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Review article

A scientometrics review of solar thermal energy storage (STES) during the past forty years

Mohammad Ghalambaz [a,*], Mikhail Sheremet [a], Muhammad Ashraf Fauzi [b], Mehdi Fteiti [c], Obai Younis [d,e]

[a] Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 634045 Tomsk, Russia
[b] Faculty of Industrial Management, University Malaysia of Pahang (UMP), Gambang 26300, Malaysia
[c] Physics Department, Faculty of Applied Science, Umm Al Qura University, Makkah 24381, Saudi Arabia
[d] Department of Mechanical Engineering, College of Engineering in Wadi Addwasir, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia
[e] Department of Mechanical Engineering, Faculty of Engineering, University of Khartoum, Sudan

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ABSTRACT

The number of research articles on the issue of Solar Thermal Energy Storage STES has increased significantly in recent years due to the large potential of solar radiation in providing renewable and clean energy. The number of studies aiming to alleviate the intermittency character of solar radiation by storing solar thermal heat during daylight has amazingly increased. The present study is a scientometric investigation that aims to explore researchers on Solar Thermal Energy Storage STES during the past forty-one years. The scientometric analysis aims to provide the number of publications, citations, and dynamic mapping of the connections between authors, institutions, and countries in the STES domain. The method is based on the retrieval from the Web of Science database (WOS) of the bibliographic data published between 1982 and 2022. A total of 1835 items were collected on May 14th, 2022. The data have been analyzed using the VOSViewer Software to plot, visualize and map dynamic network connections between authors, institutions, and countries. The results showed that Cabeza (Current affiliation Universitat De Lleida in Spain) is the most productive author with 47 publications, 2954 total citations, an H-index of 26, and the highest TC/TP ratio, equal to 62.9. The Universitat De Lleida in Spain was ranked in the first place as the best influential and productive institution with a TP = 59 and TC/TP index equal to 59. The five top productive and influential nations are China, the USA, India, Spain, and Germany, with total publications of 1129 and contributing by 50 % to the total publications. Analysis of keywords shows China and India focused on researching “Phase Change Materials,” whereas the USA and Spain have focused on “Concentrated Solar Power” with some attention to “Molten Salt.” France has a comparable emphasis as the USA but pays less attention to “Molten Salt,” whereas Australia emphasizes all three terms.

1. Introduction

In 2016, about a quarter of the electricity produced worldwide was supplied by renewable energy sources. The total renewable energy is 23.7 %, with pumped hydroelectricity at 16.6 %, wind at 4 %, and solar at only 1.5 %. Despite the comparatively low values for solar energy, its implementation rate is astonishingly fast, and future projections are hopeful [1]. Goodall [2] investigated that in 90 min, the sun supplies the energy the world needs for a year. Some major solar energy applications include electric power generation, water heating, building comfort, water distillation, Solar pumping, Solar drying of agricultural and animal products, Solar furnaces, and Solar thermal power production.

Solar thermal energy storage (STES) is a technology that stores solar energy for later uses, such as producing heat or electricity through concentrated Solar Power plants [3], domestic water heaters [4], or building heating [5]. Since solar energy is not always available, and its amount changes with changing seasons and weather conditions, an energy storage system is required to regulate the energy flow and compensate for energy usage and prevent energy disruptions. STES systems can store thermal energy on bright days and retrieve it later on

* Corresponding author.
E-mail addresses: m.ghalambaz@gmail.com (M. Ghalambaz), sheremet@math.tsu.ru (M. Sheremet), ashrafauzi@ump.edu.my (M.A. Fauzi), mafteiti@uqu.edu.sa (M. Fteiti).

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gloomy days or at night [2]. Features of solar energy, such as endless amounts of energy, no CO2 emissions during operation, and cost savings, have made STES a vital research topic over recent decades [6]. However, the intermittency of solar energy is the biggest challenge of using this clean energy. Therefore, the STES are essential for utilizing solar energy in renewable energy applications [7].

Thermal energy storage (TES) is a kind of energy storage in which heat is used to store energy in materials. The energy stored in TES can be used later for heating and cooling applications [8]. Various materials are utilized to store thermal energy in TES applications [6]. TES systems are designed to function cyclically and are predominantly employed in buildings and industrial applications. Peak demand, energy consumption, carbon dioxide emissions, energy costs, and environmental pollution could be minimized by employing TES while total efficiency is enhanced [6].

Increasing the temperature of a substance without causing it to change phase is an example of sensible heat storage. Storing heat by heating a material like water or rock and keeping it in insulated containers is a common technique for storing heat over shorter time periods or at lower temperatures. Changing the phase of a substance, usually from solid to liquid or liquid to gas, is how latent heat storage works to store thermal energy. The energy gained or lost during the phase transition may be used for either heating or cooling. Phase change materials (PCMs) like paraffin or salt hydrates are given as examples of materials for latent heat storage [9]. Storing heat energy through reversible chemical processes constitutes thermo-chemical heat storage. In this case, the heat is stored in a substance that may undergo chemical processes to release or absorb energy [10,11] []. Metal oxides, for instance, may be used to store and release heat energy via their reaction with water to generate metal hydroxides. Dehydrating metal hydroxides releases the thermal energy they have been storing [12].

Some recent studies comprehensively reviewed various aspects of STES. For example, Badenhorst [13] extensively reviewed the usage of carbon materials in STES systems. The author considered a wide range of energy-storing carbon composites (such as synthetic and natural graphite) and different types of low and high-temperature PCMs. The author concluded that compressed expanded graphite composites were found to be the most cost-effective additives; they were able to achieve huge heat transfer improvements.

Liu et al. [9] produced a comprehensive literature review on improving the rates of heat transmission in latent heat thermal energy storage (LHTES) systems. The authors focused on and analyzed the impacts of the materials (such as PCM and NEPCM), the structure (such as fins and heat pipe), and the system arrangement (cascaded LHTES) on the thermal performance of LHTES. It was revealed that topology optimization of fins and cascaded LHTES arrangement considerably improved the thermal performance of the system, while materials optimization needs to be investigated more due to the complexity of the interaction between PCM and nanoparticles, and also PCM and porous media. A state-of-the-art review on solar air heating systems (SAHS) incorporating LHTES was introduced by Sharma et al. [14]. The review included the influence of thermal conductivity enhancement methods (such as porous media and fins) and the type of collector storage (integrated (INC) and Non- integrated (NINC)) and their configurations. It was confirmed that the thermal performance of SAHS integrated with LHTES was better than conventional SAHS. Charging and discharging rates of PCMs were considerably enhanced by using thermal conductivity improvement methods such as the addition of nanoparticles, using fins and porous media. Moreover, NICS-SAHS achieved higher thermal storage capacity than ICS-SAHS.

Caraballo et al. [15] introduced a detailed review of TES materials used for concentrating solar power. The authors analyzed the performance of fifteen various molten salts. Three key performance indicators were used for the analysis, namely, specific mass-energy density, Specific volumetric-energy density, and energy storage cost. It was concluded that nitrate-based materials are appropriate for low-temperature applications, while chloride-based materials are preferable for high-temperature applications. Suresh et al. [16] reviewed the different technologies and designs used in STES systems. Their review was extended to include the impacts of heat transmission improvement methods, heat transfer fluids, and energy-storing materials. The authors concluded that combined sensible and latent heat storage systems are cost-effective and capable of storing more energy than conventional systems.

There are few scientometric studies on either thermal energy storage [17–20] or solar energy [21–23] that address the field directions and collaboration maps of publications. The literature review showed there are excellent reviews on STES [4,5,9,13–16], but there is no scientometrics investigation to address the growth of the field and the maps of collaborations among the countries, institutes, and scientists in STES. The present study aims to utilize a bibliometric approach and study the STES field for the first time to analysis the most significant authors, institutions, and nations. The results, which sought to identify the authors, institutions, and nations that have made the greatest contributions to STES research, were presented using a number of different data visualization techniques. Search term tendencies were also analyzed in depth.

2. Research method and data

For the purpose of this investigation, The Web of Science (WOS) database was used in this study to extract bibliographic data from articles related to STES. WOS was searched on May 14th, 2022, for the research items published between 1982 and 2022 years (Over the past forty-one years). A total of 1835 documents were Found. VOSviewer software was used to analyze the data. Bibliographic mapping and clusters are created by VOSviewer mapping and clustering. VOSviewer can be used to visualize commonalities. The Science website, PubMed, Embase, and Scopus are just a few of the many databases that index papers. Because of its reputation for carefully curating high-quality and significant papers, the Web of Science (WOS) database was chosen to serve as the indexing database for this investigation. WOS gives users access to a vast library of academic resources, such as journals, books, and conference papers. In addition, it provides superior search and citation analysis features, which facilitate in-depth and all-encompassing investigation. To assure the quality and dependability of the data utilized in this investigation, WOS was selected as the recommended database.

The formula that is used for searching and extracting data related to the STES is as follows:

$$\textbf{Search String} = \left(\left(\text{TI} = \left(\text{"solar*"}\right)\right) \text{ OR } \left(\text{AK} = \left(\text{"solar*"}\right)\right)\right) \text{ AND } \left(\left(\text{TI} = \left(\text{"thermal energy storage*"}\right)\right) \text{ OR } \left(\text{AK} = \left(\text{"thermal energy storage*"}\right)\right)\right)$$

The present article uses the Boolean operator to select related articles. Based on the search formula, articles using the term solar or thermal energy storage in the title or keyword were searched on WOS. Also, based on the logical “AND” operator, articles that use both terms of “solar*” and “thermal energy storage*” in their titles or keywords are considered the statistical population of the present study.

3. Results and discussions

In the subsequent sections, our results will be presented. A bibliometric analysis is first discussed: publications and citations of the most productive influential authors, universities, and countries. In the second part, a network visualization will be presented and analyzed: co-citation of authors' co-authorships, and bibliographic coupling of authors, institutions, and countries.

3.1. Bibliometric analysis

In this section, the publications and citations are reported by year. Then, the most productive and influential authors, universities, and countries are identified and discussed.

3.1.1. Publications and citations by year

Firstly, we examined the publication and citation history of STES in the past forty-one years (1982 to 2022 years). In Fig. 1 and Table 1, there is a presentation of the total number of published articles (TP) and the total number of citations (TC) for each publication year. In addition, the table indicates the number of articles that have reached a certain citation threshold. Minimum thresholds of 200, 100, 50, 25, 10, 5, and 1 citation were considered.

The result shows that approximately 78.15 % of publications received at least one citation, and 61.25 % received at least five citations. Generally, the overall count of articles and citations increased over time except for 1984, 1988, and 2004. The number of publications has increased significantly since 2009, with more than 20. The number of citations increased nearly eight-fold in 2009 than the previous year. Publications receiving more than ten citations also increased significantly since 2009. Publications with more than 25 and 50 citations have increased by 2 digits since 2010 and have increased gradually. The quantity of citations declined in 2021 and 2022 due to the time lag between the published article and citations received by future publications.

3.2. The foremost impactful and fertile authors

Table 2 presents the best forty leading authors in STES studies. It is arranged based on the highest number of TP. We verify that the most influential authors producing STES publication output are Cabeza, with 46 publications (current affiliation is Universitat De Lleida), Prieto, with 26 publications (current affiliation is Universidad De Sevilla) and Bauer, with 23 publications (current affiliation is German Aerospace Centre) and Bonk with 21 publications (current affiliation is German Aerospace Centre). These four authors have more than 20 total publications and more than 20 TC/TP, indicating their influential work on the subject area. Cabeza produced nearly twice the number of publications as the second-ranked author, indicating the author as the most productive in the STES area.

Among these top authors, Tyagi from Shri Mata Vaishno Devi University (India) earned the most citation. Tyagi has published 16 articles in STES, earning 3652 citations. Tyagi's top-cited publication entitled "PCM thermal storage in buildings: A state of the art" (Tyagi & Buddi, 2007) [28] analyzes how PCM thermal impact and its influence on buildings. The second-ranked author based on citation is Cabeza, with 47 publications, earning 2954 citations, while the third is Donghyun Shin, with 18 publications and 1153 citations. Between the best 40 authors based on the number of publications in STES, 36 have acquired more than 100 citations. Furthermore, 12 scientists with an h-index value equal to or larger than 10 (h-indices are based only on publications in STES). Cabeza earned the highest h-index (26). This implied that out of 47 publications by Cabeza, 26 of them received 26 citations each.

Authors are shown in Fig. 2, along with their total number of publications and citations. Cole and Cole (1973) [29] categorized academics into four categories based on two major factors: citations and productivity. Authors who are very productive and cited are considered prolific. High production but few citations characterize mass producers. Perfectionists are individuals who produce little yet receive a lot of citations. Simultaneously, the productivity and number of citations of quiet authors are poor. Compared to other great writers, Cabeza and Tyagi are considered to be prolific. The bottom part of the graph shows a concentration of additional writers within the lower bound of perfectionist and silent categories. No other significant authors can be classified as either perfectionists or mass producers.

