

Evolution, Hotspots and Trend of Global Geothermal Energy Research

Peng Lv^{1,a}, Xishun Wu^{1,b}, Wanlun Li^{1,c}, Mingjuan Shao^{1,d}, Minghan Wang^{1,e}, Li Li^{1,f}, Jing Zhang^{1,g}

¹National Geological Library of China(Geosciences Documentation Center of CGS), Beijing 100083, China

^alpeng@mail.cgs.gov.cn, ^bwxishun@mail.cgs.gov.cn, ^csmingjuan@mail.cgs.gov.cn,

^dlwlanlun@mail.cgs.gov.cn, ^ewminghan@mail.cgs.gov.cn, ^flli@mail.cgs.gov.cn,

^gzjing_a@mail.cgs.gov.cn

Abstract: The exploitation of geothermal energy plays an important role in meeting human energy demand and reducing greenhouse gas emission. Firstly, using HistCite scientific metrology visualization software and using WoS (Web of Science) database as literature source, the published years and citation time series of the literature on geothermal energy research was analyzed, which shows that the global geothermal energy research has been very active in recent 20 years, it is a high-yield period for the important literature in this field. Starting from the early basic theory of geothermal energy, it has evolved into two relatively obvious research areas: direct utilization of geothermal energy and geothermal power generation, since then it has continued to evolve into a number of sub-domains that blend with each other and have different themes.

Keywords: Geothermal energy; Bibliometrics; Citation analysis; HistCite; Review.

1. Introduction

The global demand for energy is continuously increasing, with a projected 275% rise in global electricity consumption from 1990 to 2050 [1]. One approach to alleviate energy challenges involves the introduction of renewable energy technologies to replace traditional fossil fuel methods. Geothermal energy stands as one such option, being virtually inexhaustible. For a geothermal extraction system, its geothermal energy production capacity can sustain for up to 30 years or even longer. Unlike weather-dependent energy sources such as tidal, wind, and solar power, geothermal energy can be produced at any time of the year without additional concerns about weather conditions. Furthermore, it is estimated that even if only 1% of the estimated available geothermal energy is harnessed by humanity, it could meet the electricity demand for 2800 years [2]. Hence, the development of geothermal energy holds immense potential in meeting the growing demands for energy.

Bibliometrics focus on the study of literature systems and their quantitative characteristics using mathematical and statistical methods. This field examines the distribution structure, quantity relationships, change patterns, and quantitative management of literature, providing insights into the current status and trends of academic disciplines [3]. Currently, there is a lack of specialized reports, both domestically and internationally, that explore the current state of geothermal energy research from the perspective of literature metrics. Only adjacent fields have seen literature metric analyses and reviews, such as the analysis of academic output in global renewable energy research [4], a comparison of building energy efficiency impacts on climate using different literature databases [5], and a metric mapping study of carbon capture and utilization technologies [6]. There is a notable absence of quantitative analyses regarding the publication years and key research areas of geothermal energy research papers.

This study utilizes Web of Science (WoS) database as the primary source of literature and employs the citation visualization analysis software, HistCite, for statistical analysis to quantify the current development status of geothermal energy research.

2. Method and Data

HistCite is a citation chronology visualization program designed to analyze and construct the core literature achievements within a particular field based on the analysis of a sample of literature data. It helps identify key literature outcomes, analyze the peaks and valleys of disciplinary development trends, and enables researchers to quickly grasp the research evolution and important directions in a specific field [7]. This study employs the citation timeline analysis feature of HistCite to illustrate the citation relationships among literature. By examining the content of the key literature identified through HistCite, the study aims to delineate the knowledge landscape of geothermal energy research, providing readers with an overview of the subject. The analysis involves various bibliometric indicators, including the Global Citation Score (GCS) provided by the Web of Science (WoS) database and the Local Citation Score (LCS) provided by HistCite.

Data were retrieved from the Science Citation Index Expanded (SCI-Expanded), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index - Science (CPCI-S), and Conference Proceedings Citation Index - Social Science & Humanities (CPCI-SSH) databases within the Web of Science (WoS) by Clarivate Analytics. To extract a comprehensive collection of literature related to geothermal energy from the WoS database, a broad search query, TS="geothermal energy," was used to query the core collection literature from 1900 to the present. A total of 5,471 documents were retrieved. To gather all necessary information, the 'Export Full Record and Cited References' option was selected on the search results page, and the data were saved as a plain text file, serving as the raw data sample.

3. Results

3.1 Distribution of Publication Years

Publication quantity and citation frequency are important indicators for assessing the development level of research in a particular field. The literature retrieved in this study spans nearly a century (Fig 1). Before 1970, the total number of publications was only 11, averaging less than 2 per year, and the Total Local Citation Score (TLCS) was at a relatively low level, indicating that the field was in its early stages of research. The literature during this period was not directly related to geothermal energy research but provided theoretical foundations, such as the wellbore heat transfer coefficient proposed for thermal oil recovery [8], the classical linear poroelastic theory [9], and the Theis solution for calculating the non-consolidated confined aquifer's transmissivity [10].

