Where is Thermal Energy Storage (TES) research going? - A bibliometric analysis

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ABSTRACT

Energy storage technologies can provide energy security, fight climate change, and improve the value of current or future energy systems. Thermal Energy Storage (TES) is a key enable technology, it allows to stock thermal energy that can be further used for heating and cooling applications and power generation. The methods and tools used to analyse all the literature about the evolution of TES systems research are described in this paper. Bibliometrics is the science that studies, in a statistical way, the written publications of a certain field of research, and it is considered one of the few interdisciplinary research fields that can be extended to almost all scientific areas. The bibliometric analysis of the database Web-of-science (core collection) shows highlighted information in order to figure out the scientific outputs. The importance of the bibliometrics is to analyse a knowledge development from a strategic point of view in order to detect its evolution regarding the research in such a field and to detect which are the opportunities within this area. This study presents the publication evolution in TES field over the last two decades, per year, per country, per authors, per journal, and per TES technology, taking into account sensible heat TES (SHTES), latent heat TES (LHTES), and thermochemical energy storage (TCS), and considering the connection between authorship communities and country interactions. The communities are obtained from the co/authorships, regardless of the country or affiliation; this permits to view the size of the communities, as well as to identify collaboration opportunities between communities with low or no interaction. Furthermore, studies are included regarding detailed analysis on each TES technology, as well as other factors (such as funding) that can influence the current and future research.

Keywords: Bibliometrics; thermal energy storage; sensible heat; latent heat; thermochemical

1. INTRODUCTION

Nowadays, the global energy supply is one of the most important concerns for developed countries. Trends in energy supply and use are economically, environmentally and socially unsustainable. Both population growth and industrial development have led to a continuous increase of energy consumption [1,2]. This usually results in an increased use of fossil fuels that today remain as the main source of energy generation. However, the high pollution associated with their use is a major concern for the producers and consumers of fossil fuels. For several decades, the implementation of renewable energy that helps supply the large energy demand has contributed towards the reduction in the consumption of conventional polluting energy [3,4].

Energy storage technologies can provide energy security, fight climate change, and improve the value of current or future energy systems [5]. Thermal Energy Storage (TES) is a key enable technology, as it allows to stock thermal energy that can be further used for heating and cooling applications and power generation.

Because of its relevance for the monitoring of information and management of knowledge, bibliometrics has become an important field of information science. In recent years, many studies have provided a bibliometric overview of their research fields, such as management, econometrics, health economics, marketing, statistics, ecological economics, entrepreneurship, production and operations management, data envelopment, gray systems, and innovation, among others [6].

In this way, Gao et al. published a bibliometrics study targeted to the field of wind power price [7] and conducted a bibliometric and network analysis based on the data from Scopus. The results show that the numbers of total related publications are gradually increasing, with the US as the leading country. In addition, Mao et al. published a bibliometric analysis regarding the forward for alternative energy research during 1994-2013 [8]. Thereby, the stated that the conversion devices such as the wind turbines and solar cell were paid most attention in order to improve the production efficiency. These are examples of the very few bibliometric studies available in SCOPUS database. There are not bibliometric studies regarding thermal energy storage (TES) field.

The aim of this study is to provide an overview of the history of TES research and development, by using bibliometric methods. Identifying different technology tendencies and developments, as well as the most productive and influential research, can be interesting for everyone involved on TES development. Regional particularities,

policies, financing efforts and economic growth have been evaluated from the point of view of knowledge production. In addition, technological maturity has been observed according to the most dynamic knowledge areas for each specific technology.

2. Methodology

The methods and tools used to analyze all the literature about the evolution of TES systems research are described in this section. Bibliometrics is the science that studies, in a statistical way, the written publications of certain field of research, and is considered one of the few interdisciplinary research fields that can be extended to almost all scientific fields [9]. Bjork et al. (2014) defined that the main purpose of bibliometric studies is to bring the general picture of the development of a certain research field, as well as the analysis of the leading researchers (authors, journals, institutions and countries) in such area of knowledge [10]. Therefore, this important information science has become more and more relevant for the monitoring of information and management of knowledge. In recent years, many are the studies that have provided a bibliometric overview of their research fields such as management, econometrics, health economics, marketing, statistics, ecological economics, entrepreneurship, production and operations management, data envelopment, gray systems, and innovation, among others [6].