3.3. The best influential and productive institutions

Based on the top 40 best influential and productive institutions (Table 3), the institution of Lleida from Spain is the most stand-out and influential institution with 50 total publications, 2996 total citations, and 26 h-index. The institution also has a significantly high TC/TP ratio of 59.9. German Aerospace Centre (Germany) and National Renewable Energy Lab (USA) ranked second and third with 36 publications, respectively. China's institutions (9) lead this position generally, America (6), and five from Spain and India. Other countries with two or more institutions are Australia (3), France (2), Malaysia (2), and Sweden (2).

Subsequently, universities are plotted in Fig. 3 based on total publications and total citations. University Lleida stands out from the rest as a highly prolific institution. National Renewable Energy Lab (USA) German Aerospace Center DLR (Germany), Anna University (India), Chinese Academic Science (China) Xian Jiao Tong University (China), University Perpignan (France), University Barcelona (Spain) made up of the bottom half of the prolific quadrant. While two institutions,

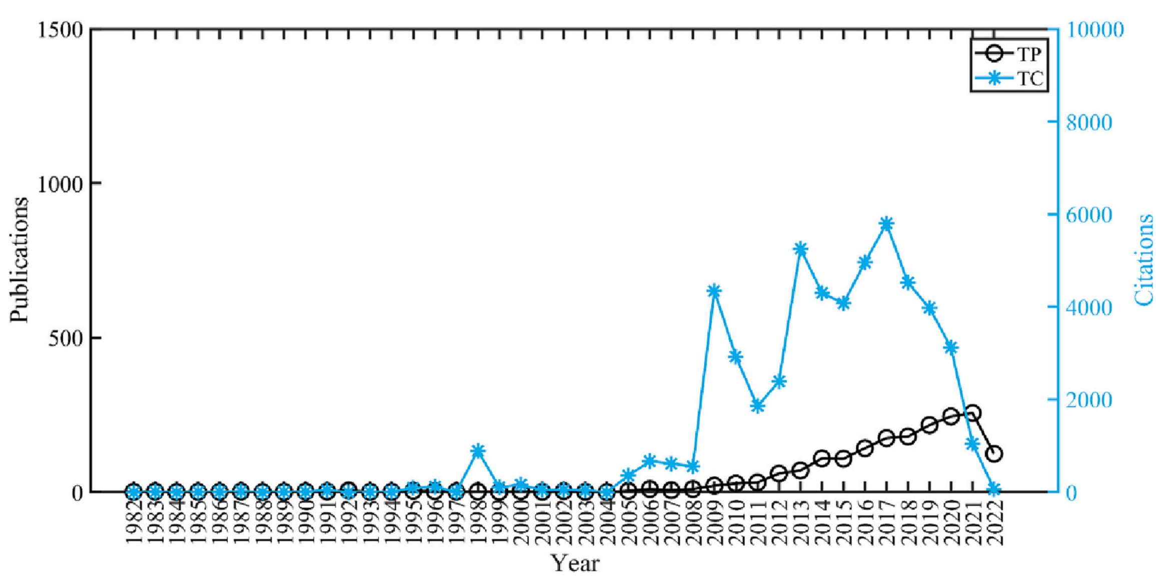

Fig. 1. The time history of TC = Total Citations and TP = Total Papers.

Table 1
The total number of publications and citations by year.

Year	TP	TC	The number of publications with citations more than:							Decades	TP	TC
			200	100	50	25	10	5	1			
1982	1	0	0	0	0	0	0	0	0	80'	8	32
1983	2	6	0	0	0	0	0	1	1			
1984	0	0	0	0	0	0	0	0	0			
1985	1	1	0	0	0	0	0	0	0			
1986	1	6	0	0	0	0	0	1	1			
1987	2	18	0	0	0	0	1	1	2			
1988	0	0	0	0	0	0	0	0	0			
1989	1	1	0	0	0	0	0	0	0			
1990	2	13	0	0	0	0	1	1	1	90′	23	1280
1991	2	40	0	0	0	1	1	2	2			
1992	5	0	0	0	0	0	0	0	0			
1993	1	7	0	0	0	0	0	1	1			
1994	1	6	0	0	0	0	0	1	1			
1995	4	91	0	0	0	2	3	3	4			
1996	3	118	0	0	1	1	2	3	3			
1997	2	1	0	0	0	0	0	0	0			
1998	2	893	1	1	2	2	2	2	2			
1999	1	111	0	1	1	1	1	1	1			
2000	3	156	0	0	2	2	3	3	3	00′	59	6820
2001	1	43	0	0	0	1	1	1	1			
2002	3	47	0	0	0	1	2	3	3			
2003	1	42	0	0	0	1	1	1	1			
2004	0	0	0	0	0	0	0	0	0			
2005	4	353	0	2	3	3	3	3	4			
2006	10	666	0	2	4	7	10	10	10			
2007	6	613	2	3	3	3	4	4	4			
2008	10	556	0	2	3	7	8	8	8			
2009	21	4344	3	5	8	9	16	17	20			
2010	28	2924	3	8	14	17	18	21	25	10′	1120	40,036
2011	31	1854	1	5	15	20	23	23	27			
2012	60	2386	0	7	17	31	37	41	45			
2013	70	5254	4	7	33	49	58	61	62			
2014	109	4302	2	8	27	50	74	83	95			
2015	108	4074	2	7	22	51	76	90	100			
2016	142	4958	2	9	30	65	92	106	125			
2017	175	5793	5	9	34	67	107	132	151			
2018	180	4519	0	4	27	69	110	129	154			
2019	217	3972	0	1	14	57	122	158	186			
2020	245	3120	0	1	9	28	98	152	219	20′	625	4227
2021	256	1046	0	0	0	5	24	60	159			
2022	124	61	0	0	0	0	0	1	13			
Total	1835	52,395	25	82	269	550	898	1124	1434			
%	100 %	–	1.36 %	4.47 %	14.66 %	29.97 %	48.94 %	61.25 %	78.15 %			

University Seville (Spain) and North China Electric Power University (China), are considered to be low-level mass producers.

3.4. The best influential and productive nations

As shown in Table 4, based on the top 40 most influential countries, there are 1835 publications in all. China is ranked highest, with 318 publications. USA and India ranked second and third with 269 and 265 publications, respectively. The top five countries contributed 1129 publications, approximately 50 % of total publications. China (14.1 %), the USA (12.05), India (11.8 %), Spain (7.8 %), and Germany (4.5 %).

The total population per million inhabitants and R&D investments were included to measure a country's publication productivity and % of GDP in R&D investment. Regarding total citations, the USA leads the list, followed by China, India, Spain, and France. When considering the overall publications and citations in relation to R&D expenditure, India tops the list with a substantial ratio of TP/R&D (378.6) and TC/R&D (12,122.9), followed by China's TP/R&D (151.4) and TC/R&D (4,091.9) and Spain TP/R&D (145.8) and TC/R&D (5,569.2). Considering citations per million people as a percentage, Spain and Australia has ratio well above 100, with 141.1 and 108.2, respectively. Therefore, it can be concluded that according to the number of people, Spain and Australia have a bigger impact on STES research.

Countries are shown in Fig. 4 based on the total number of articles and citations. Fig. 4 shows a map of the country's influence based on the total number of articles and citations. Compared to the author's and institution's overall citations and publications, it is deduced that there are significant correlations between countries' total publications and total citations map. China, the USA, India, Spain, Germany, and Australia are considered to be prolific countries in STES. Other countries are within the non-significant prolific quadrant and silent category.

3.5. Author, university, and national distribution across time

The number of authors, universities, and nations throughout time are shown in Fig. 5 and Table 5. From 1982 until 1999, there were only 30 publications produced by 66 writers from 16 universities and 5 nations. The number of publications stayed relatively small for a couple of years until 2006 when 10 publications were produced. It dipped in 2007 but resurged in 2008 until 2014 when 109 publications were produced. Since then, yearly publications have been more than 100. The ratio of authors per published paper reached 3.25 in 2005 and continued to increase. The ratio of institutions and countries per published paper lagged behind authors due to shared affiliation and the countries of some authors.

Table 2
List of forty leading authors in STES sorted by total publications (TP).

R	Author name	Affiliation	Country	TP	TC	HI	TC/TP
1	Cabeza, Luisa F.	Universitat De Lleida	Spain	47	2954	26	62.9
2	Prieto, Cristina	Universidad De Sevilla	Spain	26	887	15	34.1
3	Bauer, Thomas	German Aerosp Ctr Dlr	Germany	23	709	12	30.8
4	Bonk, Alexander	German Aerosp Ctr Dlr	Germany	21	470	9	22.4
5	Calvet, Nicolas	Khalifa Univ Sci & Technol	U Arab Emirates	19	613	12	32.3
6	Fernandez, Angel G.	Univ Antofagasta	Chile	19	375	10	19.7
7	Py, Xavier	Univ Perpignan	France	18	665	12	36.9
8	Shin, Donghyun	Cent Michigan Univ	USA	18	1153	11	64.1
9	Moth-Poulsen, Kasper	Chalmers Univ Technol	Sweden	17	604	10	35.5
10	Tyagi, V. V.	Shri Mata Vaishno Devi Univ	India	16	3652	8	228.3
11	Abdessamad Faik	Mohammed Vi Polytech Univ	Morocco	14	402	10	28.7
12	Nithyanandam, Karthik	Univ Calif Los Angeles	USA	14	623	11	44.5
13	Senthil, Ramalingam	Srm Inst Sci & Technol	India	14	149	6	10.6
14	Barreneche, Camila	Univ Barcelona	Spain	13	377	10	29
15	Ines Fernandez, A.	Univ Barcelona	Spain	13	476	10	36.6
16	Bruno, Frank	Univ South Australia	Australia	12	656	7	54.7
17	Falcoz, Quentin	Promes Cnrs Upr 8521 Lab	France	12	238	8	19.8
18	Grosu, Yaroslav	Basque Res & Technol Alliance Brta	Spain	12	194	8	16.2
19	Dincer, Ibrahim	Univ Ontario Inst Technol	Canada	11	144	7	13.1
20	Gil, Antoni	Mit	USA	11	1838	9	167.1
21	Guedez, Rafael	Kth Royal Inst Technol	Sweden	11	76	5	6.9
22	Liu, Ming	Univ South Australia	Australia	11	640	7	58.2
23	Banerjee, Debjyoti	Texas A&M Univ	USA	10	721	6	72.1
24	Belusko, Martin	Univ South Australia	Australia	10	693	6	69.3
25	Denholm, Paul	Natl Renewable Energy Lab	USA	10	438	7	43.8
26	Ding, Wenjin	German Aerosp Ctr Dlr	Germany	10	289	6	28.9
27	Ding, Yulong	Univ Birmingham	England	10	109	6	10.9
28	Laumert, Bjorn	Kth Royal Inst Technol	Sweden	10	74	5	7.4
29	Pandey, A. K.	Sunway Univ	Malaysia	10	411	6	41.1
30	Pitchumani, R.	Virginia Tech	USA	10	553	8	55.3
31	Yang, Yongping	North China Elect Power Univ	China	10	265	8	26.5
32	Agalit, Hassan	Univ Birmingham	England	9	86	4	9.6
33	Boretti, Alberto	Prince Mohammad Bin Fahd Univ	Saudi Arabia	9	33	3	3.7
34	Garimella, Suresh V.	Purdue Univ	USA	9	756	9	84
35	Saidur, R.	Sunway Univ	Malaysia	9	991	8	110.1
36	Velraj, R.	Anna Univ	India	9	747	8	83
37	Xu, Ben	Univ Texas Rio Grande Valley	USA	9	548	7	60.9
38	Borjesson, Karl	Univ Gothenburg	Sweden	8	371	7	46.4
39	Chandramohan, V. P.	Natl Inst Technol Warangal	India	8	146	7	18.3
40	Grange, Benjamin	Khalifa univ. sci & technol	UAE	8	98	5	12.3

R = Rank; h = h-index (only in STES).

