Despite these limitations in comparison to different renewable energy resources, geothermal energy that is generated within geothermal systems lowers the rates of detrimental environmental outcomes and hazardous gas emissions [4]. Other advantages are its continuity, reliability, high efficiency and long lifetime. Geothermal energy sources are generally classified as low, medium and high temperature sources. Low- and medium-temperature sources are utilized directly in heating, tourism and industrial applications, while high-temperature resources are utilized indirectly in electricity generation [5, 6].

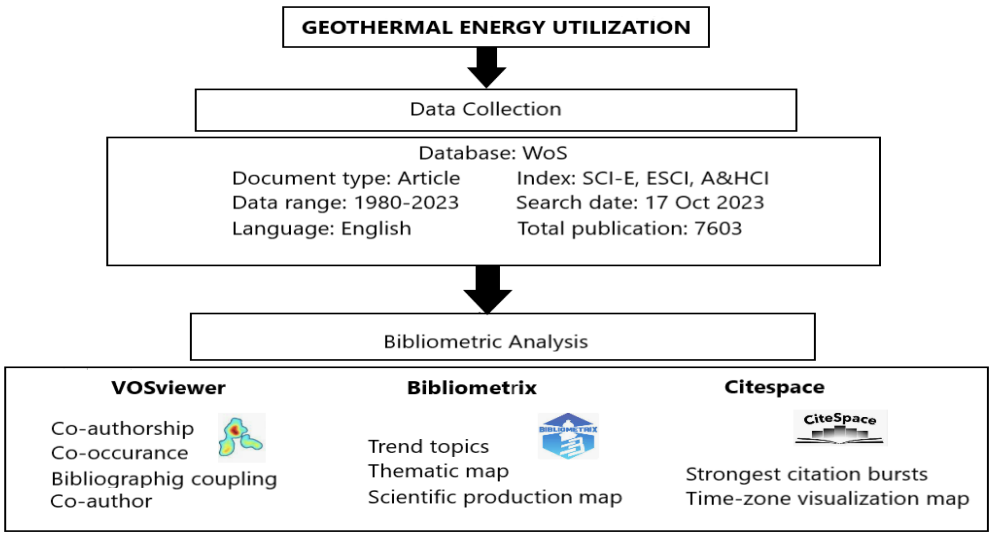
The global technical electricity potential of geothermal energy is estimated as 12,500 TWh and the direct utilization potential as 289,000 TWh [7]. According to the results of the World Geothermal Congress held in Iceland in 2020; the overall installed capacity of geothermal energy worldwide was determined as 10,897 MWe, 12,283 MWe and 15,950 MWe in 2010, 2015 and 2020, respectively. It is estimated to reach 19,361 MWe by the year 2025. Based on research presented in the World Geothermal Congress in 2020; while only 30 countries directly used geothermal energy twenty years ago, today this number has reached 88. In direct geothermal energy utilization, ground source heat pumps (GSHP) are in the first place with 58.8%, followed by bathing and balneological applications with 18.0% [8, 9]. According to the International Energy Agency (IEA), it is expected that electricity generation using geothermal energy resources will reach 1400 TWh annually by 2050, constituting 3.5% of electricity generation worldwide, and geothermal heat supply is estimated to become 611 TWh [7].

Bibliometric analysis is one of the widely preferred research methods today. It involves a numerical analysis of publications made by authors or institutions in a selected field and period. Bibliometric analysis reveals the research components and scientific mapping of the related field [10]. Since a large amount of data has accumulated in scientific research related to energy over the last few decades, many bibliometric analyses have been conducted in this field. Bibliometric methods are often used in the analysis of scientific research trends in the field of renewable energy [11-15]. However, despite the increasing number of studies on geothermal energy, there are insufficient number of studies in the literature on global mapping and information space. In particular, there is no reported literature on the research topic of this study, which investigates the GEU topic. This study aimed to characterize publications on GEU globally and to identify the most popular research areas, the most active journals, the most important authors, collaborations between institutions, countries and researchers, as well as to visualize the knowledge space on GEU. In this direction, a bibliometric analysis is presented, taking into account the articles published until October 17, 2023, when the data was obtained. By using advanced bibliometric techniques, including VOSviewer, Biblioshiny (R) and Citespace software, this study aimed to reveal the general view of current research and identify opportunities for future studies.

2. MATERIAL AND METHOD

Considering bibliometric studies in the literature, analyzes can be made using databases such as WoS Core Collection, Scopus, Google Scholar, PubMed, Medline [16]. Since the WoS Core Collection database is more preferred in engineering applications, this study analyzed the articles indexed in the WoS Core Collection database. Diverse software such as VOSviewer, Bibliometrix, Citespace, CitNetExplorer, and SciMAT are widely used for graphical visualization purposes [17, 18]. This study utilized VOSviewer (version 1.6.18), Bibliometrix (version R.4.2.2) and CiteSpace (version 6.2.R4) software for visualization purposes. VOSviewer is software tool that can be employed to generate bibliometric maps of scientific publications, authors, journals, countries, and keywords and create visuals for these maps [19]. Bibliometrix is software developed in the R environment for the systematic mapping of the scientific literatüre [20]. CiteSpace is a free java-based software for visualization of scientific publications and analysis of trends and patterns. CiteSpace includes scientific data collection, data processing, function selection for parameters, visualization, and interpretation [21].

In this context, the design of the present study was organized and a bibliometric study was carried out according to the WoS Core Collection (October 17, 2023). The search query in the database is TITLE-ABS-KEY ("geothermal energy usage" or "geothermal power plant" or "geothermal district heating system" or "geothermal heat pump" or "ground source heat pump" or "geothermal direct usage" or "geothermal energy hybrid systems" or "geothermal greenhouse heating" or "geothermal industrial application" or "geothermal agricultural drying"' or "heating of aquaculture pools with geothermal energy" or "snow melting with geothermal energy, "encanced geothermal systems" or "hot dry rock" or "geothermal energy hot dry rock"). Then, the data was limited as "Article". The research was designed to cover the period between 1980-2023, publications in English, SCI-Expanded, ESCI, A&HCI indexes and all research areas. A total of 7603 documents were accessed. Co-Authorship Network, Co-Creation Network, Bibliographing Coupling, Co-Citation Network were analyzed using VOSviewer software, Trend Topics, Thematic Map, Scientific Production Map Bibliometrix; while Strongest Citation Bursts and the Time Zone Visualization Map were analyzed by CiteSpace. Figure 1 shows the systematic flow diagram of the processes of data collection and analysis.



3. RESULTS

This study reports a bibliometric analysis of GEU research worldwide from 1980 to 2023 (43 years). A total of 7603 results were obtained from the WoS Core Collection on October 17, 2023. The main information is given in Table 1, showing that 7603 papers has been published in 975 journals by 16,763 authors between 1980-2023. The average number of citations per document is 22.86 and the number of references cited in the studies is 176,103. The collaboration index for the in documents was found to be 4.12. The number of single-author documents is 495 and the number of multi-author documents is 7108. Additionally, the Collaboration Index (total authors of multi-authored articles/total multi-authored articles) is 2.30.