Starting from the 1970s, geothermal energy began to attract attention as an untapped resource [11, 12]. From 1970 to 2002, a total of 701 articles were published. Before 2001, TLCS showed slow fluctuations with several core papers appearing in 2001 and 2002 (see Figure 2), creating the first peak in TLCS. From 2003 to 2019, the number of publications increased rapidly, accounting for 86.3% of the total dataset. TLCS sharply increased, reaching its peak in 2011 before declining, still constituting 89.3% of all the data. Four distinct peaks in TLCS were observed during this period, primarily due to the emergence of classical review papers, such as those on ground source heat pumps (2003) [13], geothermal heat exchangers (2007) [14], a review of direct use of geothermal energy (2011) [15], shallow geothermal energy development (2013) [16], and enhanced geothermal systems (2018) [17].

From 2020 to the present, there has been a slight decrease in the number of publications, and TLCS has significantly decreased. This may indicate that the field is awaiting new breakthroughs or could be attributed to recent publications that have not yet gained widespread attention.

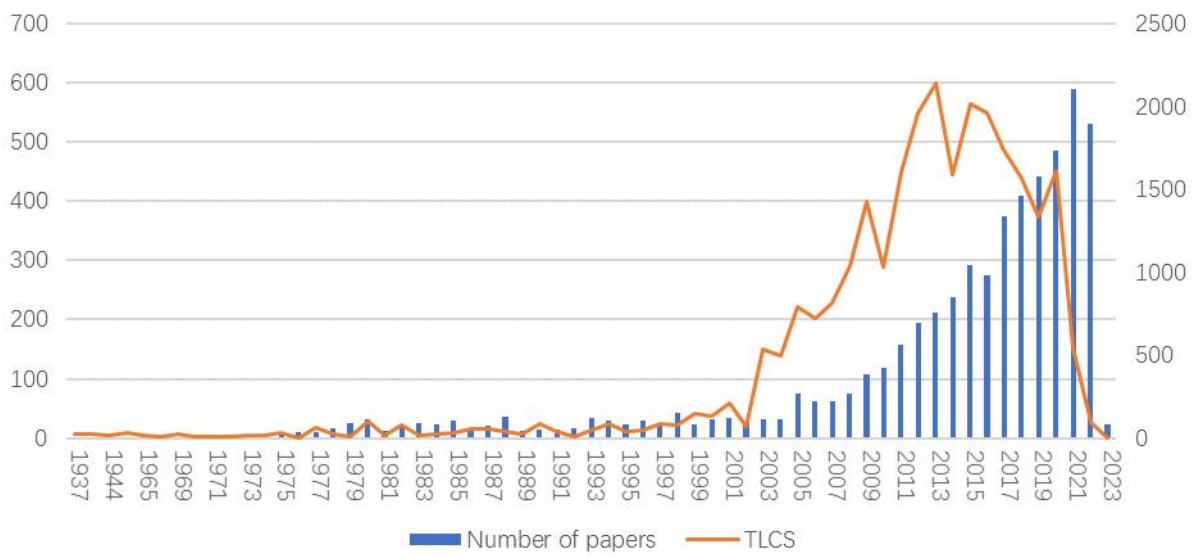


Fig 1 Annual literature output of geothermal energy.

3.2 Citation Timeline

The construction of citation chronology graphs is one of the standout features of HistCite, revealing the evolutionary trajectory and research focal points within a given field. In this study, a citation chronology graph was generated based on the LCS (Local Citation Score) metric, selecting the top 50 most frequently cited documents in the dataset (Fig 2). On the left side of the graph are the publication years of the literature, represented by circles parallel to the timeline. These circles, varying in size, denote the importance of the literature in the field, with the size proportional to the LCS value of each document. Arrows signify citation relationships between literature nodes, with the arrowhead pointing to the cited document and the arrowtail pointing to the citing document. Larger circles and more interconnected arrows indicate higher citation frequencies and greater attention for a particular document.



Fig 2 A citation chronology of 50 papers with the highest LCS

In Fig 2, it is evident that among the 5,471 retrieved documents related to geothermal energy, the top 50 important literature based on LCS are distributed between the years 1978 and 2016. Remarkably, 20 of these documents are concentrated in the period from 2001 to 2016 (Table 1). This suggests a highly active phase in global geothermal energy research over the past two decades, representing a prolific period for significant publications in this field. Examining the citation relationships, the nodes originating from earlier years, such as 695, 711, 726, and 733, evolve into two prominent networks corresponding to the distinct research boundaries of direct utilization and power generation of geothermal energy. Subsequently, these two major networks further evolve into multiple interconnected sub-networks with diverse themes.