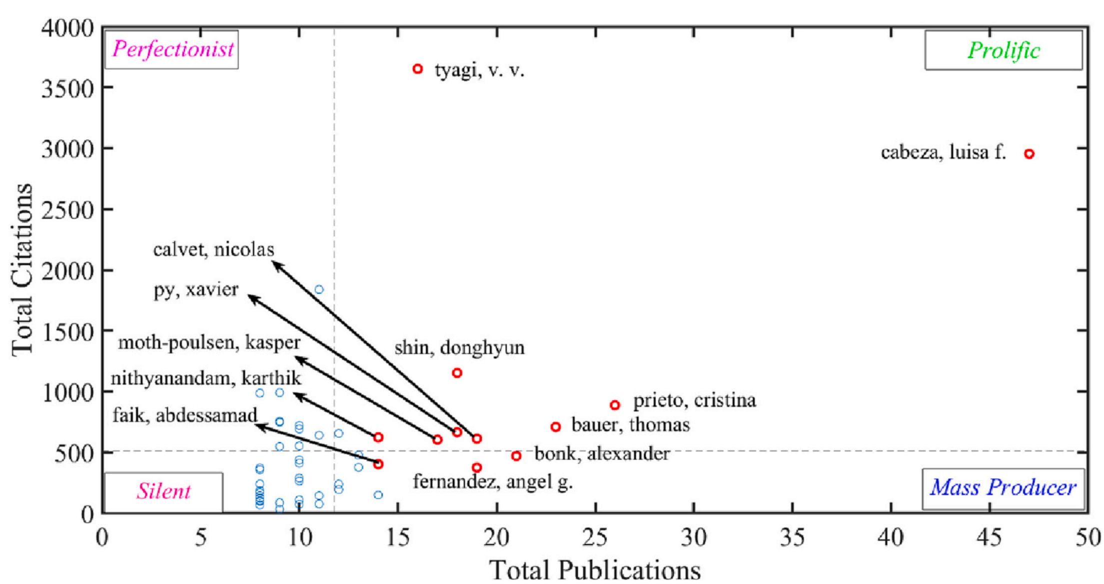

Fig. 2. Mapping of the fifty top authors based on the total number of publications and citations.

4. Network visualization maps

The following section analyzes the network visualization of the co-citation of authors; co-authorships; and bibliographic coupling of authors, institutions, and countries. VOSviewer software was used to present a network visualization (see Fig. 8) of co-authorship mapping

Table 3
Most frequent university affiliations of authors published in STES.

Rank	Institution name	Country	TP	TC	HI	TC/TP
1	Univ Lleida	Spain	50	2996	26	59.9
2	German Aerosp Ctr Dlr	Germany	36	842	16	23.4
3	Natl Renewable Energy Lab	USA	36	1038	17	28.8
4	Chinese Acad Sci	China	35	582	13	16.6
5	Anna Univ	India	23	854	12	37.1
6	Xi an Jiao Tong Univ	China	23	772	11	33.6
7	Univ Seville	Spain	22	394	9	17.9
8	Univ Barcelona	Spain	21	798	16	38
9	Univ Perpignan	France	21	707	13	33.7
10	North China Elect Power Univ	China	20	370	9	18.5
11	Univ Birmingham	England	20	227	7	11.4
12	Univ Antofagasta	Chile	19	372	10	19.6
13	Harbin Inst Technol	China	18	274	7	15.2
14	Natl Inst Technol	India	18	305	9	16.9
15	Univ Chinese Acad Sci	China	18	360	11	20
16	Indian Inst Technol	India	17	496	11	29.2
17	South China Univ Technol	China	15	334	11	22.3
18	Tsinghua Univ	China	15	347	8	23.1
19	Abengoa Res	Spain	14	692	11	49.4
20	Chalmers Univ Technol	Sweden	14	455	9	32.5
21	Cic Energigune	Spain	14	411	11	29.4
22	RMIT Univ	Australia	14	251	7	17.9
23	Shri Mata Vaishno Devi Univ	India	14	418	7	29.9
24	Srm Inst Sci & Technol	India	14	147	6	10.5
25	Univ Malaya	Malaysia	14	766	10	54.7
26	King Fahd Univ Petr & Minerals	Saudi Arabia	13	653	7	50.2
27	Sunway Univ	Malaysia	13	606	7	46.6
28	Univ South Australia	Australia	13	262	7	20.2
29	Univ Wollongong	Australia	13	245	7	18.8
30	Purdue Univ	USA	12	764	9	63.7
31	Texas A&M Univ	USA	12	771	7	64.3
32	Arizona State Univ	USA	11	605	5	55
33	Cnrs	France	11	959	8	87.2
34	Mit	USA	11	269	7	24.5
35	Shanghai Jiao Tong Univ	China	11	1690	9	153.6
36	Univ Texas Arlington	USA	11	629	8	57.2
37	Beijing Univ Chem Technol	China	10	391	8	39.1
38	Kth Royal Inst Technol	Sweden	10	214	6	21.4
39	Masdar Inst Sci & Technol	U Arab Emirates	10	161	6	16.1
40	Politecn Milan	Italy	10	227	7	22.7

among different authors.

4.1. Co-citation of authors

Co-citation is considered if two documents are cited by the same third document [24]. The idea that two articles are closely connected when they are referenced together is the foundation of the co-citation analysis [25] and hence should be grouped in a cluster solution of a visualization map. The mapping of the co-citation of authors is illustrated in Fig. 6, showing the most representative authors. The minimum number of citations of an author is 100, and of the 25,539 authors, 38 met the threshold. The map illustrated that there are three distinct clusters. Authors Sari, Sharma and Dincer are the main authors in cluster 1 (red with 15 authors). Sari recorded the highest total link strength (TLS) with 1461, followed by Sharma (1461 TLS) and Dincer (1050 TLS). The second cluster (green color, total number of authors =14) is anchored by authors Gil, Herrmann and Laing. Gil recorded the highest TLS of 1874, followed by Herrmann (1403 TLS) and Laing (1793 TLS). The third cluster (blue color, total number of authors =9) is anchored by Liu (2000 TLS), Fernandez (1376 TLS), and Zhang (1040 TLS).

4.2. Co-authorships

One of the most obvious manifestations of collaborative research is the practice of co-authorship. A co-authorship network is a social network where the authors have related to each other by involvement in one or more articles via an indirect path. Fig. 7 shows the co-authorship network of authors producing STES publications. This mapping used the fractional counting method. Each author had at least five publications and 300 citations to be included in the analysis. Among 4974 authors, only 52 meet the threshold. The map suggests there are four visible and distinct clusters interconnecting the co-authors. Cluster 1 (red): Tyagi, Saidur, Rahman, and Romero. Cluster 2 (green): Cabeza, Calvet and Fernandez. Cluster 3 (blue): Bruno, Belusko, and Liu. Cluster 4 (yellow): Bauer and Xu and cluster 5 (Prieto and Ines Fernandez). As expected, the top 3 authors in the leading authors in Table 2 (Cabeza, Prieto and Bauer) anchored the network of co-authorship groups.

4.3. Connections between writers, organizations, and nations in the literature

Bibliographic coupling occurs when a document is cited by two other documents. As described by Martyn [26], "two papers that share one reference contain one unit of coupling, and the value of a relationship between two papers having one or more references in common is stated as being of strength one, two, etc., depending on the number of shared references." Citations give information about bibliographic coupling to show the similarities between two documents, authors, institutions or countries. This connection is clustered in the visualization map when two papers referencing the third paper are highly related. The total number of references or citations and any other shared document determines the strength of the bibliographic coupling.

Fig. 8 illustrates the author's bibliographic coupling network. This analysis measures the connection strength between authors that share the same third paper. The map presents 5 clusters and their links. The map is based on authors having a minimum of 10 documents and acquiring at least 100 citations to be included in the analysis. Of the 4774 authors, 29 met the threshold. Based on the total link strength (TLS), Cabeza (9584 TLS), Bauer (8832 TLS), and Bonk (8263 TLS) are the top three in the author's bibliographic coupling. This finding suggests that in tandem with leading authors and co-authorship, the three authors are the most influential and, at the same time, have the highest bibliographic links.

When works from two different universities cite works from a third, shared university, this is known as bibliographic coupling. A chain of bibliographic coupling is depicted in Fig. 9. Each institution had at least ten publications and 100 citations to be included in the analysis. Among these 1481 institutions, only 44 met the threshold. Table 6 lists the top ten institutions ranked by their TLS. It is observed that institutions dominating the coupling among the institution are the University of Lleida (Spain), Chinese Academic Sciences (China), University of Barcelona (Spain). In reference to influential institutions based on TP and TC (Table 3), only the University of Lleida (12,892 TLS) ranked highest in both the most influential institution and institution bibliographic strength, respectively. Chinese Academic Science (9397 TLS) ranked second in institution bibliographic coupling but is ranked fourth in the influential institution. The University of Barcelona (8277 TLS) ranked third in bibliographic coupling but eighth in the influential institution. This finding suggests that influential institutions in total publications and citations might not necessarily have high bibliographic strength with other institutions.

The bibliographic coupling of the nations in STES is shown in Fig. 10. When two papers from two different nations cite papers from a third state, this is known as the bibliographic coupling of nations. Each country had at least ten publications and 100 citations to be included in the analysis. Of 85 countries, only 31 countries meet the thresholds, showing their substantial research collaboration. Table 7 ranked the top-

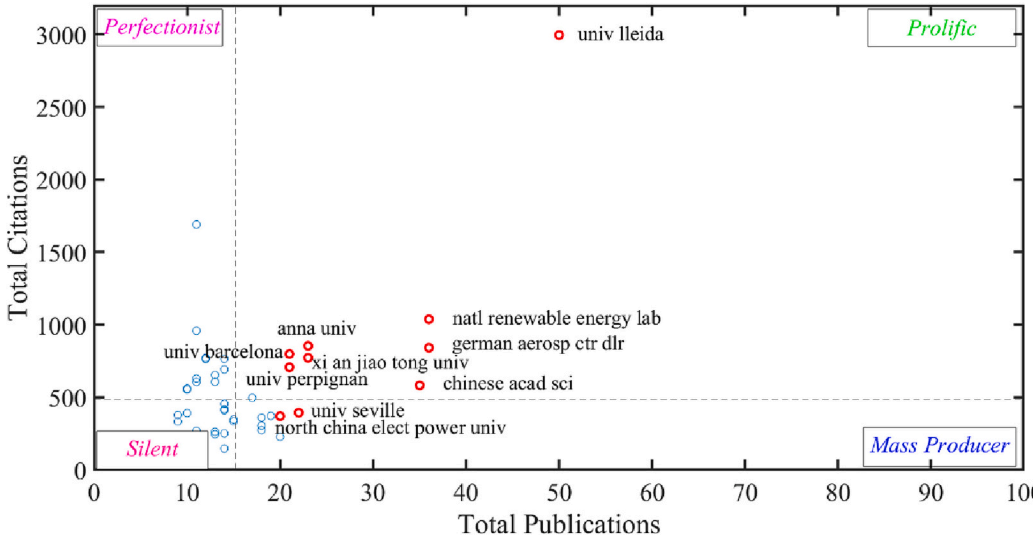

Fig. 3. Mapping of the fifty top institutions based on the total number of publications and citations.

Table 4
List of top forty leading productive and influential countries in STES sorted by TP.

R	Country	TP	TC	HI	TC/ TP	Pop.	TP/ Pop.	TC/ Pop	R&D	TP/ R&D	TC/ R&D
1	China	318	8593	48	27	1410.9	0.2	6.1	2.1	151.4	4091.9
2	USA	269	9879	54	36.7	329.5	0.8	30.0	2.8	96.1	3528.2
3	India	265	8486	41	32	1380	0.2	6.1	0.7	378.6	12,122.9
4	Spain	175	6683	45	38.2	47.4	3.7	141.1	1.2	145.8	5569.2
5	Germany	102	2617	28	25.7	83.2	1.2	31.4	3.1	32.9	844.2
6	Australia	96	2780	28	29	25.7	3.7	108.2	1.9	50.5	1463.2
7	Italy	94	1963	26	20.9	59.6	1.6	33.0	1.4	67.1	1402.1
8	France	78	3035	28	38.9	67.4	1.2	45.0	2.2	35.5	1379.5
9	England	74	2551	23	34.5	67.2	1.1	38.0	1.7	43.5	1500.6
10	Turkey	74	1966	25	26.6	84.3	0.9	23.3	1	74.0	1966.0
11	Canada	69	1810	26	26.2	38	1.8	47.6	1.5	46.0	1206.7
12	Iran	58	993	18	17.1	84	0.7	11.8	0.8	72.5	1241.3
13	Saudi Arabia	58	2472	17	42.6	34.8	1.7	71.0	0	–	–
14	Malaysia	43	1813	19	42.2	32.4	1.3	56.0	1	43.0	1813.0
15	Sweden	43	1171	19	27.2	10.4	4.2	113.1	3.3	13.0	354.8
16	U Arab Emirates	43	512	13	11.9	9.9	4.3	51.8	1.3	33.1	393.8
17	Morocco	41	575	15	14	36.9	1.1	15.6	0	–	–
18	Chile	31	542	14	17.5	19.1	1.6	28.4	0.4	77.5	1355.0
19	Egypt	30	567	11	18.9	102.3	0.3	5.5	0.7	42.9	810.0
20	Switzerland	28	553	11	19.8	8.6	3.2	64.0	3.4	8.2	162.6
21	Denmark	25	411	9	16.4	5.8	4.3	70.5	3	8.3	137.0
22	Japan	22	639	14	29	125.8	0.2	5.1	3.3	6.7	193.6
23	South Korea	19	238	7	12.5	51.8	0.4	4.6	4.5	4.2	52.9
24	Pakistan	18	405	8	22.5	220.9	0.1	1.8	0.2	90.0	2025.0
25	Portugal	18	293	9	16.3	10.3	1.7	28.4	1.3	13.8	225.4
26	South Africa	17	291	9	17.1	59.3	0.3	4.9	0.8	21.3	363.8
27	Iraq	13	107	6	8.2	40.2	0.3	2.7	0	–	–
28	Poland	13	174	7	13.4	38	0.3	4.6	1.2	10.8	145.0
29	Finland	12	56	5	4.7	5.5	2.2	10.1	2.8	4.3	20.0
30	Jordan	12	62	4	5.2	10.2	1.2	6.1	0.7	17.1	88.6
31	Netherlands	12	241	6	20.1	17.4	0.7	13.8	2.2	5.5	109.5
32	Norway	12	268	7	22.3	5.4	2.2	49.8	2.1	5.7	127.6
33	Greece	10	151	6	15.1	10.7	0.9	14.1	1.2	8.3	125.8
34	Algeria	9	120	4	13.3	43.9	0.2	2.7	0.5	18.0	240.0
35	Mexico	9	93	5	10.3	128.9	0.1	0.7	0.3	30.0	310.0
36	Brazil	8	21	3	2.6	212.6	0.0	0.1	1.2	6.7	17.5
37	Cyprus	8	128	3	16	1.2	6.6	106.0	0.5	16.0	256.0
38	Israel	8	164	5	20.5	9.2	0.9	17.8	4.9	1.6	33.5
39	Slovenia	8	259	7	32.4	2.1	3.8	123.3	2	4.0	129.5
40	Thailand	8	190	6	23.8	69.8	0.1	2.7	1	8.0	190.0