Table 1. Main information

Description	Results
Timespan	1980:2023
Sources	975
Documents	7603
Document Average Age	6.68
Average citations per doc	22.86
References	176,103
Keywords Plus (ID)	7287
Author's Keywords (DE)	15,544
Authors	16,763
Authors of Single-authored documents	393
Authors of Multi-authored documents	16,370
Single-authored documents	495
Co-Authors per documents	4.12
International co-authorships %	25.61
Collaboration Index	2.30

3.1. Analysis of Annual Publications Numbers And Citations Numbers by Years

The main criteria for determining the interest of researchers in a scientific field include the numbers of publications and citations. Figures 2 present the number of publications and citations by years in the field of GEU. There is an increasing trend in the studies conducted especially after 2010. The number of studies conducted after 2010 constitutes 88% of the total number of studies. The number of studies conducted after 2020 constitutes 42% of the total number of studies. This trend shows that there is a growing interest in this field, as in all renewable energy sources. The renewable energy sector is one of the leading fields in today's knowledge production. The rapidly increasing number of studies highlights the significance of the subject.

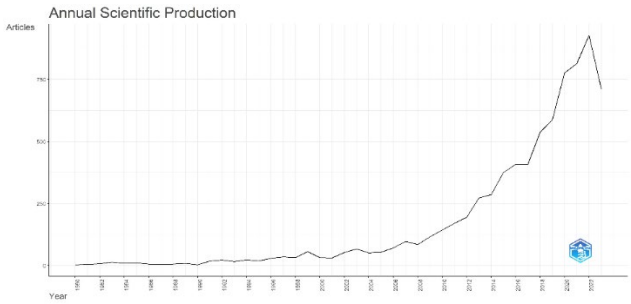


Figure 2. Number of publications by years

3.2. Research Analysis

According to the WoS Core Collection categories, research on the subject of GEU (Geothermal Energy Utilization) has been conducted in 95 different categories to date, and these studies exhibit a multidisciplinary and interdisciplinary character. Table 2 shows the top 20 research areas and the number of publications. The three most popular main research areas were "Energy Fuels" (4462), "Engineering" (2469) and "Thermodynamics" (1703). Since each researched paper can belong to more than one category, the number of papers from each dimension is much higher than the total number of papers selected.

Table 2. WoS categories in studies on GEU

	Research	No. of Doc.		Research	No. of Doc.
1	Energy Fuels	4462	11	Chemistry	231
2	Engineering	2469	12	Materials Science	170
3	Thermodynamics	1703	13	Physics	123
4	Geology	1576	14	Mining Mineral Processing	89
5	Science Technology Other Topics	1025	15	Nuclear Science Technology	85
6	Mechanics	955	16	Computer Science	79
7	Environmental Sciences Ecology	655	17	Economics Electrochemistry	74
8	Construction Building Technology	517	18	Business	61
9	Geochemistry Geophysics	325	19	Metallurgy Engineering	53
10	Water Resources	282	20	Mathematics	50

3.3. Country Analysis

The VOSviewer software represents each label in network visualization maps with a colored node, and the size of nodes are determined by the frequency of use of the items. The more frequently an item is used, the larger its node label becomes. The thickness of the lines between nodes and connection lines also indicates the strength level of the connection between labels [22]. Academic collaboration with different countries is a significant factor accelerating the pace of scientific progress. Figure 3 provides a map of country co-author connections. Seventy-seven countries were selected by the software, with a minimum document count of five from each country, resulting in a total of six clusters. The leading country, China, is at the center of the green cluster. Other countries in the green cluster that support China and have high interaction with each other include Middle Eastern countries such as Saudi Arabia and Iran, as well as Asian countries such as India, Egypt, and Malaysia. The USA forms the second-largest node and is at the center of the blue cluster. In the blue cluster, other collaborating countries include France, Switzerland, Canada, and Turkey. Germany forms the third-largest node and is at the center of the red cluster. European countries such as Italy, Spain, and Iceland are included in this cluster.

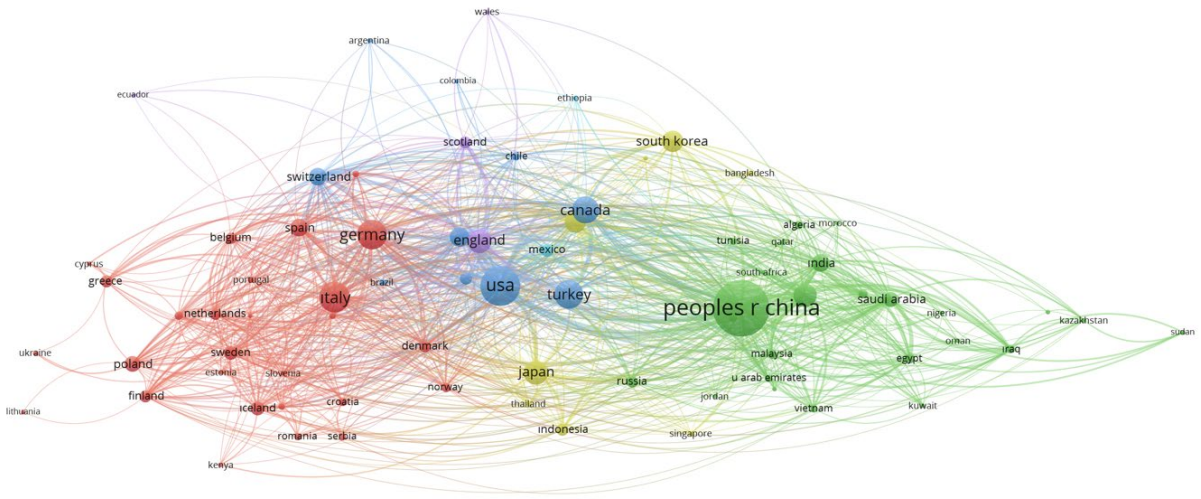


Figure 3. Co-author country map

Figure 4 shows a world map visualizing the most productive countries. China, the USA, Italy, Germany, Germany and Turkey are the top five countries. However, researchers in countries in the African continent have shown less interest in the topic. These regions appear as regions in need of research. Considering the publications addressed to China, it is observed that China started to make progress after 2013 and progressed very rapidly after 2018, surpassing other countries. China's scientific progress in this field, or more broadly in the development of renewable energy, is a positive result of the state playing an active role. Considering energy as a strategic field, China has been open to foreign investors but has never relinquished centralized control. In China, renewable energy has been put on the agenda with state policy and investments and development in this field have yielded results in a short time.

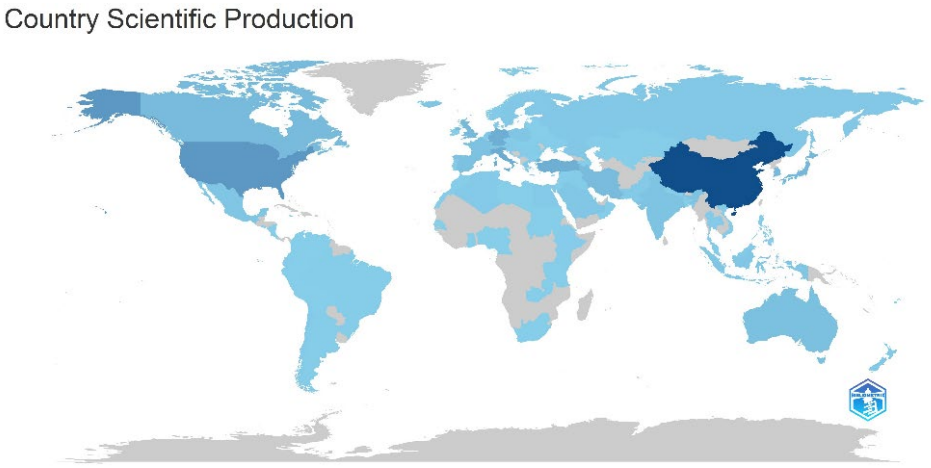


Figure 4. World map visualizing the most productive countries

Table 3 shows the 10 most productive countries in the field of GEU according to the total numbers of publications and citations. China, which has more than 57% share in the number of publications and more than 25% share in the number of citations, is the most productive country in the ranking, followed by the USA. China has approximately 2.5 times more publications than the USA, which is in the second place regarding publication numbers. Italy ranked third in the context of publication numbers, and Turkey ranked third in terms of the number of citations.