Table 1 Basic information on the top 20 nodes of the LCS

ID	Thesis Information	LCS	GCS	Topic
139	Muffler LJP, 1978, GEOTHERMICS, V7, P53	83	218	1
593	Hung TC, 1997, ENERGY, V22, P661	53	617	2
695	Lund JW, 2001, GEOTHERMICS, V30, P29	71	123	1
708	Lee KC, 2001, GEOTHERMICS, V30, P431	57	76	1
711	Fridleifsson IB, 2001, RENEW SUST ENERG REV, V5, P299	126	219	1
726	Zeng HY, 2002, Heat Transfer-Asian Research, V31, P558	83	324	4
733	Barbier E, 2002, RENEW SUST ENERG REV, V6, P3	202	436	1
750	Kanoglu M, 2002, GEOTHERMICS, V31, P709	67	146	2
808	Sanner B, 2003, GEOTHERMICS, V32, P579	119	317	3
822	Zeng HY, 2003, INT J HEAT MASS TRAN, V46, P4467	76	279	1
879	DiPippo R, 2004, GEOTHERMICS, V33, P565	107	264	2
882	Hepbasli A, 2004, RENEW SUST ENERG REV, V8, P433	57	83	1
885	Diao NR, 2004, INT J THERM SCI, V43, P1203	86	239	4
947	Lund JW, 2005, GEOTHERMICS, V34, P691	117	222	1
978	Brandl H, 2006, GEOTECHNIQUE, V56, P81	175	496	5
1003	Laloui L, 2006, INT J NUMER ANAL MET, V30, P763	98	296	5
1008	Pruess K, 2006, GEOTHERMICS, V35, P351	126	284	7
1067	Lamarche L, 2007, ENERG BUILDINGS, V39, P188	66	248	4
1087	Hamada Y, 2007, ENERG BUILDINGS, V39, P517	60	160	5
1096	Majer EL, 2007, GEOTHERMICS, V36, P185	55	331	7

4. Summary

Geothermal energy plays a positive role in meeting human energy needs and reducing greenhouse gas emissions. This study employed the HistCite scientific metric visualization software to analyze the publication years and citation timelines of 5,471 geothermal energy research papers from the core collection of Web of Science (WoS). The analysis aimed to delineate the research trends in the field, highlighting seven significant research directions. The objective is to provide valuable insights for researchers in related fields. However, it is important to note that HistCite has certain limitations, such as its reliance on search results exclusively from WoS, subjectivity in the threshold selection for citation chronology graphs, and a potential lag in citing the latest literature. Therefore, future efforts should focus on optimizing research tools to enhance their effectiveness.

Acknowledgments

This study was supported by China Geological Survey project "Geoscience Literature Information Update and Service" (Grant No. DD20190413).

References

- [1] Fridleifsson I B. Geothermal energy for the benefit of the people [J]. *Renewable & Sustainable Energy Reviews*, 2001,5(3):299-312.
- [2] Olasolo P, Juarez M C, Morales M P, et al. Enhanced geothermal systems (EGS): A review [J]. *Renewable & Sustainable Energy Reviews*, 2016,56:133-144.
- [3] Qiu J. The definition and research object of bibliometrics [J]. *Journal of Library Science in China*, 1986,(2):71-71.
- [4] Manzano-Agugliaro F, Alcayde A, Montoya F G, et al. Scientific production of renewable energies worldwide: An overview [J]. *Renewable & Sustainable Energy Reviews*, 2013,18:134-143.
- [5] Cabeza L F, Chafer M, Mata E. Comparative analysis of web of science and scopus on the energy efficiency and climate impact of buildings [J]. *Energies*, 2020,13(2):409
- [6] Osman A I, Hefny M, Abdel Maksoud M I A, et al. Recent advances in carbon capture storage and utilisation technologies: A review [J]. *Environmental Chemistry Letters*, 2020.
- [7] Garfield E. Historiographic mapping of knowledge domains literature [J]. *Journal of Information Science*, 2004,30(2):119-145.
- [8] Willhite G P. Over-all heat transfer coefficients in steam and hot water injection wells [J]. *Journal of Petroleum Technology*, 1967,19(5):607-&.
- [9] Biot M A. General theory of three-dimensional consolidation [J]. *Journal of Applied Physics*, 1941,12(2):155-164.
- [10] Theis C V. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage [J]. *Transactions-American Geophysical Union*, 1935,16:519-524.
- [11] Hammond A L. Geothermal energy: An emerging major resource [J]. *Science*, 1972,177(4053):978-980.
- [12] Rex R W. Geothermal energy - neglected energy option [J]. *Bulletin of the Atomic Scientists*, 1971,27(8):52-56.
- [13] Sanner B, Karytsas C, Mendrinis D, et al. Current status of ground source heat pumps and underground thermal energy storage in europe [J]. *Geothermics*, 2003,32(4-6):579-588.
- [14] Florides G, Kalogirou S. Ground heat exchangers - a review of systems, models and applications [J]. *Renewable Energy*, 2007,32(15):2461-2478.
- [15] Lund J W, Freeston D H, Boyd T L. Direct utilization of geothermal energy 2010 worldwide review [J]. *Geothermics*, 2011,40(3):159-180.
- [16] Hahnlein S, Bayer P, Ferguson G, et al. Sustainability and policy for the thermal use of shallow geothermal energy [J]. *Energy Policy*, 2013,59:914-925.
- [17] Lu S M. A global review of enhanced geothermal system (EGS) [J]. *Renewable & Sustainable Energy Reviews*, 2018,81:2902-2921.