However, over the years, several issues have emerged in order to provide nurturing bibliometric information, mainly behind the determination of the most significant information sources and indicators for measuring the bibliographic material. Therefore, in order to be the more informative and neutral with the information, Web of Science (WoS) Core Collection database was used to search the most relevant scientific articles related to TES. The Web of Science Core Collection includes more than 14,000 high-quality journals indexed with the most complete information for all the articles, including all the authors' names, authors' affiliations, abstracts, keywords, funding information, etc. This rich database allowed us extracting very valuable information unavailable with other databases.

To develop the search process, authors have used the keywords "thermal storage" OR "thermal energy" OR "cold storage" OR "concentrated solar power" OR "phase change material" OR "thermochemical storage" OR "molten salts" OR "CSP" OR "heat storage" OR "latent heat" OR "sensible heat" OR "thermochemical" OR "PCM" searched in the topic, abstract or keywords sections. One of the main challenges faced was that, through the years, papers that addressed TES systems do not use the same

keywords to refer to this technology. In fact, from our first attempts of data gathering, several important documents were missing behind this keyword “incongruence”. Within this scenario, a more complex and inclusive keyword map, which includes not only the main keywords used in the literature of TES, but also a combination of these keywords with other complement phrases was developed (see Table 1.). Additionally, some exclusion phrases were included, behind the elevated number of papers that emerged from our first search that, even they use some of our selected keywords, they were not related to TES systems (i.e. Photovoltaic systems). This improved roadmap allowed us to reach, in a more efficient manner, almost all the papers in TES systems.

Table 1. TES Keyword Search Roadmap.

EXCLUSION PHRASES			MAIN PHRASES	COMPLEMENT PHRASES					TOTAL PAPERS
			thermal storage						2620
			thermal energy	storage					5703
			cool storage	thermal					80
			concentrated solar power						703
			phase change material						4503
			thermochemical storage						75
PV	photovoltaic		molten salts	solar	energy	power plant	storage		1108
cloud	internet	software	csp	solar	energy	renewable	power	storage	1528
			heat storage						4368
			latent heat	storage					2911
			sensible heat	storage					646
			thermochemical	energy storage					361
			PCM	energy storage					2765

From the Table 1, it is important to note that only articles and reviews were considered in this analysis, resulting on 14,754 papers published during 109 years (papers can be considered in more than one main category).

Finally, with this database, more specific analysis has been performed according to sensible, latent and thermochemical technologies showing interesting and promising results. Relevant authors, journals, funding initiatives, regional cooperation and other relevant information will be showed in the following sections.

Analyses were made using python coding and graphic tools. Other reports were provided using VOS viewer [11] and Complexity Lab Barcelona (CLabB) [12] software. VOS viewer is a tool for visualizing bibliometric networks. Communities analysis was made using CLabB tool in order to identify scientific communities working together, regardless their country or affiliation.

3. Results

3.1. Number of publications

Based on the available data in this new bibliometric database, the total of publications per year regarding thermal energy storage field is presented in Figure 1 for the last 20 years. The TES field in the scientific sector is growing up in the last 10 years as can be observed in Figure 1, and this fact remarks that this field is in a highlighted growth, which is supposed to become as a huge market deployment in the near future.