Table 3. The most productive countries

	Country	TA	SCP	MCP	MCPratio		Country	TC	AAC
1	China	4542	1829	2713	0.59	1	China	32801	17.90
2	USA	1727	727	1000	0.58	2	USA	23451	32.30
3	Italy	1026	474	552	0.53	3	Turkey	16201	34.50
4	Germany	968	392	576	0.59	4	Italy	12197	25.70
5	Turkey	924	470	454	0.49	5	Germany	11092	28.30
6	Japon	677	280	397	0.59	6	Iran	8263	30.60
7	UK	651	251	390	0.60	7	Canada	7811	24.30
8	Canada	593	392	201	0.33	8	UK	5273	21.00
9	Iran	575	270	305	0.53	9	Japan	5195	18.60
10	Korea	567	242	325	0.57	10	Australia	5130	30.00

TA: Total article, SCP: Single country publication, MCP: Multi country publication, TC: Total citation, ACC: Average article citation

In the further phase of the country analysis, the most active institutions were investigated (Table 4). As expected, China was ranked first in the most influential institution (Chinese Academy of Sciences), followed by the USA (United States Department of Energy (DOE)) and Germany (Helmholtz Association). In the fourth and fifth place were two universities from China (Jilin University and Tianjin University). In the light of all evaluations, China is the leader in this field. As renewable energy becomes more and more important because of increasing global problems, it is likely that the number of research on renewable energy and GEU will increase even more, especially with the use of new technologies.

Table 4. The most productive affiliations by documents

	Affiliations	No. of Doc
1	Chinese Academy of Sciences	285
2	United States Department of Energy (DOE)	251
3	Helmholtz Association	214
4	Jilin University	174
5	Tianjin University	165
6	China University of Petroleum	128
7	Eth Zurich	119
8	Centre National De La Recherche Scientifique (CNRS)	101
9	Helmholtz-Center Potsdam Gfz German Research Center for Geosciences	87
10	Udıce-French Research Universities	86

3.4. Most Productive Journals

The effectiveness of a journal goes in parallel with the numbers of publications and citations it publishes. For this reason, the number of articles and citations and the indexes related to citations are analyzed. The most commonly used bibliographic matching in citation analysis is when two different sources cite the same source [23]. Accordingly, the bibliographical matching map of the journals that are most strongly associated with a particular focus journal in publications related to the GEU topic was created (Figure 5). Provided that the number of documents in a journal was at least five, 201 sources were selected by the software and a total of five clusters were formed. The journal with the strongest bibliographic matching citation network is "Renewable Energy", which forms the largest node and is at the center of the blue cluster. Some of the other journals in the blue cluster are "Applied Thermal Engineering", "Energies" and "Applied Energy". The journal that forms the second largest node is "Geothermics" and is at the center point of the red cluster. Some of the other journals in the red cluster are "Geothermal Energy" and "Environmental Earth Sciences". The journal "Energy", which forms the third largest node, is at the center point of the green cluster. Some of the other journals in the green cluster are "Energy Conversion and Management" and "Journal of Cleaner Production".

Table 5 shows the most productive journals. "Geothermics" (752) ranks first in the ranking based on the number of articles. The journal has an h-index of 64. "Geothermics" is published by the Elsevier group. A total of nine journals in the list are published by the Elsevier group. The other journal "Energies" belongs to the MDPI group. Seven journals are from England, two from the Netherlands and one from Switzerland. "Energy" ranks third based on the number of articles and second based on the number of citations. "Energy" has the highest h-index in the list. In the field of GEU, "Geothermics", "Renewable Energy" and "Energy" can be considered as notable, high-impact and target journals.

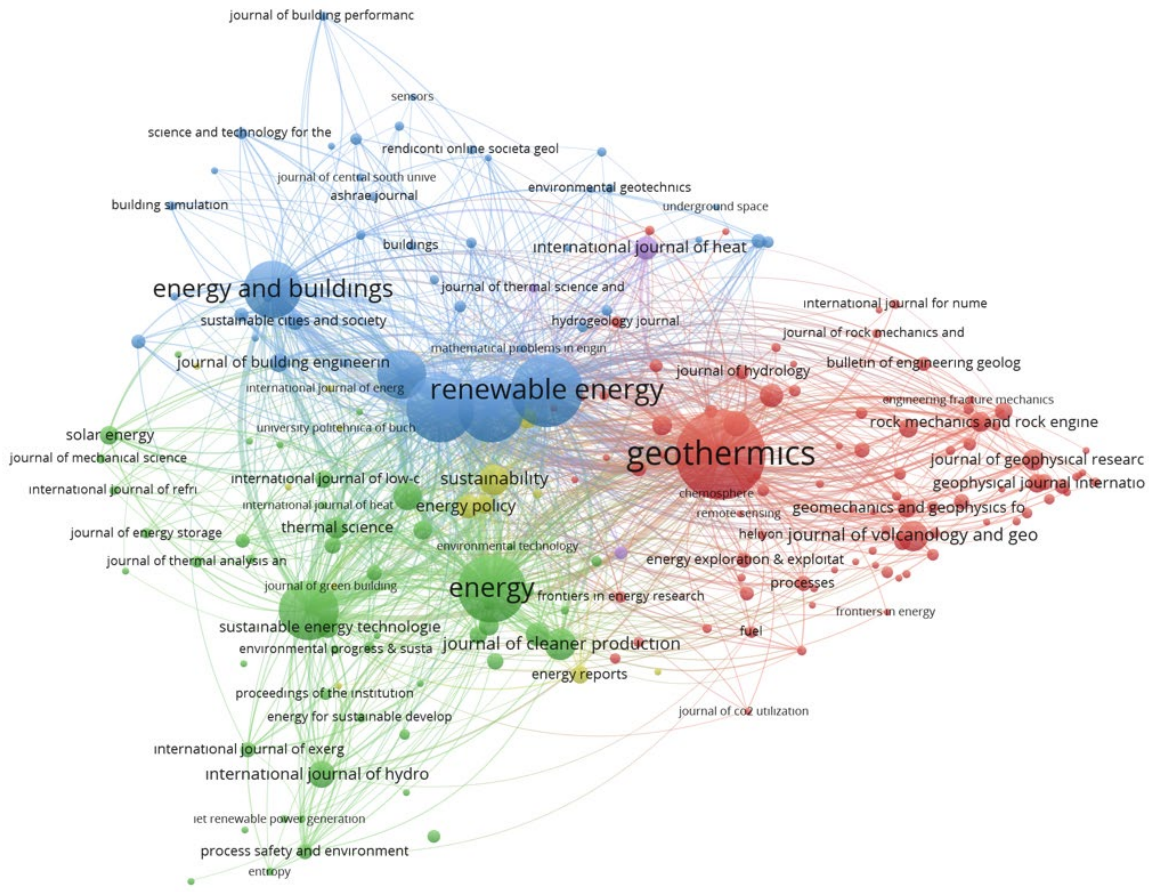


Figure 5. Bibliographical matching map of the journals

Table 5. The most productive journals

	Journals	Indeks	Publishers	Country	TA	TC	H-Indeks	First Article
1	Geothermics	SCIE	Elsevier	England	752	18700	64	1982
2	Renewable Energy	SCIE	Elsevier	England	487	12972	56	1994
3	Energy	SCIE	Elsevier	England	423	16488	66	1984
4	Applied Thermal Engineering	SCIE	Elsevier	England	423	13349	59	1997
5	Energies	SCIE	MDPI	Switzerland	419	3629	27	2010
6	Energy Conversion and Management	SCIE	Elsevier	England	337	12997	58	1988
7	Energy and Buildings	SCIE	Elsevier	Netherlands	303	9120	48	1999
8	Applied Energy	SCIE	Elsevier	England	226	11501	63	1994
9	Journal of Cleaner Production	SCIE	Elsevier	England	95	3068	32	2002
10	Journal of Volcanology and Geothermal Research	SCIE	Elsevier	Netherlands	87	2310	30	1983