h = h-index (only in STES); "R&D = Research and development expenditure (% of GDP) from the World Bank (https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS); Pop. = total papers per million inhabitants; The World Bank Population estimates are used for Pop. "(https://datos.bancomundial.org/indicador/SP.POP.TOTL)"; The last year available data was used, i.e., (2015–2016–2017)."

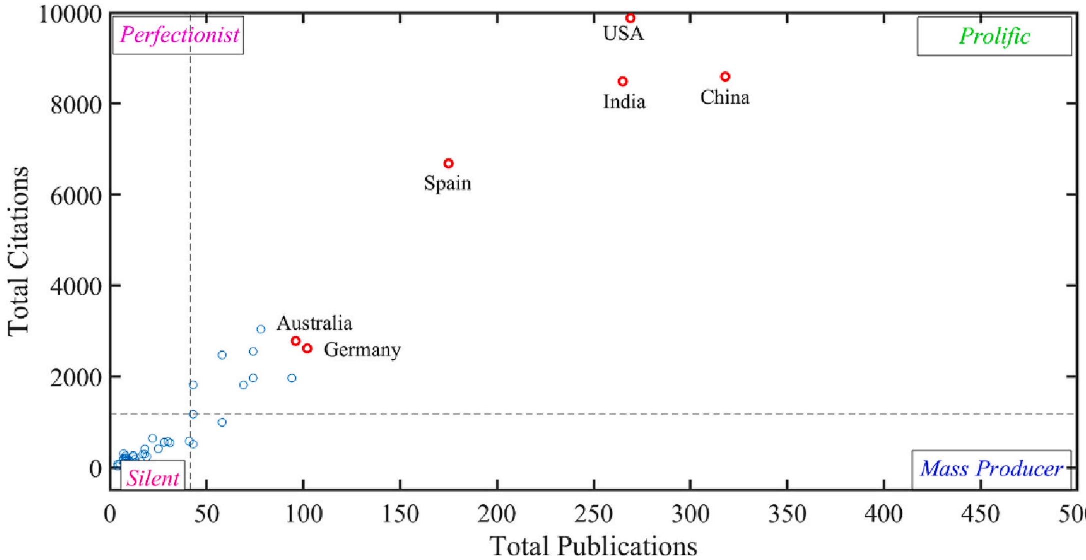

Fig. 4. Mapping of the forty top countries based on the total number of publications and citations.

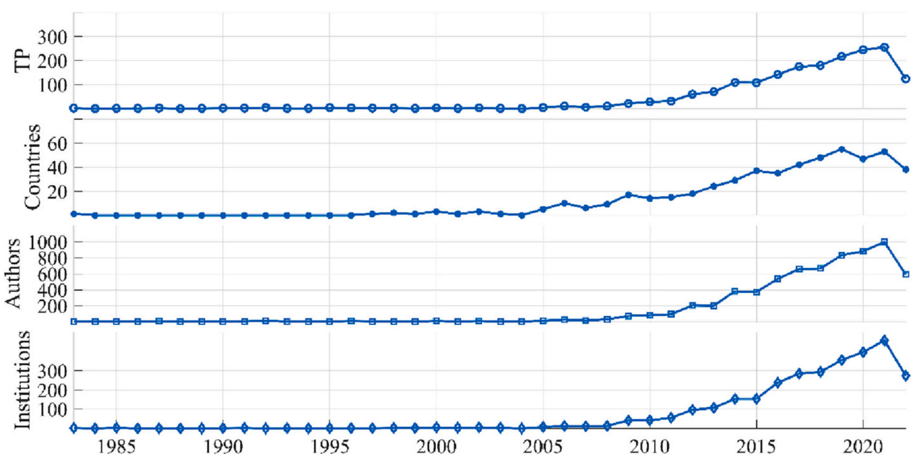

Fig. 5. Time history of the numbers of authors, institutions, countries, and total publications.

10 most linked country based on TLS. It shows that China (129,161 TLS) has the highest bibliographic coupling strength, followed by India (116,540 TLS), the USA (114,576 TLS), and Spain (96,604 TLS). In comparison with the best influential and productive countries (Table 4), the same four countries are ranked highest, with the only difference of India (third) and the USA (second) swapping places. It shows that these four countries have central influence and strong bibliographic strength among countries producing STES studies.

5. Most influential publication sources and publications

In this section, the journals with the most publications related to STES are identified first. Then, the most cited publications were reported and discussed.

5.1. Most relevant and most cited sources

Fig. 11 presents the 20 most relevant sources published in STES with 1096 publications. It can be depicted that Solar Energy (Elsevier) has the highest number of publications, with 164. The second, third, and fourth-ranked journals are Renewable Energy (Elsevier), Applied Energy (Elsevier), and Solar Energy Materials and Solar Cells, with 118, 112, and 104 publications, respectively. These four journals produced more than 100 STES publications, with cumulative publications of 498 accounting for 45 % of overall publications. It can be deduced that STES-related literature is concentrated within these mainstream journals, contributing to its relevance to the subject area and high impact factor, thus attracting more audience.

The list of top-cited sources is presented in Fig. 12, with a total citation of 39,365. Solar Energy received the highest citation, with 6110. The list is followed by Renewable and Sustainable Energy Review (4673), Applied Energy (4528), and Energy Conversion Management (3460). The top four journals acquired 18,771 citations, accounting for 47.7 % of overall citations. The first and third spots are the same in the most relevant sources (Solar Energy and Applied Energy). However, Renewable Energy received a lower citation than its produced publication, ranked at number 6, replaced by Renewable and Sustainable Energy Review.

5.2. Analysis of the keyword and the trend of the field

Analysis of publishing keywords is an important part of research in a variety of domains. In this part concerns the analysis of publication keywords. To reliably identify the many variations of each term, a tokenization approach, a method that entails separating each keyword into its constituent parts or tokens, was employed. After tokenizing each

Table 5
Time history of the distribution of authors, institutions, and countries for TP.

Year	TP	Authors	Institutions	Countries	Authors /TP	Institutions /TP	Countries /TP
1982–1999	30	66	16	5	2.20	0.53	0.17
2000	3	9	5	3	3.00	1.67	1.00
2001	1	2	3	1	2.00	3.00	1.00
2002	3	8	5	3	2.67	1.67	1.00
2003	1	1	3	1	1.00	3.00	1.00
2004	0	0	0	0	0.00	0.00	0.00
2005	4	13	7	5	3.25	1.75	1.25
2006	10	26	12	10	2.60	1.20	1.00
2007	6	16	11	6	2.67	1.83	1.00
2008	10	30	13	9	3.00	1.30	0.90
2009	21	72	41	17	3.43	1.95	0.81
2010	28	82	42	14	2.93	1.50	0.50
2011	31	93	55	15	3.00	1.77	0.48
2012	60	205	96	18	3.42	1.60	0.30
2013	70	201	107	24	2.87	1.53	0.34
2014	109	383	154	29	3.51	1.41	0.27
2015	108	373	154	37	3.45	1.43	0.34
2016	142	536	238	35	3.77	1.68	0.25
2017	175	660	285	42	3.77	1.63	0.24
2018	180	666	294	48	3.70	1.63	0.27
2019	217	833	356	55	3.84	1.64	0.25
2020	245	881	397	47	3.60	1.62	0.19
2021	256	997	458	53	3.89	1.79	0.21
2022	124	590	274	38	4.76	2.21	0.31

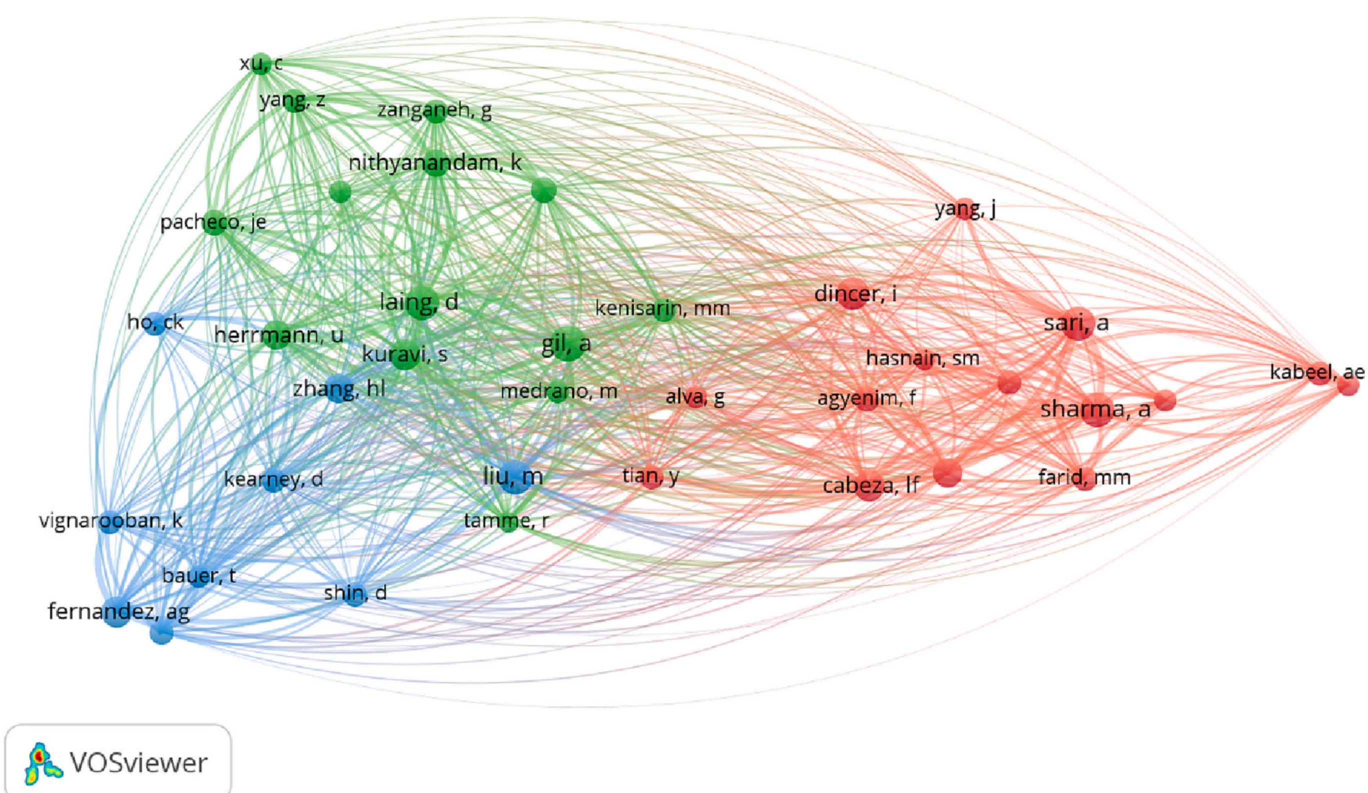

Fig. 6. Mapping of co-citation of authors in STES.

term, the keyword was converted to its base form using Lemmatization [27,28]. This phase is crucial for recognizing variants of the same term that may exist in the literature under multiple forms. By reducing each keyword to its root form, one can determine and analyze the frequency and distribution of each phrase across different publications with more precision.