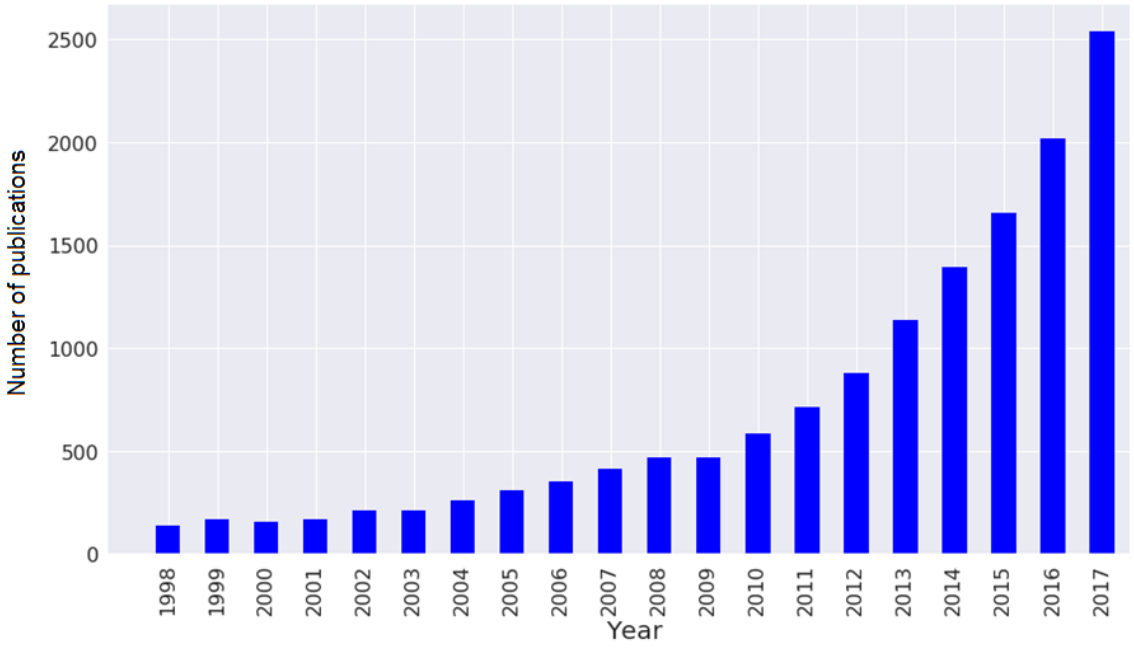


Figure 1. Thermal energy storage publications during the last two decades.

3.2. Countries bibliometric evolution

In addition, Figure 2 shows the analysis of the data available in the new bibliometric database regarding the publications by countries in the TES field. European Union publications are grouped, and it is the top one publishing zone in the world, followed by China, USA, and Japan. Furthermore, the European countries are also accounted separately. Germany is the country that published more papers in TES research field, followed by France, Spain and England. Canada, India and Italy are also included in the top 10 TES publishing countries.