TA: Total article, TC: Total citation

3.5. Keyword Analysis

Keywords reflect the main idea of an article and represent its research content. Therefore, the keyword co-occurrence information map and the distribution and evolution of high frequency keywords are analyzed [22].

Figure 6 shows the keyword co-occurrence network map. The software lists 944 different keywords and a total of 16 clusters are formed, provided that the number of keywords is at least five. Table 6 shows the number of occurrences and network strength of the top ten keywords.

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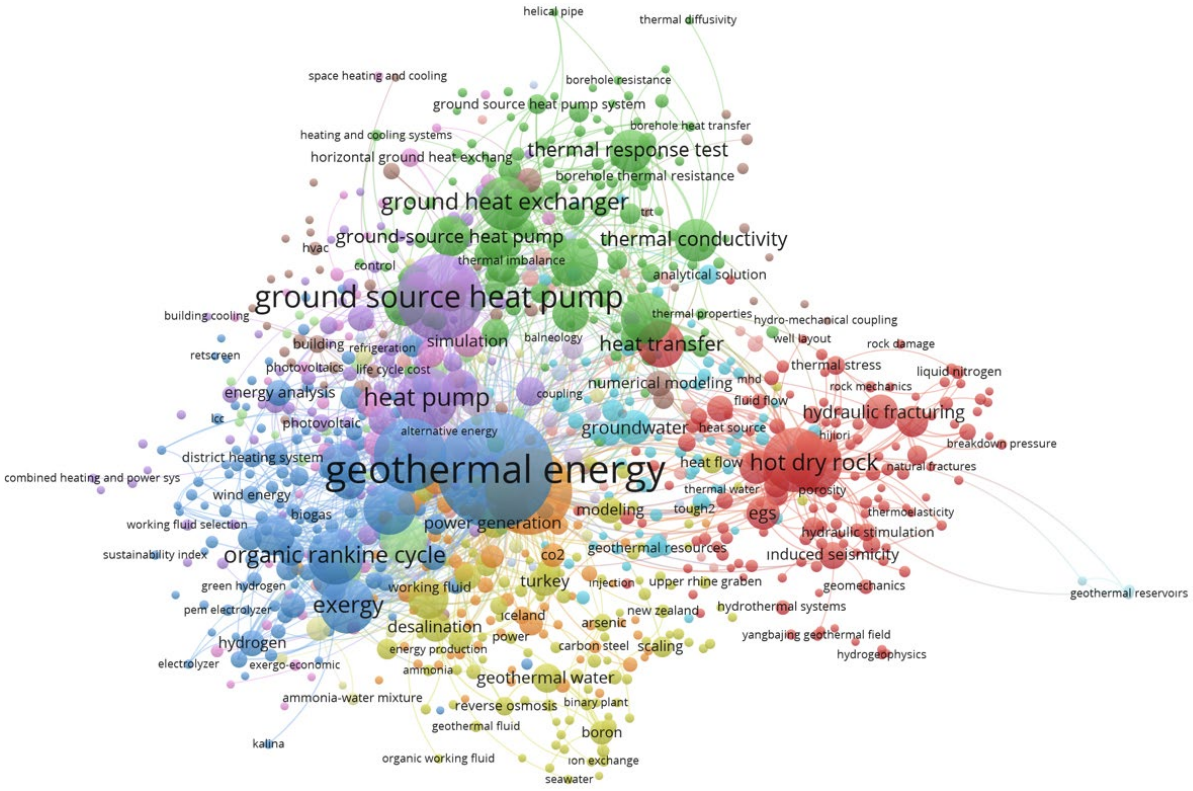

Figure 6. Keyword co-occurrence network map

Table 6. The 10 main words with the highest occurrence

	Keywords	Occurrences	Total Link Strength
1	Geothermal energy	913	2182
2	Geothermal	521	1418
3	Ground source heat pump	507	1100
4	Renewable energy	357	950
5	Enhanced geothermal system	279	586
6	Heat pump	265	783
7	Organic Rankine cycle	218	498
8	Ground heat exchanger	202	495
9	Exergy	210	792
10	Optimization	187	506

Figure 7 visualizes the change of keywords over time after 2010 in the Trend Topic graph. The graph is prepared according to plus keywords. In 2010, "hydrothermal system" was the trending topic, while "Turkey" was the trending topic in 2011. Within the scope of scientific development, academic studies have been actively carried out in Turkey, which ranks first in the world in terms of geothermal energy potential in these years, and several studies with the themes of energy, exergy, exergonomic, performance analysis and generally covering the direct utilization of geothermal energy have been carried out in Turkey. In 2015, "geothermal power plant" was the trending topic. In 2017, the topic of "working fluid" in geothermal power generation plants has been addressed many times. Again, in 2017, "heat pump system" is among the trending topics. High system costs are a significant disadvantage for these systems. Later, as a result of the global problems in the supply of energy, the themes of "energy" and "optimization" became trending topics in 2019 in parallel with the increase in studies on energy efficiency. In 2020, the keyword "performance" was trending and energy efficiency and cost have become more important. Then, with technological development, the scientific trend evolved towards "EGS" in 2021. In 2021, a noteworthy point in scientific studies was the use of "numerical-simulation" method to develop and analyze products in a digital environment. From 2022 to the present day, "hydrogen" themed studies are trending. This emphasizes the importance of hydrogen production from geothermal energy.