Table 8 presents an overview of the top 20 keywords used in solar thermal energy storage-related research (STES). Each term is accompanied by its root form, total publications, percentage of total publications, total citations, and h-index (HI). With a TP of 1057, "Thermal Energy Storage" is the most commonly used term, appearing in 58.1 % of all articles evaluated. This term indicates the major emphasis of STES research and emphasizes the significance of creating effective and efficient thermal energy storage technologies.

Also appearing often are "Phase Change Materials" and "Concentrated Solar Power," with TP%s of 24.9 % and 24.4 %, respectively. These keywords emphasize the significance of researching materials that can store and release thermal energy during phase shifts and the

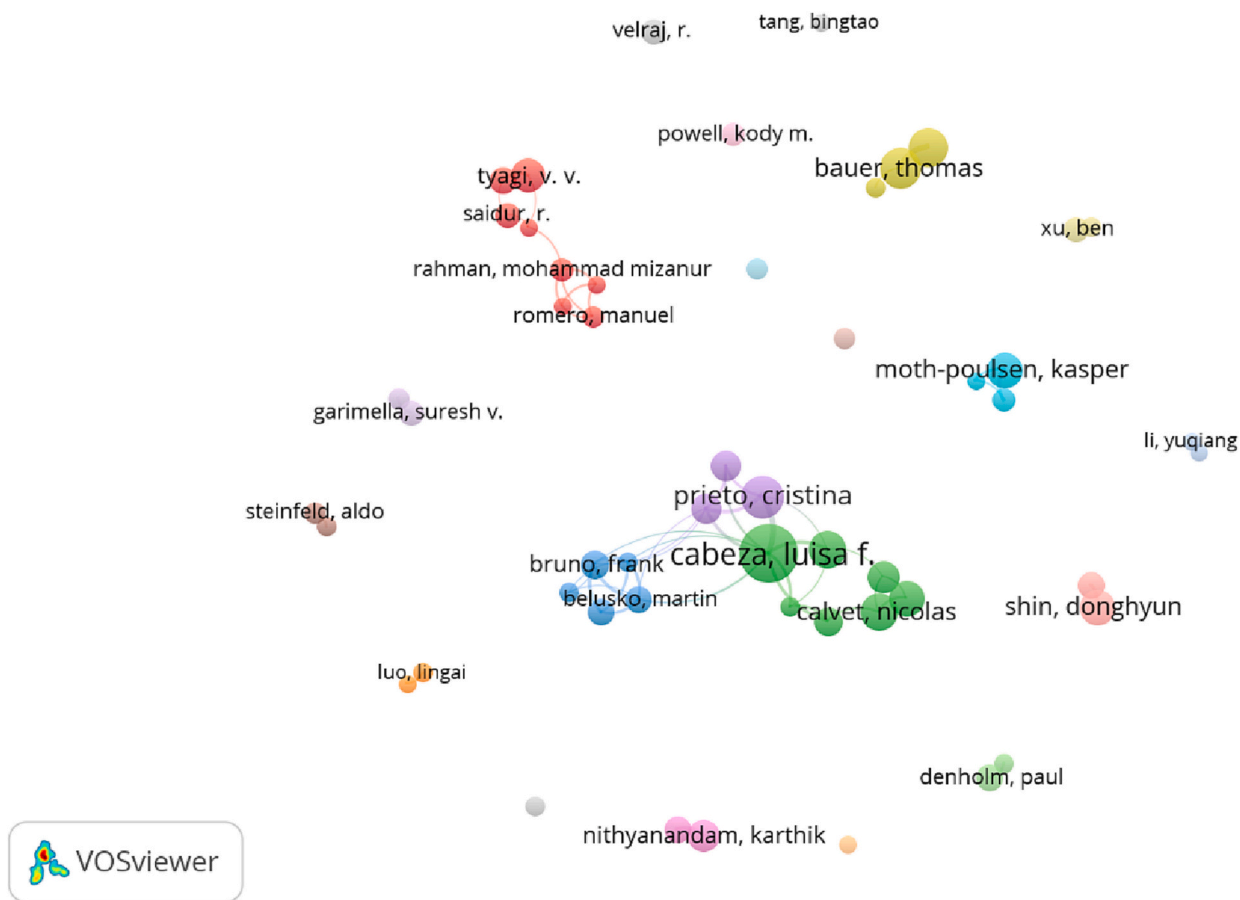

Fig. 7. Co-authorship of author publishing in STES. A minimum document number and citations of 5 and 300 were adopted to create the map.

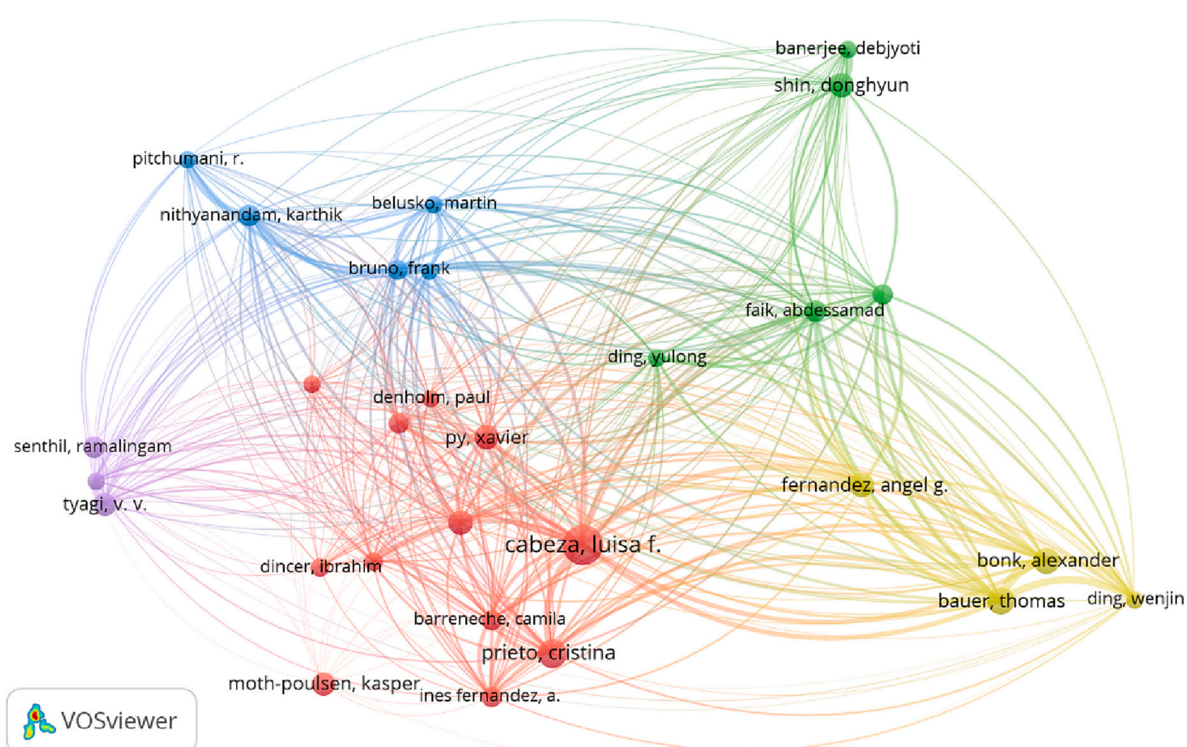

Fig. 8. Bibliographic coupling of authors publishing in STES: A minimum document number and citations of 10 and 100 were adopted to create the map.

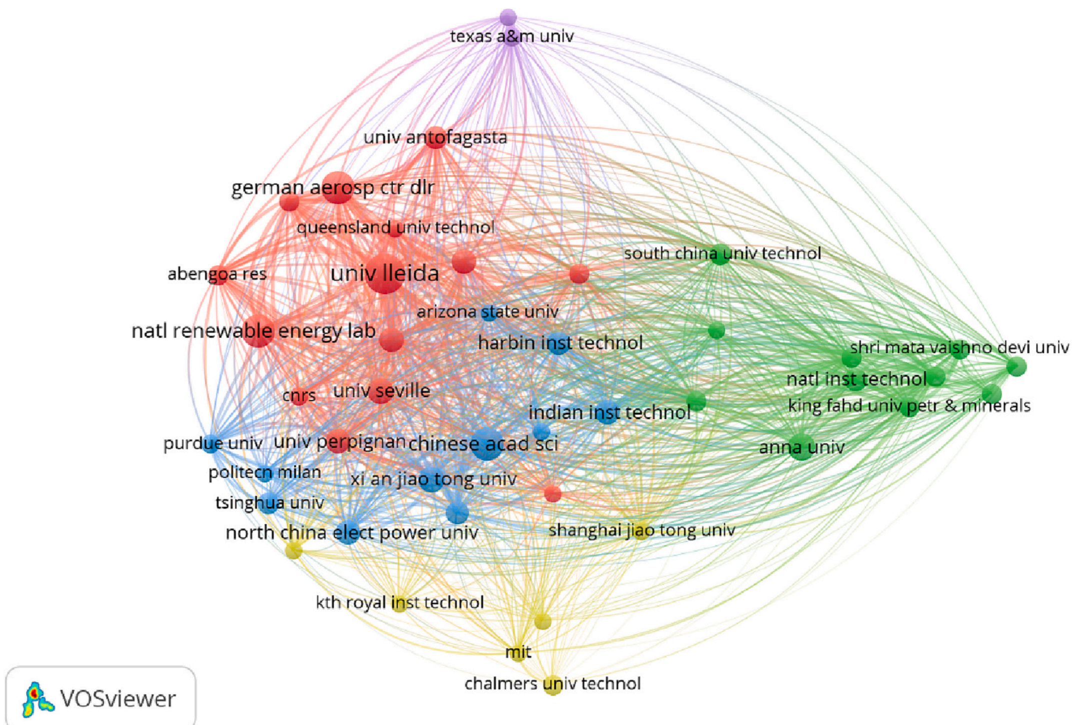

Fig. 9. Bibliographic coupling of institutions publishing in STES. A minimum documents number and citations of 10 and 100 were adopted to create the map.

Table 6
Top-10 most linked institution base total link strength.

Rank	Institutions	Documents	Citations	Total link strength
1	Univ Lleida (Spain)	52	3211	12,892
2	Chinese Acad Sci (China)	35	582	9397
3	Univ Barcelona (Spain)	21	798	8277
4	German Aerosp Ctr Dlr (Germany)	36	842	7005
5	Univ Birmingham (England)	20	227	6874
6	Univ Perpignan (France)	21	707	6496
7	Sunway Univ (Malaysia)	13	606	6269
8	Univ Chinese Acad Sci (China)	18	360	6070
9	Natl Renewable Energy Lab (USA)	36	1038	5759
10	Cic Energigune (Spain)	14	411	5554

function of concentrated solar power in STES systems.

"Molten Salt" has a TP% of 6.6 %, "Heat Transfer Fluid" has a TP% of 3.5 %, and "Thermal Storage" has a TP% of 1.8 %. These keywords emphasize the significance of building efficient thermal storage systems and the function of various materials and fluids in these systems. It is noteworthy to see that some terms, such as "Latent Heat" and "Thermal Conductivity," exist in the context of thermal energy storage, which links solar energy storage to heat transfer and phase change materials.

Fig. 13 is a cloud representation of the top 100 keywords in the area of solar thermal energy storage (STES), where the size of each term corresponds to its publication frequency. Table 8's frequency rankings for most-appearing terms are indicated by greater font sizes in the graphic. In addition to the most prominent phrases, the cloud also displays additional relevant keywords in the root form, such as "nanofluid," "heat transfer," "optim," "paraffin," and "metal hydride." These keywords give more insight into the most widely explored topics and technologies in the subject of STES.

Overall, Fig. 13 provides a complete summary of the most commonly used terms in STES, providing researchers and professionals with a useful tool for finding significant areas of interest and staying abreast of the most recent advancements in the field. This cloud depiction of the most frequently used keywords might assist academics to discover significant themes and subjects that are driving research in the area of STES, hence guiding future research and development activities.

Based on their reciprocal publications, Fig. 14 illustrates the interconnectedness of the top 20 term roots in solar thermal energy storage (STES). Each circle in the picture represents a keyword root, with the size of each circle proportional to the total number of links to other keyword roots. The thickness of the lines linking two keyword roots reflects the intensity of their relationship, with stronger lines indicating a greater number of publications that include both keyword roots.

The keyword roots "Thermal Energy Storag", "Phase Chang Materi", and "Solar Energi" form a clear triangle. This suggests that the bulk of energy in solar systems is stored in phase-changing materials. In addition, there is a significant relationship between the root words "Thermal Energy Storag" and "Concentr Solar Power," indicating that thermal energy storage plays a crucial part in concentrated solar power applications.

The keyword roots "Thermal Energy Storag", "Concentr Solar Power", and "Molten Salt" form another triangle. This suggests that molten salt is an appropriate storage medium for concentrated solar energy in STES applications. Yet, the keyword root "Molten Salt" has very few weak links with other keyword roots, suggesting that its significance is mostly restricted to solar power storage.