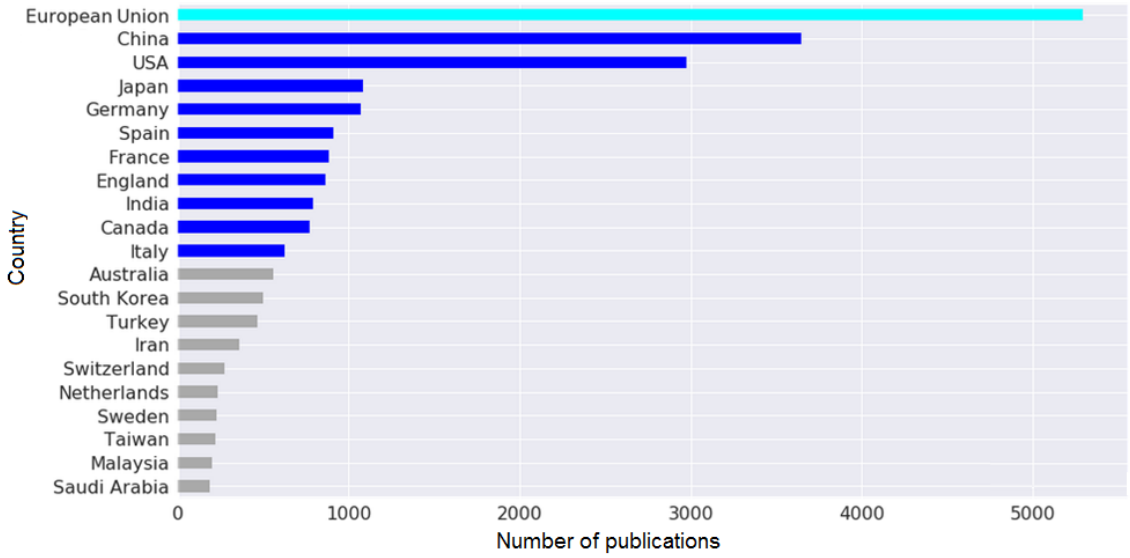
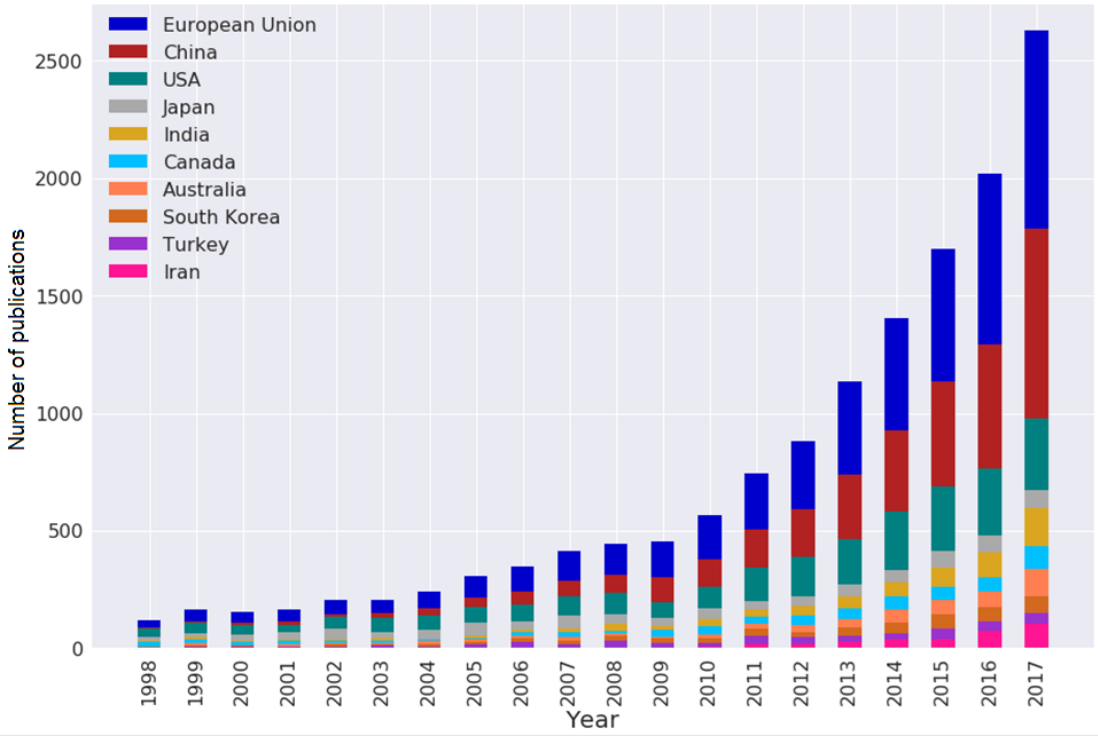


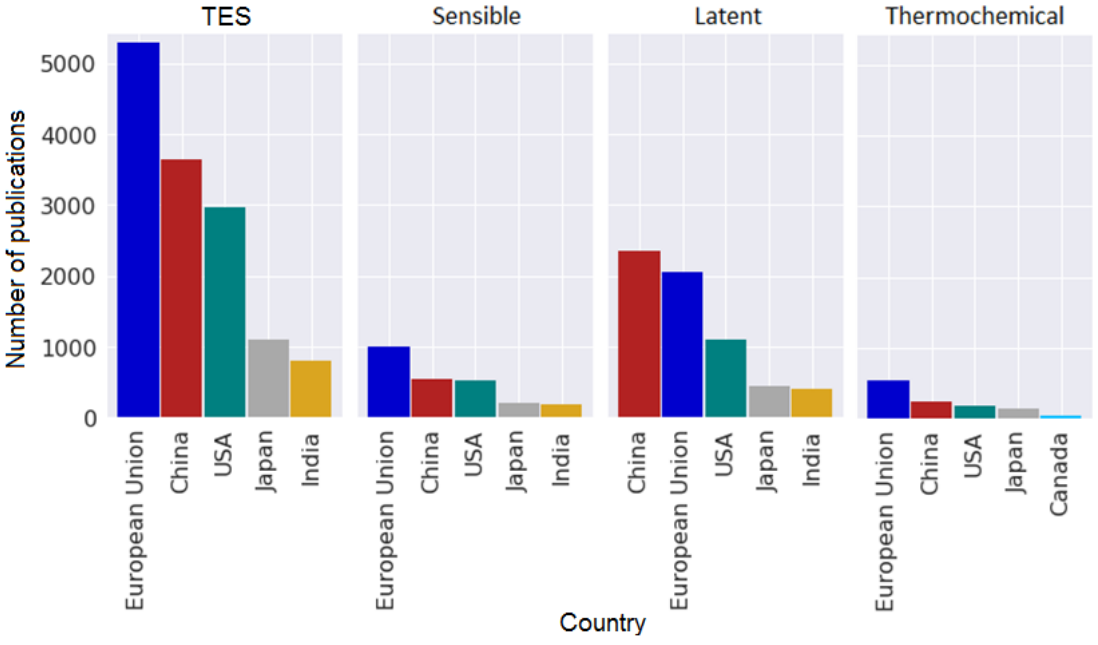
Figure 2. Top 20 publishing countries in the TES field.