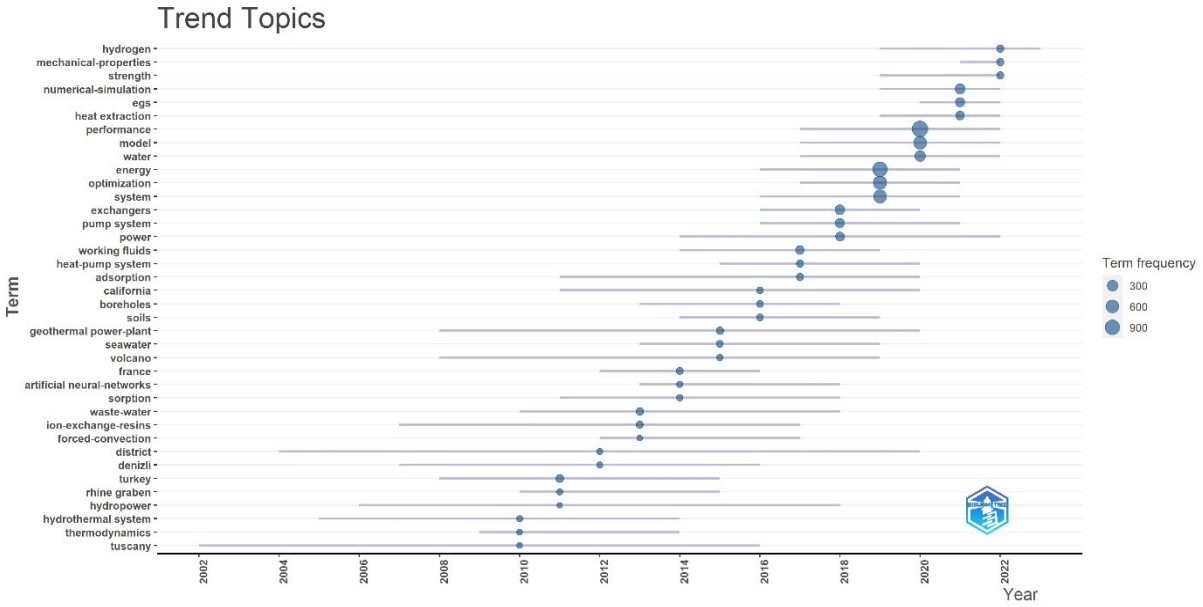

Figure 7. Keyword plus trend topics

While many keywords play an important role in the field of GEU, some keywords attract more attention and have a stronger value. Figure 8 shows the keywords with the strongest citation burst. "optimization" ranked first between 2015-2020, "geothermal energy" ranked second between 2012-2016, and "performance" ranked third between 2016-2018.

Keywords	Year	Strength	Begin	End	2000 - 2022
renewable energy	2001	4.94	**2004**	2006	
geothermal power plant	2005	5.28	**2005**	2008	
ground source heat pump	2003	5.55	**2007**	2011	
geothermal energy	2001	14.46	**2012**	2016	
energy	2002	11.29	**2014**	2015	
optimization	2012	17.38	**2015**	2020	
performance	2002	13.6	**2016**	2018	

Figure 8. Keywords with the strongest citation bursts

The strategic diagram illustrates the centrality and density of the obtained clusters based on the horizontal and vertical axes. The centrality is represented by the horizontal axis, indicates the external fit of the network and determines the degree of interaction between one network and others. The density is shown on the vertical axis, on the other hand, indicates the internal fit of the network and determines its internal strength. The upper right, upper left, lower left, and lower right quadrants show the most basic (motor) clusters, highly developed but isolated clusters, newly emerging or declining clusters, and basic and transforming clusters, respectively. Therefore, to understand the prominent themes of scientific studies during the examined period, it is necessary to look at the upper-right and lower-right quadrants [24, 25]. Figure 9 presents a "keywords thematic map" created based on the author's keywords. Keywords related to technologies involving the generation of electrical energy from geothermal energy and its direct use, as well as scientific studies conducted within the scope of energy efficiency, such as "Organic Rankine cycle," "exergy," and "optimization," are in the motor theme group. "power generation," "sensitivity analysis," and "modeling" belong to the niche theme group, exhibiting high density but low centrality, indicating intense research in these areas with limited connections to other studies. This group also includes the keywords "boron" and "geothermal water," emphasizing the importance of re-injection, which is the process of disposing of geothermal water from an environmental perspective. The "enhanced geothermal system (EGS)" and "hot dry rock" group has low density and represents a newly developing area. "geothermal energy," "geothermal," and "renewable energy" are fundamental keywords in this area, and "ground source heat pump," "ground heat exchanger," and "numerical simulation" group are also fundamental keywords indicating ongoing developments in the field.

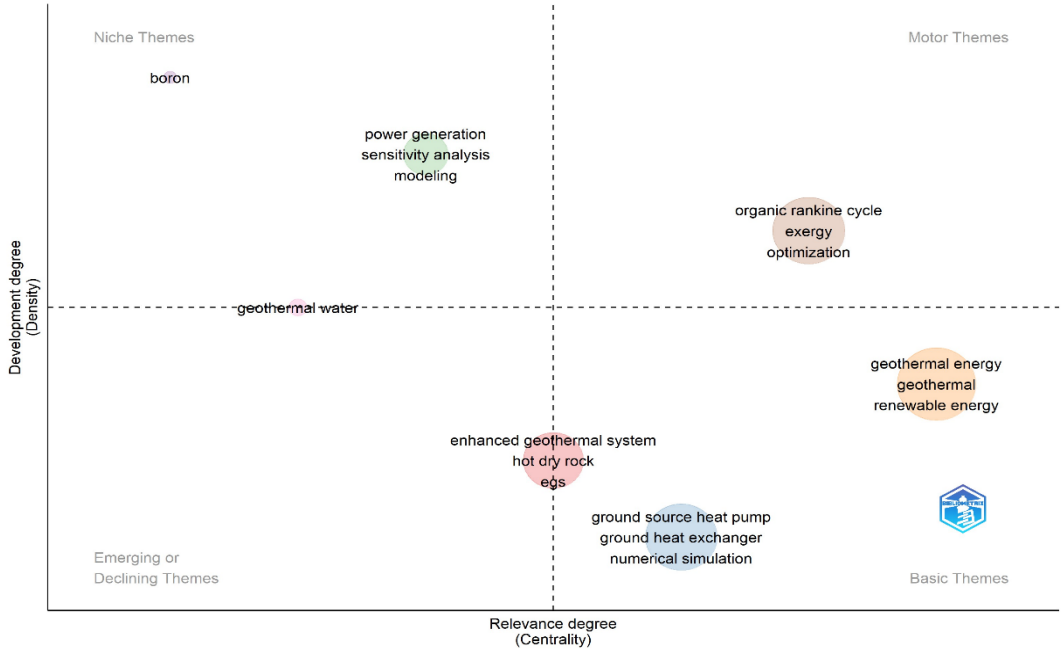

Figure 9. Keywords thematic map

Figure 10 presents the temporal relationship of the keyword network in the research area. The horizontal axis represents the years, and the vertical axis forms the labels of the identified clusters. Publications between 2000 and 2023 were analyzed for each one-year time period. The size of the labels changes proportionally with the number of articles, and the distance between two labels indicates the collaboration between two keywords. As a result of the analysis, a total of six clusters were formed. The clusters included fundamental keywords as follows: Cluster #0 (enhanced geothermal systems, hot dry rock, resource management); Cluster #1 (geothermal energy, exergonomic evaluation, geothermal heat exchanger); Cluster #2 (district heating, exergo-environmental analysis, exergo-economic analysis); Cluster #3 (heat pump, geothermal heating, simulation); Cluster #4 (ORC, thermodynamic optimization, life cycle assessment, energy transition); and Cluster #5 (Turkey, district heating, space heating, energy prices). Studies related to geothermal energy started to be conducted around 2005, with an increasing focus on electricity generation from geothermal energy, GSHP, and regional heating after 2010. After 2015, there is an increase in studies related to Enhanced Geothermal Systems (EGS) technology. Turkey also demonstrates remarkable performance in studies related to GEU.