Fig. 15 is an analysis of the top 20 keyword roots that have been trending in the area of solar thermal energy storage throughout time (STES). The y-axis of the graph depicts the scale of keyword use during the duration of the term, ranging from 0 to 1. The popularity of the keyword stem "Thermal Energy Storag" is rising from 2005 and 2009, after which it levels out. Significant interest in the keyword stem "Phase Chang Materi" began in 2005 but subsequently waned until 2014. Following then, it attracted prominence again, and it continues to do so to the current.

The keyword stem "Concentr Solar Power" elicits negligible interest from 2005 to 2009 but experienced a substantial increase in popularity

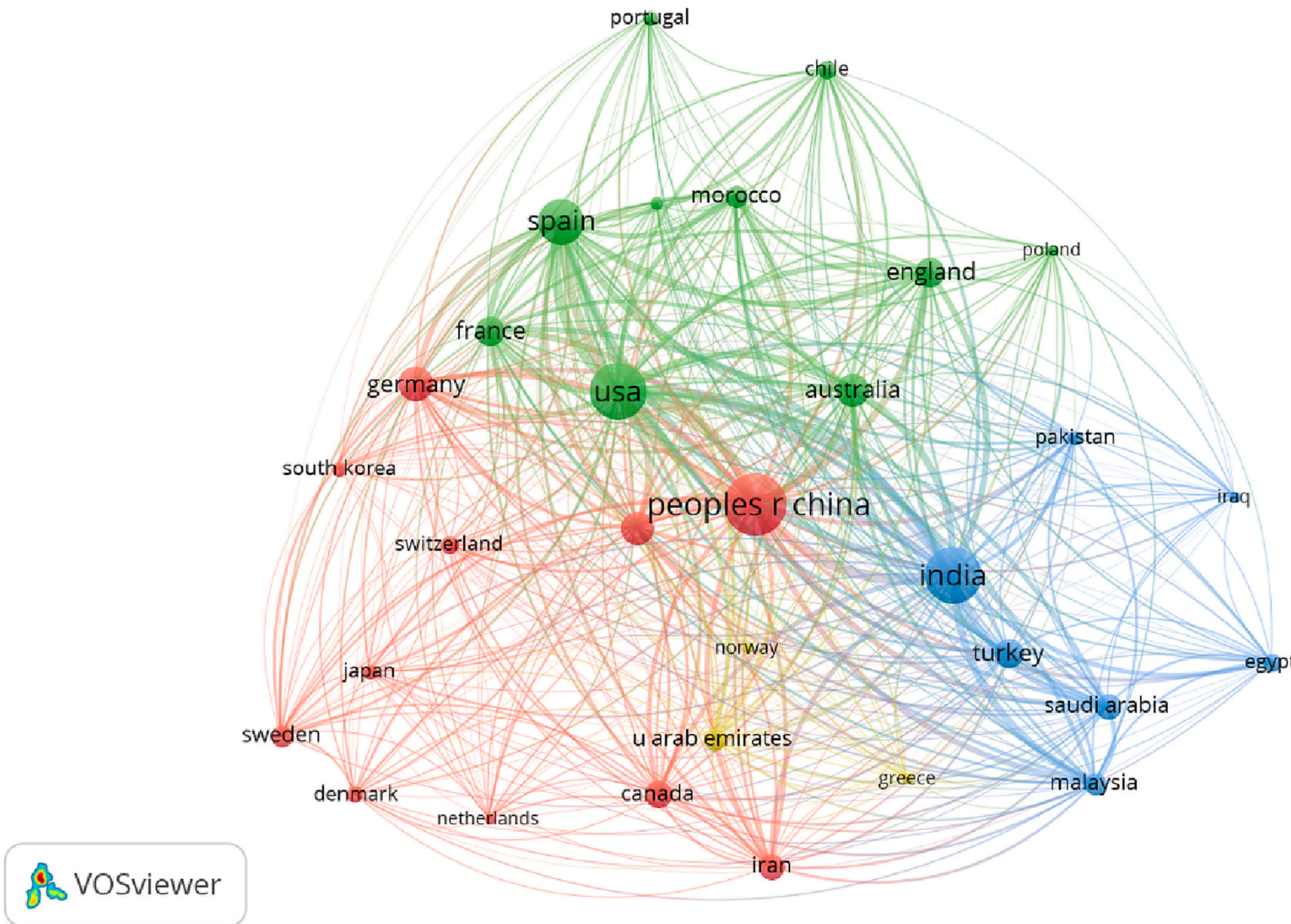

Fig. 10. Bibliographic coupling of countries publishing in STES. A minimum document number and citations of 10 and 100 were adopted to create the map.

Table 7
Top-10 most linked Country base Total link strength.

Rank	Country	Documents	Citations	Total link strength
1	China	318	8593	129,161
2	India	266	8498	116,540
3	USA	273	9907	114,576
4	Spain	175	6683	96,604
5	Australia	96	2780	64,660
6	Italy	94	1963	48,239
7	France	78	3035	46,701
8	England	74	2551	46,212
9	Malaysia	43	1813	39,658
10	Saudi Arabia	58	2472	38,397

between 2009 and 2014 and is still popular through 2021. Around 2022, though, it began to lose some of its popularity.

Other keyword stems, including “Sun Thermal”, “Thermoclin”, and “Molten Salt” have had varied levels of popularity since 2005. These changes suggest that certain keyword roots have been researched repeatedly and continue to be significant to the area of STES.

Fig. 16 compares the frequency of the top term roots in STES research from China, the USA, India, Spain, Germany, Australia, Italy, and France across eight nations in the form of radar maps. The top six keyword stems are “Thermal Energi Storag”, “Phase Chang Materi”, “Concentr Solar Power”, “Solar Energi”, “Molten Salt” and “Heat Transfer Fluid”.

China and the USA rank first and second, respectively, in terms of the number of publications in STES research, with 167 and 157 articles connected to the root keyword “Thermal Energy Storage”. The keyword root “Phase Change Materials” has 111 articles in India, followed by 94 publications in China. With just 33 articles relating to this keyword, root to the USA.

China and India have a strong interest in boosting solar energy via thermal energy storage and phase change materials, with a particular emphasis on “Thermal Energy Storage” and “Phase Change Materials.” The USA and Spain, on the other hand, are more focused on creating and storing high-temperature solar energy, with a particular emphasis on “Thermal Energy Storage” and “Concentrated Solar Power.” with some attention to the “Molten Salt” technique.

France, on the other hand, follows a trend similar to that of the USA in terms of emphasis on “Thermal Energy Storage” and “Concentrated Solar Power,” but gives “Molten Salt” technology less attention. By emphasizing all three terms, “Phase Change Materials,” “Concentrated Solar Power,” and “Molded Salt,” Australia exhibits a pattern similar to that of the USA and China.

5.3. Most cited publications

The top twenty published articles in STES with the highest citations are summarized in Table 9. A brief highlight of these articles is provided here. Sharma et al. [29] investigated the application of PCMs in buildings heating and cooling within the past decade. Their study in this area primarily aims to evaluate the thermal characteristics of various PCMs. Additionally, they reported melt fraction analyses of the few discovered PCMs employed in different storage system applications using diverse heat exchangers and container materials. The study covers diverse systems such as waste heat recovery systems, off-peak electricity storage

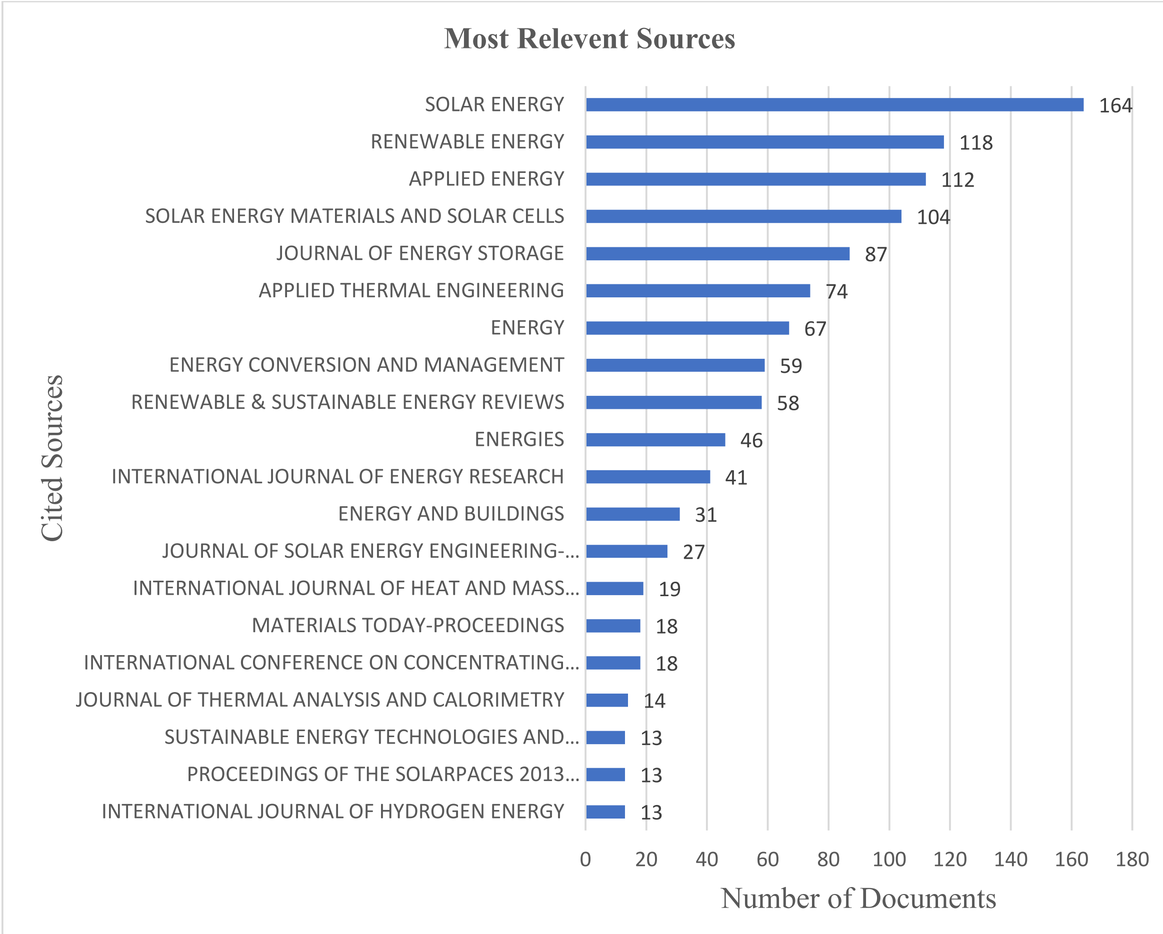

Fig. 11. Most relevant sources in STES and the number of documents for each source.

systems, solar water heating systems, solar air heating systems, solar cooking systems, solar greenhouses, space heating and cooling applications, and off-peak electricity storage systems all use heat storage applications.

In their assessment of storage media systems, Gil et al. [30] emphasized the modelization, materials, and material qualities, as well as storage principles and categorization. They concluded that creating higher thermal efficiency storage systems is essential for the advancement of concentrated solar power in the future because it provides for improved power plant dispatchability and a higher power capacity factor.

The main primary subsystems, solar collectors, and TES unit were the subjects of Tian and Zhao's [31] study of state of the art in solar thermal applications. There have been discussions about both concentrating and non-concentrating forms of solar collectors. A comparison between several kinds of TES systems as well as between different materials employed for thermal energy storage at high-temperature systems has been given. Their study suggests that good-quality molten salts are the best materials for thermal storage applications at high temperatures. Heat transfer improvement is also crucial to improve the weak heat transmission in these applications.

Hasnain [32] analyzed the evolution of TES technologies used for space and water heating applications and their particular benefits and drawbacks. It has been established that, in addition to the PCM's internal heat transmission mechanisms, the choice of phase change material (PCM) is crucial for the design of a latent heat TES system.

The design of different thermal energy storage systems that are incorporated into the power plant were explored by Kuravi et al. [33], along with thermal and exergy efficiency have been assessed. They also provide a summary of the economic characteristics of these systems and pertinent literature. They demonstrated that combining various forms of storage can provide a low-cost means of achieving the requisite level of power plant efficiency.

Liu et al. [34] provided a comprehensive summary of concentrating solar power (CSP) plants in operation and under construction. They discussed the different items of the storage system, the collector, thermal storage, power block, and heat transfer fluid technologies at their disposal. The research examines the sensible and latent heat storage advancements in high-temperature TES during the previous ten years. These systems' economic implications and high-temperature corrosion are also covered. Their findings show that recent advancements in latent TES aim to increase heat extraction rate from storage systems by encapsulating PCMs to reduce thermal resistance, employing heat pipes, and making PCMs mobile.