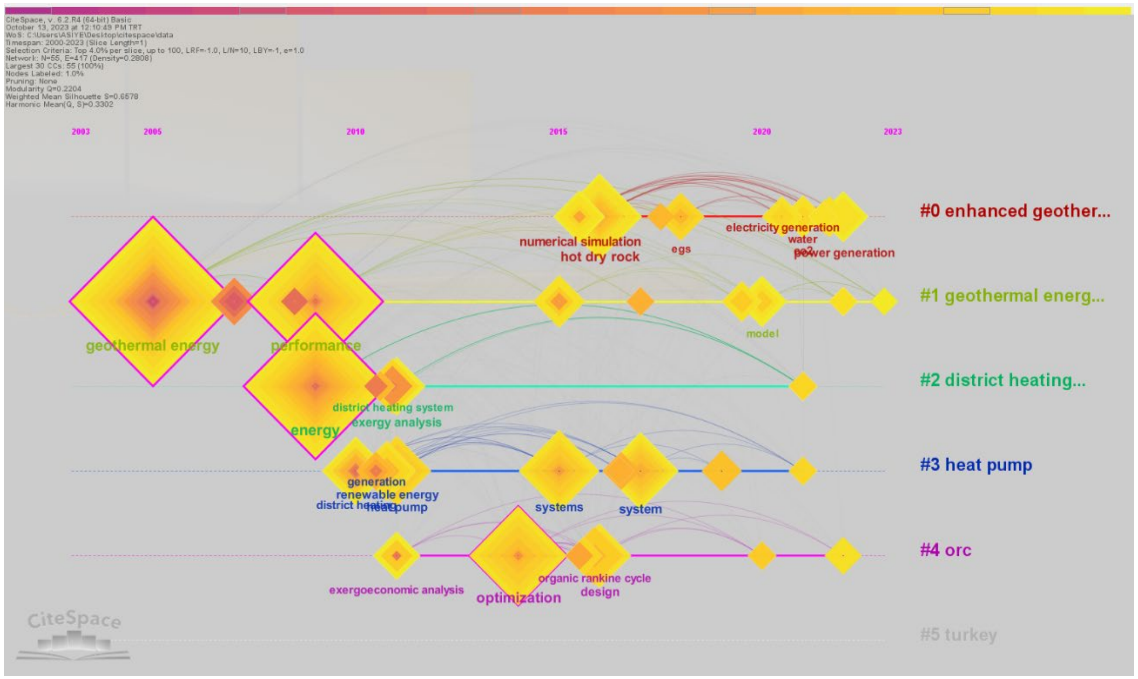

Figure 10. Temporal relationship of the keyword network

3.6. Author And Co-Authorship Analysis

Co-authorship is the most important type of scientific collaboration [26]. Co-author analysis is conducted to reveal central researchers and research communities [27, 28]. Co-authorship analysis increases the creativity and quality of academic work by providing a basis for authors to share ideas and knowledge. Figure 11 shows the co-authorship network map. In the co-authorship analysis, among 16,763 authors, 839 authors with the strongest ties were selected by the software, fulfilling the requirement of at least five documents per author. These authors are represented in 37 different clusters. The authors have collaborated with each other in small groups and the collaboration is generally stronger among authors from the same country. As the first ranked author, Xianzhi Song is in the center of the turquoise cluster. The other two authors with strong ties in this cluster are Shi Yu and Wang Gaosheng. As the second ranked author, Zhang Yanjun is in the red cluster. The other two authors with strong ties in the red cluster are Xu Tianfu and Feng Bo. Shi Yu is the third ranked author. Xianzhi Song is the most strongly affiliated author and works at the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, China. His research interests include geothermal resources, EGS, HDR technology, and fluid rock technology in geothermal systems.

Table 7 shows the 10 authors who had the greatest number of publications among all. İbrahim Dinçer ranks first in the list of the most prolific authors with a total of 81 papers. The author, who works at Ontario Tech University, Canada, made his first publication in this field in 2004. He ranks second in the list in terms of citations. The author, who has studies in many categories of renewable energy systems, draws attention to his studies on the use of geothermal energy for hydrogen production. He also has studies on hybrid renewable energy systems and performance evaluation of geothermal power plants. Second on the list is Arif Hepbasli from Yasar University, Turkey. The author ranks first with 3320 global citations. The author has studies in all areas of GEU. Zhang Yanjun and Xu Tianfu from Jilin University, China are ranked third and fourth in the list. Xianzhi Song, who ranked first in the co-author analysis, is ranked ninth in this list. Although China and the United States are leading countries in terms of productivity, they are not at the very top of this list. In particular, the increase in the number of scientific publications in China can be attributed to the emergence of new researchers and authors. Many Chinese authors are publishing their first papers and do not yet have an extensive publication history. This can present a different picture in terms of total productivity compared to more experienced authors. Additionally, China's more recent interaction with the international scientific community or the fact that countries like the U.S. and China specialize in different scientific fields, while some countries may show concentrated productivity in more specific areas, are factors that influence this situation.

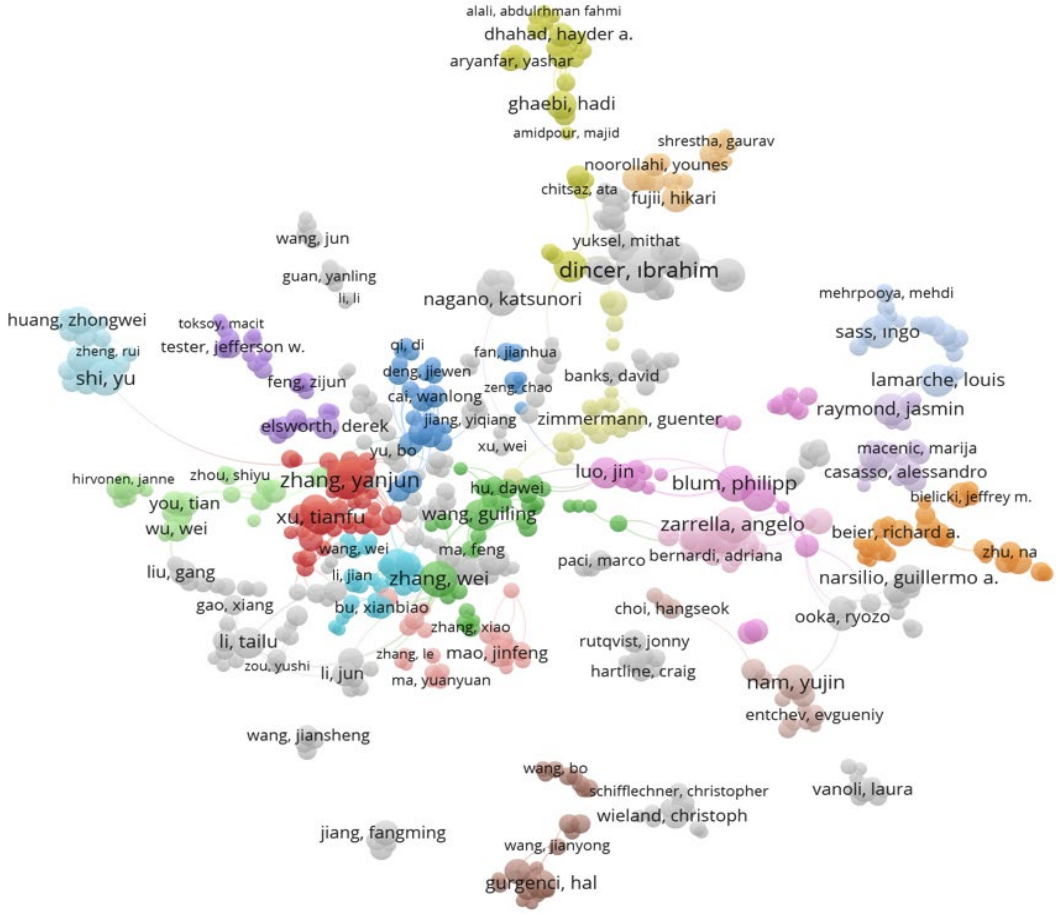

Figure 11. Co-authorship network map

Table 7. The most productive authors

	Authors	TA*	LC*	TC*	Affiliations	H-Indeks	First Article
1	DINCER Ibrahim	81	831	2977	Ontario Tech University, Canada	37	2004
2	HEPBASLI Arif	61	1091	3320	Yasar University, Turkey	39	2001
3	ZHANG YanJun	45	439	813	Jilin University, China	16	2014
4	XU Tianfu	38	317	1049	Jilin University, China	14	2000
5	GALGARO Antonio	35	312	660	University of Padova, Italy	14	2012
6	ZARRELLA Angelo	34	563	1232	University of Padova, Italy	21	2010
7	DE CARLI Michele	32	531	1192	University of Padova, Italy	20	2010
8	BLUM, Philipp	32	731	1781	University of Tübingen, Germany	19	2010
9	SONG, Xianzhi	32	478	818	China University of Petroleum, China	15	2017
10	LAMARCHE, Louis	30	612	1296	École de Technologie Supérieure, Canada	19	2007