The state-of-the-art of the most recent experimental and computational studies on chemical processes for high-temperature thermochemical heat energy storage was introduced by Pardo et al. [35]. They reported that a thermochemical TES system has an energy density of 5 to 10 times higher than the latent and sensible heat storage systems. Thermochemical TES devices are also the most viable method for long-term solar thermal energy storage. Since items may be held at ambient temperature, there is no thermal energy loss during storage. Hence, the storage duration and the transit distance are potentially endless.

Vignarooban et al. [36] focused on the current state of the heat transfer fluid HTF, which is one of the essential components for the storing and transmitting of TES in concentrating solar power systems. The melting point, stability limit, and corrosion effects are deeply examined for various HTFs, including air, water/stream, thermal oils,

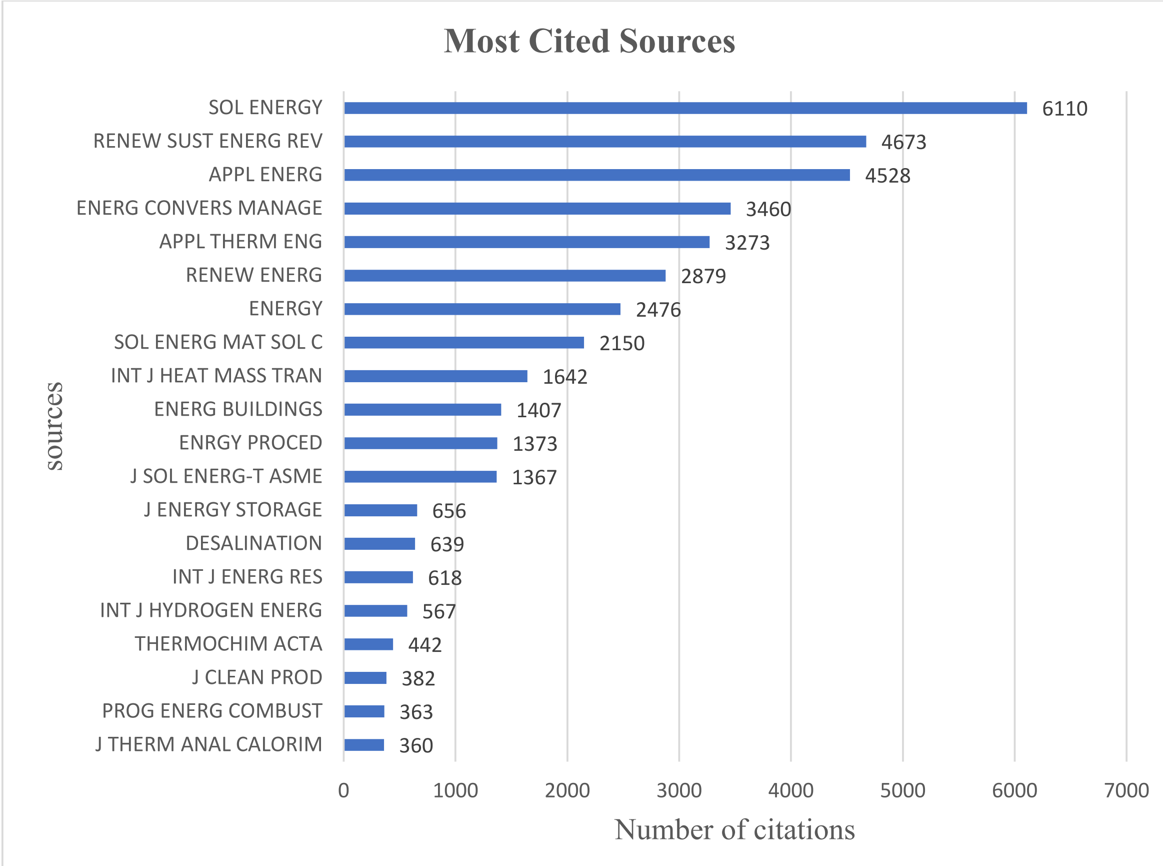

Fig. 12. Most cited sources in STES and the number of citations for each source.

Table 8
Top 20 keywords in solar thermal energy storage (STES).

Keyword root	TP	TP (%)	TC	HI
Thermal Energi Storag	1057	58.1	35,594	83
Phase Chang Materi	452	24.9	20,092	69
Concentr Solar Power	444	24.4	12,286	55
Solar Energi	255	14	9904	46
Molten Salt	120	6.6	4559	37
Heat Transfer Fluid	63	3.5	2038	21
Solar Thermal Energi Storag	58	3.2	1461	20
Energi Storag	53	2.9	1318	16
Thermoclin	49	2.7	1547	23
Latent Heat	49	2.7	5002	19
Pack Bed	40	2.2	1198	19
Solar Thermal	38	2.1	1370	18
Season Thermal Energi Storag	37	2	831	16
Solar Collector	37	2	1999	16
Solar Thermal Energi	36	2	1336	19
Renew Energi	36	2	697	13
Latent Heat Storag	32	1.8	1679	16
Heat Transfer	32	1.8	568	12
Thermal Storag	32	1.8	515	13
Thermal Conduct	31	1.7	835	15

organic fluids, molten salts, and liquid metals. Despite the variety of HTFs, molten salts with lower melting points (200 °C) and better thermal stability (working range) are the most desirable ones. The main drawback of the molten salts is the relatively in their high level of corrosion that to metal alloys.

Real-world experiences with active storage systems and passive storage systems were collated by Medrano et al. [37], who also provided thorough information on the benefits and drawbacks of each. A list of various technologies and materials utilized in solar power plants with thermal storage systems that are now in use throughout the globe was also offered. The following inferences may be made: Several choices, including steam, mineral oils, molten salts, and ammonia, are used as the HTF in the solar field. Steam is used as the heat transfer fluid in the majority of the newly constructed facilities, all of which are located in Spain. Direct steam generation's key benefits include a simpler overall plant layout and the ability for the solar field to operate at greater temperatures.

Numerous current technologies of TES and used STES materials were summarized by Alva et al. [7]. The study covered the characteristics of materials used to store solar thermal energy. They discovered that sensible and latent heat storage materials have quite developed and commercialized technology in contrast to thermochemical materials, which are still in the laboratory. Additionally, due to their largest volumetric energy storage capacity, thermochemical materials have enormous promise as TES materials in the future.

State-of-the-art on Sorption long-term Solar Heat Storage (SSHS) and challenges facing researchers were given by N'Tsoukpoe et al. [38]. Recent initiatives, such as those involving absorption and adsorption, were highlighted. They established that up to that point, SSHS experiments had proved the viability of such systems, but the highest-performing ones had been replaced by chemical heat pumps or short-term storage devices. Inadequate materials (storage density/efficiency for a given investment and discharge temperature), technical challenges, and component costs were the major causes of this.

PCMs have recently been used in TES technologies for a variety of applications, most notably CSP generating systems, according to Xu et al. Conclusions from the literature indicated that such a phase change material could give a lower storage tank space if the cutoff temperature can be kept constant with the melting temperature of a PCM, which will result in a considerable decrease in material and construction costs.

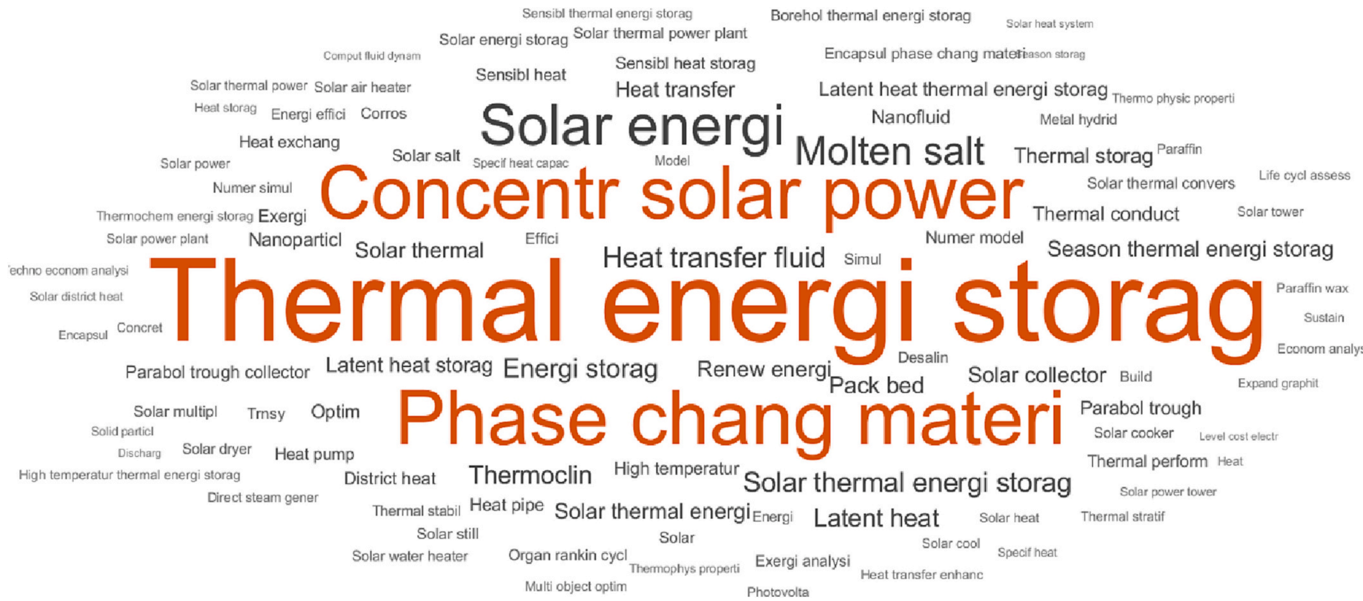

Fig. 13. Keyword cloud map of top 100 keywords in STES.

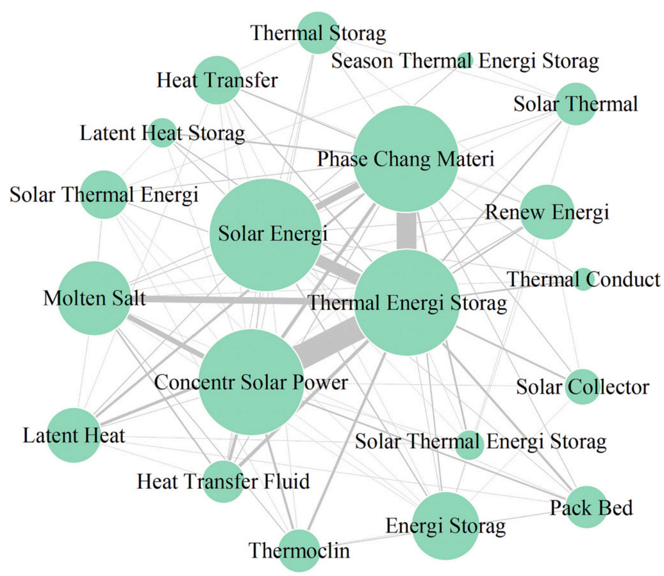

Fig. 14. Connectivity map of keywords. The line thickness shows the connection strength based on number of mutual publications.

High-temperature nanofluids' abnormally increased specific heat capacity was observed by Shin and Banerjee [39]. By doping molten salt eutectics with minuscule amounts of nanoparticles, they were able to create high-temperature nanofluids for TES, which was the goal of their work. In conclusion, their study investigated the specific heat capacity of plain chloride eutectics and the nanofluids made by doping them with SiO2 nanoparticles (at 1 % weight concentration) with nominal diameters of 20–30 nm. Additionally, they concluded that compared to the clean chloride salt eutectic, the SiO2 nanofluid increased the specific heat capacity by 14.5 %.

Sensible heat storage, latent heat storage, and chemical storage are currently used to store seasonal heat, according to Xu et al. [40]. Sensible heat storage is a somewhat established technology that has been used and assessed in several substantial demonstration facilities. Latent heat and chemical storage may significantly lower the storage volume and seldom experience heat loss issues since they have far better energy storage densities than sensible storage. The latter two technologies, however, are still undergoing laboratory-scale testing and material studies.

Thermal energy storage technologies implemented in CSP facilities were examined by Pelay et al. [41]. The state-of-the-art on CSP plants globally and the direction of development, various technologies of TES system operating at high-temperature (200–1000 °C), with an emphasis on thermochemical heat storage, and the storage models for their integration in CSP plants were only a few of the topics covered. They concluded that more than 70 % of new CSP facilities require TES systems as choices. Most CSP in operation reactors employs sensible heat storage technology because of its dependability, affordability, ease of implementation, and an enormous amount of accessible experimental feedback.

Mohamed et al. [42] presented a comprehensive analysis of research findings and recent technological breakthroughs in inorganic PCMs by offering solutions to the related drawbacks of this class of PCMs. They demonstrated the critical role of inorganic PCMs in high-temperature energy storage applications, although salts and salt hydrates still have several problems, including corrosion, phase separation, and supercooling.