TA: Total article, LC: Local citation, TC: Total citation

Figure 12 presents a three-dimensional Sankey Diagram showing the relationships between keywords (left), authors (center) and journals (right). This diagram shows the authors' contributions to the journals and their choice of keywords. As the number of connections between variables increases, the connection lines become thicker. İbrahim Dinçer, the most prolific author, has published in journals such as "Energy", "Applied Thermal Engineering", "Energy and Buildings", "Energy Conversion and Management" and most frequently used the keywords "geothermal energy", "exergy" and "renewable energy". Arif Hepbaşlı, who ranked second, has published in journals such as "Energy and Buildings", "Energy Conversion and Management" and most frequently used the keywords "exergy" and "renewable energy".

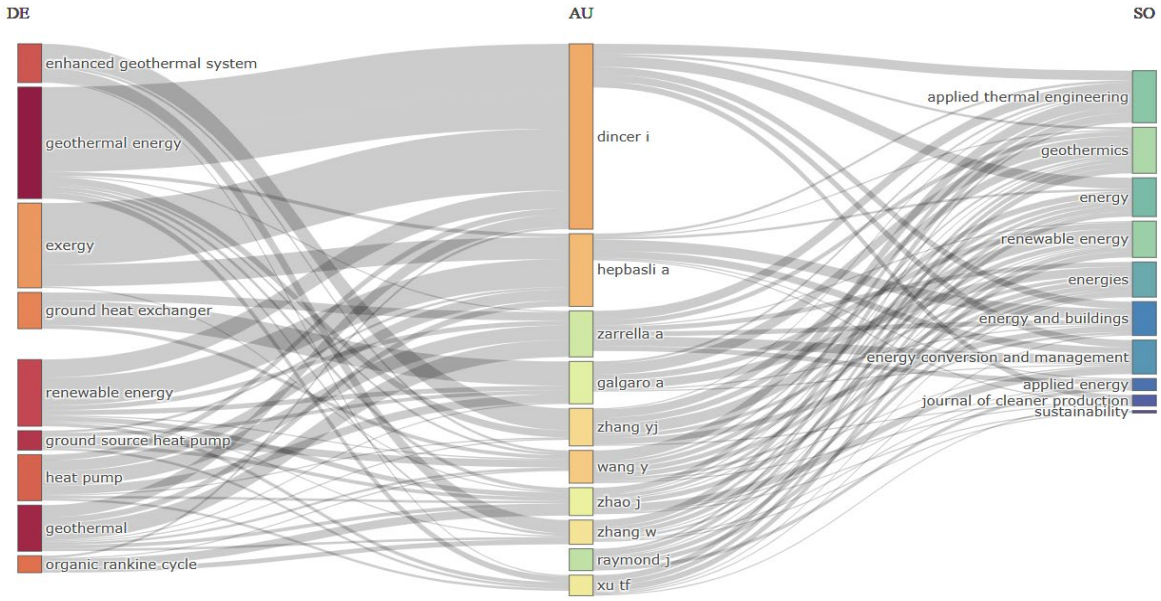

Figure 12. Sankey diagram of author, journal and keywords

3.7. Most Influential Publications

Table 8 lists the top 10 papers by the number of citations. The most cited publications include studies on geothermal power plant, GSHP, geothermal hybrid system, heat transfer of geothermal reservoir and also studies that examine several alternative sources simultaneously. Among the journals that publish the most articles in this field, "Geothermics", "Renewable Energy", "Energy", and "Energy and Buildings" are included in the list of most cited publications. Among the authors who published the most papers, only XU Tianfu is included in this list.

The article published by Jacobson and Delucchi [29] ranks first in the list. The paper analyzes the feasibility of providing energy from renewable energy resources worldwide and for all purposes. The article published by Saleh et al. [30] ranks second in the list and discusses different types of processes that match the thermodynamic properties of working fluids in Organic Rankine cycle. The third-ranked article by Brandl [31] focuses on energy piles used through structural elements of buildings in the context of geothermal geotechnics.

4. DISCUSSION

In this study, the objective was to perform a bibliometric analysis to better understand the field of Geothermal Energy Utilization (GEU). The topic of harnessing geothermal energy is one of the scientific research areas with an increasing number of publications, contributing to long-term climate neutrality and enhancing energy security. This study is expected to further increase the interest in this research topic.

The study has three main contributions. Firstly, it displays the annual publications and citation counts related to GEU and it identifies influential authors, journals, countries, and specific articles in this field. This literature profile provides a comprehensive introduction to the GEU literature for future researchers.

Secondly, this study highlights the parallel scientific development alongside technological advancements in the field of Geothermal Energy Utilization (GEU). Throughout the process, there have been different focal points evolving over time. Studies focusing on hydrothermal systems and investigating the detection, utilization, and performance of geothermal reserves can be considered as the starting point of academic development. After 2010, significant research has been conducted on the utilization and development of geothermal resources, including geothermal power plants, Ground Source Heat Pumps (GSHP), and hybrid systems. After 2015, the focus of studies has shifted more towards Enhanced Geothermal Systems (EGS) and hydrogen technologies.

Economically generating electricity from geothermal energy is dependent on accessible and large geothermal resources. However, geothermal power plants are getting to a more efficient point with the development of technologies like binary cycle systems and Organic Rankine cycle systems. Using these technologies, the utilization of low-temperature geothermal sources can be enhanced, leading to increased electricity generation and improved project economics [3]. GSHP is identified as one of the most efficient systems among renewable energy systems.