According to Wang et al. [43], a brand-new hybrid substance made of form-stable polymer phase transition materials and single-walled carbon nanotubes (SWNTs) (PCMs). The materials were able to capture UV–vis sunlight and convert it into heat. They could also store thermal energy. They found that the resultant SWNT/PCM composites had some distinctive qualities, including an expanded spectrum of solar absorption, high light-to-heat conversion, energy storage efficiencies, and remarkable form stability. These composites' ease of use offers a new platform for enhancing the efficiency of solar radiation utilization, which has several applications in energy conversion and storage disciplines.

The thermal behavior of a packed bed of mixed sensible and latent heat TES unit was experimentally examined by Nallusamy et al. [44]. They discovered that the mass flow rate substantially impacts the heat extraction rate from the solar flat plate collector in the storage unit casing, which in turn impacts the pace of charging of the TES tank.

In order to provide the reader with a thorough database of thermophysical characteristics that would make the task of material selection for high-temperature applications easier, Cardenas and Leon [45] reviewed many PCMs, primarily inorganic salt compositions and metallic alloys, that could be potential candidates in storage media at

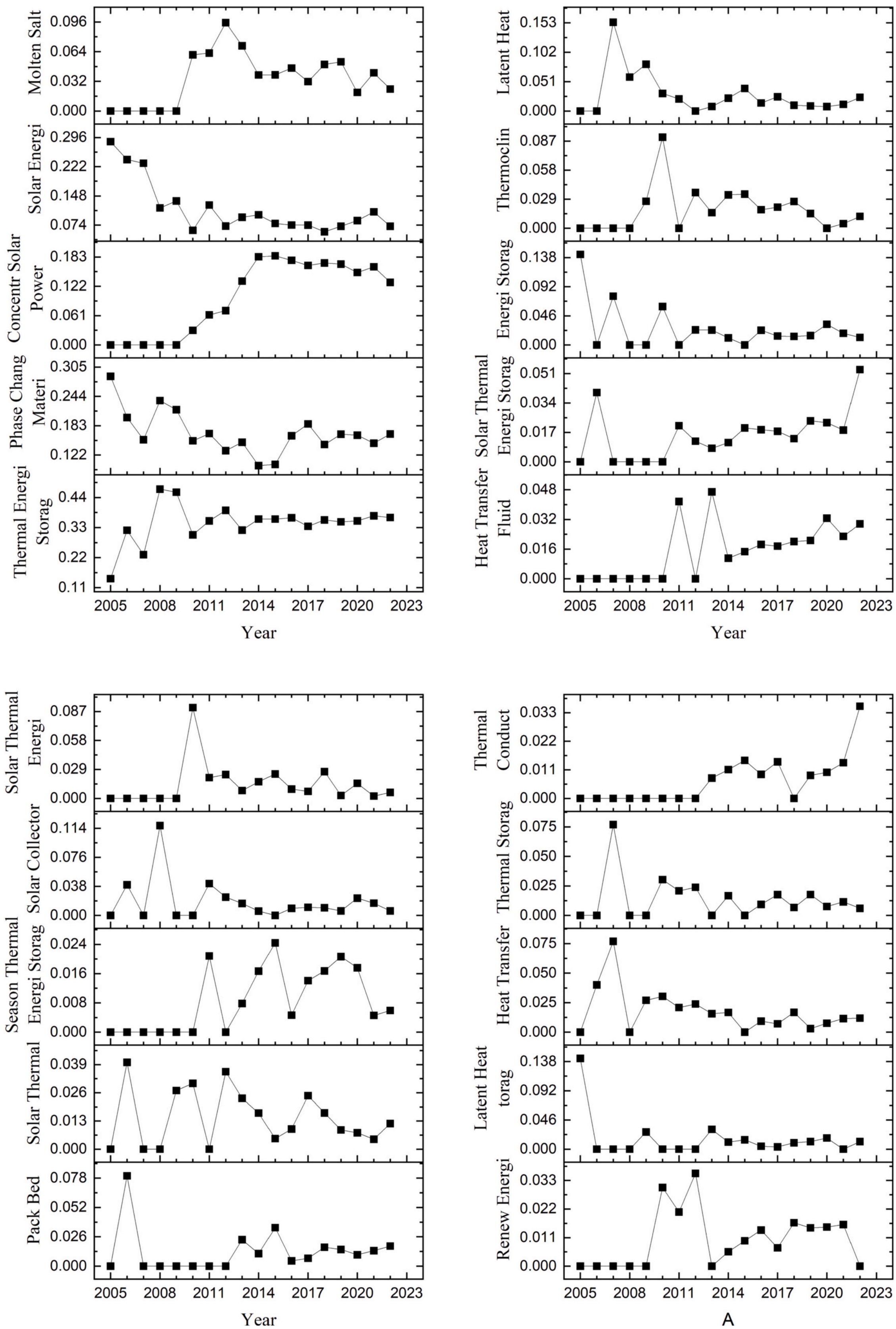

Fig. 15. The evaluation of the top 20 keywords trending over time. The y-axis shows the scale of keyword usage in the range of 0–1 over the time span of the keyword.

Fig. 16. Radar maps of top six keywords for the top eight most productive countries.

Table 9
Top twenty publications that have the most citations in STES.

Rank	Ref.	Type	Corresponding authors	Year	TC	Title	Web of Science category
1	[29]	Review	Sharma, A	2009	3117	"Review on TES with phase change materials and applications"	green & sustainable science & technology; energy & fuels
2	[30]	Review	Cabeza, LF	2010	1043	"State of the art on high-temperature thermal energy storage for power generation. Part 1-concepts, materials and modelization"	green & sustainable science & technology; energy & fuels
3	[31]	Review	Zhao, CY	2013	978	"A review of solar collectors and thermal energy storage in solar thermal applications"	energy & fuels; engineering, chemical
4	[32]	Review	Hasnain, SM	1998	812	"Review on sustainable thermal energy storage technologies, part i: heat storage materials and techniques"	thermodynamics; energy & fuels; mechanics
5	[33]	Review	Goswami, DY	2013	777	"Thermal energy storage technologies and systems for concentrating solar power plants"	thermodynamics; energy & fuels; engineering, chemical; engineering, mechanical
6	[34]	Review	Liu, M	2016	494	"Review on concentrating solar power plants and new developments in high-temperature thermal energy storage technologies"	green & sustainable science & technology; energy & fuels
7	[35]	Review	Anxionnaz-Minvielle, Z	2014	478	"A review on high-temperature thermochemical heat energy storage"	green & sustainable science & technology; energy & fuels
8	[36]	Review	Kannan, AM	2015	441	"Heat transfer fluids for concentrating solar power systems - a review"	energy & fuels; engineering, chemical
9	[37]	Review	Cabeza, LF	2010	435	"State of the art on high-temperature thermal energy storage for power generation. Part 2-case studies"	green & sustainable science & technology; energy & fuels
10	[7]	Review	Fang, GY	2017	381	"Thermal energy storage materials and systems for solar energy applications"	green & sustainable science & technology; energy & fuels
11	[38]	Review	Luo, LG	2009	378	"A review on long-term sorption solar energy storage"	green & sustainable science & technology; energy & fuels
12	[47]	Review	Li, PW	2015	367	"Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: a review of recent developments"	energy & fuels; engineering, chemical
13	[39]	Article	Banerjee, D	2011	324	"Enhancement of specific heat capacity of high-temperature silica-nanofluids synthesized in alkali chloride salt eutectics for solar thermal energy storage applications"	thermodynamics; engineering, mechanical; mechanics
14	[40]	Review	Wang, RZ	2014	300	"A review of available technologies for seasonal thermal energy storage"	energy & fuels
15	[41]	Review	Lu, LA	2017	290	"Thermal energy storage systems for concentrated solar power plants"	green & sustainable science & technology; energy & fuels
16	[42]	Review	Al-Sulaiman, FA	2017	277	"A review of the current status and challenges of inorganic phase change materials for thermal energy storage systems"	green & sustainable science & technology; energy & fuels
17	[43]	Article	Tang, BT	2013	257	"Single-walled carbon nanotube/phase change material composites: sunlight-driven, reversible, form-stable phase transitions for solar thermal energy storage"	chemistry, multidisciplinary; chemistry, physical; nanoscience & nanotechnology; materials science, multidisciplinary; physics, applied; physics, condensed matter
18	[44]	Article	Velraj, R	2007	254	"Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources"	green & sustainable science & technology; energy & fuels
19	[45]	Review	Cardenas, B	2013	247	"High-temperature latent heat thermal energy storage: phase change materials, design considerations and performance enhancement techniques"	green & sustainable science & technology; energy & fuels
20	[46]	Article	Pitz-Paal, R	2007	234	"Cascaded latent heat storage for parabolic trough solar power plants"	energy & fuels

high temperature (greater than 300 °C) latent heat storage system. Their findings suggest that latent heat storage is a promising technology for the future because it offers several benefits over sensible heat storage, including a high energy density significantly superior to sense heat storage and a nearly isothermal operation.

The experimental and numerical findings from the study of cascaded latent heat storages using alkali nitrate salts like $NaNO_3$, KNO_3, and others were published by Michels and Pitz-Paal [46]. Their work demonstrates that the design of CLHS for this temperature range is more complicated than for the temperature range up to 100 °C. On the other hand, overcoming the limited heat conductivity of the currently available PCM is a challenge to fully utilize this potential storage technology.

6. Concluding remarks

This research presents a thorough analysis of STES articles and their annual citations over the previous 41 years. The research examines the most prolific and significant writers, organizations, and nations and using several data visualization approaches. The primary objective of the research is to determine the authors, universities, and nations with the largest contribution and knowledge output in STES. The keyword analysis and trends are also addressed.

The findings indicate that the number of publications in STES has steadily risen over the previous four decades, with a notable increase in the present decade. In addition, the number of citations in the 2010s is much larger than in the 1980s, showing a rise in scientific interest in STES investigations.

- About authors, Cabeza was classified in the prolific category with the highest TC/TP index, equal to 69, and an h-index equal to 26. Cabeza is the most productive author with 47 publications and is in the second rank concerning the total citations with 2954 citations. Tyagi from Shri Mata Vaishno Devi University (India) is classified in the 10th place with 16 published articles in STES.
- Concerning the institutions, the University of Lleida from Spain is the most influential institution with 50 total publications, 2996 total

citations, and 26 h-index. The German Aerospace Centre (Germany) comes in second place with a significantly high TC/TP ratio of 59.9, and the National Renewable Energy Lab (USA) is ranked third with 36 publications.

- Based on the top selected 40 countries, China is the most productive, with 318 publications among 1835 published articles. The USA and India are in the second and third ranks, with 269 and 265 publications, respectively. A total of 1129 publications (50 %) were contributed by the top 5 countries China (14.1 %), USA (12.0 %), India (11.8 %), Spain (7.8 %), and Germany (4.5 %).
- For the co-citation of authors, three main clusters are visualized. The minimum number of citations for one author is fixed at 100 citations. Only 38 of the 25,539 met the threshold. The three clusters are anchored, respectively, by Sari, Sharma and Dincer for the first cluster (red), Gil, Herrmann and Laing for the second cluster (green) and Liu, Fernandez and Zhang for the third cluster(blue).
- In terms of co-authorship, a connection network was mapped based on a criterion of five publications in STES and 300 citations. The 52 authors satisfying the threshold are grouped into five different clusters.
- Bibliographic coupling between institutions and nations was studied. Each institution or each country should have a least 10 publications and 100 citations to be included in the study. Among the 1431 institutions, only 44 met the threshold. The top three institutions are the University of Lleida (Spain), the Chinese Academic Sciences (China), and the University of Barcelona (Spain). Concerning the bibliographic coupling of nations, China, India, and the USA come in the first three ranks. These countries have central influence and large bibliographic strength among countries producing STES studies.
- Analysis of the keyword roots STES showed “Thermal Energy Storage” is the most commonly used keyword, followed by “Phase Change Materials” and “Concentrated Solar Power.” Other relevant keywords such as “Molten Salt,” “Heat Transfer Fluid,” and “Thermal Storage” are also important in building efficient thermal storage systems. China and the USA lead STES research, while China and India emphasize “Phase Change Materials” in boosting solar energy. The USA and Spain emphasize “Concentrated Solar Power,” with some attention to “Molten Salt.” France has a similar emphasis as the USA but with less attention to “Molten Salt,” while Australia emphasizes all three terms.
- The study also shows the 20 most relevant sources published in STES. Among the 20 sources, the Solar Energy journal (Elsevier) is in the first rank in terms of published documents and citations with 164 published documents and 6110 citations; the Renewable Energy (Elsevier) comes in the second place with 118 publications and the sixth rank in terms of citations with 2879 citations. Applied Energy (Elsevier) occupies the third rank in both the number of documents and citations, with 112 publications and 4825 citations.

Declaration of competing interest

The authors clarify that there is no conflict of interest for report.

Data availability

Publicly available datasets were used in this study. This data can be found on the Clarivate database. The rest of proceed data is contained within the article.

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