Table 8. The top 10 papers by the number of citations

	Paper title	Research topic	Authors	TC	Sources	Year
1	Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials	A feasibility analysis has been conducted for the provision of energy from renewable energy sources worldwide and for all purposes [29].	Jacobson, M. Z., & Delucchi, M. A.	981	ENERG POLICY	2011
2	Working fluids for low-temperature organic Rankine cycles	The focus has been on electricity generation from geothermal power plants. Different types of processes that match the thermodynamic properties of working fluids in Organic Rankine cycles have been discussed [30].	Saleh, B., Koglbauer, G., Wendland, M., & Fischer, J.	892	ENERGY	2007
3	Energy foundations and other thermo-active ground structures	The focus has been on the use of energy piles through the structural elements of buildings within the scope of geothermal geotechnics. The article has explained the heat transfer between the ground and the absorbing fluid with concrete/soil [31].	Brandl, H	769	GEOTECHNIQUE	2006
4	Experimental evaluation of using various renewable energy sources for heating a greenhouse	An experimental study has been conducted on the greenhouse heating system with biogas, solar, and ground energy, considering climatic conditions in Elazığ, Turkey. Greenhouse heating has been successfully tested using different energy sources [32].	Esen, M., & Yuksel, T.	677	ENERG BUILDINGS	2013
5	Optimum design criteria for an Organic Rankine cycle using low- temperature geothermal heat sources	The optimal design criteria for Organic Rankine power cycles using low-temperature geothermal heat sources have been investigated. The optimum cycle performance has been examined in the context of various working fluids [33].	Hettiarachchi, H. M., Golubovic, M., Worek, W. M., & Ikegami, Y.	551	ENERGY	2007
6	Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey	Performance tests and financial analyses of a horizontal GSHP setup have been conducted. Cost analysis and payback periods for varying sources of fuel/power have been identified [34].	Esen, H., Inalli, M., & Esen, M.	439	ENERG CONVERS MANAGE	2006
7	Dynamic life cycle assessment (LCA) of renewable energy technologies	Renewable energy technologies have been evaluated with a life cycle approach (the process from research and production of materials to final recycling/disposal) [35].	Pehnt, M	434	RENEW ENERG	2006
8	Enhanced geothermal systems (EGS) using CO ($_2$) as working fluid - A novel approach for generating renewable energy with simultaneous sequestration of carbon	The thermophysical properties of a geothermal reservoir designed to operate with CO_2 have been evaluated, and numerical simulations have been performed in this regard [36].	Pruess, K.	429	GEOTHERMICS	2006
9	TOUGHREACT: A simulation program for non-isothermal multiphase reactive geochemical transport in variably saturated geologic media: Applications to geothermal injectivity and CO_2 geological sequestration	Two examples of the applicability of toughreact program have been presented. The first example is related to mineral scaling in a fractured geothermal reservoir, and the second example concerns the geogenic sequestration of CO_2 in a saline aquifer [37].	Xu, T., Spycher, N., & Pruess, K.	429	COMPUTERS & GEOSCIENCES	2006
10	Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles	The behavior of an energy pile installed in the London Clay has been investigated, including temperature cycles under long-term loading [38].	Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, C., & Payne, P.	415	GEOTECHNIQUE	2009

TC: Total citation

GSHP has gained a significant share in the market in recent years, which contin-ues to increase every year. Although these systems are popular, their disad-vantages such as high initial investment costs and infrastructure constraints prevent their widespread use. The performance of GSHPs is evaluated and optimized tak-ing into account thermal properties of the ground, groundwater conditions and eco-nomic considerations. Improving the performance of Ground Heat Exchangers (GHE), one of the system components, is easy, and it has the most significant effect on general system efficiency. Therefore, when GHE efficiency is increased, GSHP efficiency also improves [39]. In recent years, hybridization of different renewable energy sources has attracted intense interest in the energy sector. Geothermal system hybrid technologies are applied as Solar & Geothermal, Biomass & Geothermal, Wind & Geothermal and Solar & Wind & Geothermal. Hybrid generation systems offer high-performance solutions by reducing the disadvantages of individual systems. Geothermal power plants generate energy by applying various thermodynamic cycles, similar to many power plants. However, when the temperature, pressure, or mass flow rate of a geothermal source decreases, the

power output of the plant generally decreases. Enriching geothermal energy with other renewable energies will overcome these shortcomings [40].

Besides conventional geothermal systems with meteoric water circulation, HDR and EGS are also recognized as geothermal energy sources. The only difference in these two systems is the rock type. While the rock type in HDR systems is igneous rocks, the rock type in EGS is sedimentary basin type rocks. However, EGS has recently been used as a term to cover both systems. EGS technologies aim to increase access to geothermal energy and enhance improvement in limited rock structures. HDR resources are available in every field up to a certain depth. The development and utilization of these resources are considered as the most promising strategic choice for addressing resource shortages and increasing security in the future [41]. Hydrogen is suggested as one of the fuels that can help minimize the use of fossil fuels worldwide. Hydrogen generation and utilization technologies can be integrated into geothermal resources conveniently. The addition of geothermal sources to hydrogen production will accelerate the realization of hydrogen economy. The technology of producing hydrogen from geothermal energy is not limited to direct use but can also provide additional power to a hybrid geothermal system. Optimization studies in this area will lead to determining the most significant design possible, allowing for significant progress and improvements. Therefore, hydrogen production from geothermal energy is a promising technology worth future research [42].

Thirdly, some points can be presented to contribute to the field for the development and sustainability of GEU. The use of geothermal energy is relatively clean. However, various harmful effects can occur during the utilization of geothermal resources. Sulfur oxides (SOx) and CO2 produced during the extraction of geothermal resources cause air pollution. Geothermal resources also contain H2S gas. Moreover, geothermal fluids contain various chemical pollutants such as boron and arsenic. In this context, geothermal waters containing various pollutants need to be treated with efficient and economical treatment methods [43]. In this field, the use of sustainable and environmentally friendly technologies and studies for their development will contribute to the support of this field. However, laws and regulations form the basis of geothermal industry and guarantee its development [44]. Research and regulation of public policies such as R&D programs, investment incentives, tax incentives developed for the utilization of geothermal energy would be effective in maintaining the sustainability of these resources. Furthermore, the establishment of more comprehensive standards and monitoring systems for digitalization, data analytics, international collaboration, and the essential technologies and equipment manufacturing needed by the geothermal industry will accelerate progress in the field of GEU.

5. CONCLUSION

This study primarily aimed to present the main characteristics of research on GEU in a holistic way, therefore presented a bibliometric analysis of existing studies on GEU, using three different programs used to analyze 7603 articles published between 1980 and 2023 in the WoS Core Collection. The following results were obtained.

- Studies on GEU have shown significant growth since 2010, with an increasing number of academics and institutions participating in the research. "Energy and Fuels" is the most popular field.
- Collaboration in co-authored studies is most common in China, the US and Germany. China and the USA are the two most productive countries in this field. The support and encouragement given by the Chinese government to scientific studies on GEU has enabled China to progress rapidly and become a leader in this field. The most influential institution in the number of publications and citation rankings is the Chinese Academy of Sciences, China.
- "Renewable Energy," is the journal with the highest bibliographic matching citation network strength, followed by "Geothermics." In addition, "Geothermics" is ranked first among journals with the most articles published in the field, followed by "Renewable Energy".
- Geothermal energy systems have been studied from the point of view of system analysis, design, and optimization. "Performance" is the most influential keyword in current studies. However, numerical studies and artificial intelligence technologies have gained importance in the examination of such systems in recent times.
- The co-authorship analysis revealed that Xianzhi Song has the strongest connection with other authors. The two most productive scientists in the field are Ibrahim Dincer and Arif Hepbasli.
- Jacobson et al., [29] is the article with the highest citation count.
- This study provides a comprehensive review of the relevant literature, revealing the dynamics of this field over time. Innovations and research in geothermal energy will have a vital part in the expansion of this field. In this way, several goals including energy saving, carbon neutrality and emission reduction will become feasible in the field. Safe, economical, and environmentally friendly geothermal energy will be a significant constituent of future energy sources.

However, it is worth noting that this study on GEU is based on searching relevant publications using selected

keywords in English-language journals from the WoS Core Collection. Future research is recommended to broaden the scope to include other studies and applications in geothermal energy utilization.

DECLARATION OF ETHICAL STANDARDS

The author of this article declares that the materials and methods used in his studies do not require ethics committee permission and/or legal-specific.

AUTHORS' CONTRIBUTIONS

Asiye ASLAN: Applied the bibliometric analysis method, conducted data analysis, and reported the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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