Furthermore, the publication evolution per country over the last two decades is shown in Figure 3. Indeed, the increment evolution related with the TES publication is shown as an exponential increment which is accentuated in European Union and China. USA publication evolution regarding the TES field is stagnated since 3-4 years ago. The other top 10 countries publishing evolutions are similar over the last decades. Based on current tendency, China is expected to be leading TES research over the next years, followed closely by European Union.

The constant growth can be also appreciated in Table 2, in which growth compared to the total publications accumulated until the previous year is presented. It can be observed that EU has an exponential growth but less accelerated when compared to China and India. Then, it can be expected that in the following years China and India will lead TES research. Even though Iran is now on the 10th place its growing rates show that can become an important actor on TES research on the following year. USA stagnation is confirmed also when considering growing rates.



a)



b)

Figure 3. a) Publication evolution regarding TES field in the last 2 decades by countries; b) Total publications in TES field of top 5 countries and EU, and SHTES, LHTES, TCS publication of those countries/zones.

Furthermore, Figure 3.b) presents the total publications per country and EU divided by technology to store thermal energy. It is well known that TES systems are able to store energy by three different technologies: sensible heat (SHTES), latent heat (LHTES), and thermochemical storage (TCS). These three categories are the ones used in Figure 3.b.

Notice that EU has published more than 5,000 papers in this field followed by China that currently has more than 3,500 scientific publications.

On the other hand, the TES technology that accounts more amounts of scientific publications based on the data available is LHTES, followed by SHTES and TCS that presents the lower amounts of publication. This is a remarkable point what means that TCS has highest potential to perform scientific research. Notice that EU is the zone that published more papers in SHTES and TCS but China is the one that published more in LHTES technology.

Table 2. Country/region increment of TES publications compared to the accumulated from previous year.

Country	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
EU	20.3%	21.1%	19.6%	19.9%	19.8%	17.1%	16.2%	14.3%	13.2%	13.1%
China	31.7%	26.1%	28.8%	28.7%	29.4%	27.2%	28.3%	26.3%	31.0%	29.9%
USA	12.1%	12.6%	13.6%	14.0%	12.4%	12.2%	11.2%	7.9%	6.1%	9.2%
Japan	7.6%	7.8%	8.9%	6.8%	7.1%	5.8%	5.3%	7.5%	6.3%	7.3%
India	28.4%	23.4%	20.9%	18.5%	19.5%	17.1%	14.6%	18.5%	8.4%	22.0%
Canada	15.7%	11.2%	11.0%	12.2%	10.8%	10.7%	9.3%	11.7%	10.8%	4.5%
Australia	28.3%	19.4%	22.2%	25.1%	18.6%	19.0%	16.2%	11.5%	6.1%	9.5%
South Korea	17.6%	16.6%	20.7%	18.9%	17.3%	10.6%	17.5%	15.9%	14.0%	22.2%
Turkey	12.0%	11.0%	14.6%	9.6%	9.7%	14.7%	19.8%	6.9%	13.6%	23.2%
Iran	43.9%	48.4%	32.5%	44.4%	47.3%	41.0%	77.3%	57.1%	27.3%	22.2%

Figure 4 shows the publication evolution over the last 20 years for the top 10 publishing European countries (Germany followed by Spain, France, UK, Italy, Netherlands, Poland, Portugal, Denmark, and Belgium). The TES publication trends in Europe is still growing up and this trend is followed by all the countries represented in this figure. The publishing stagnation is far to be reached in EU TES as this figure clarifies.

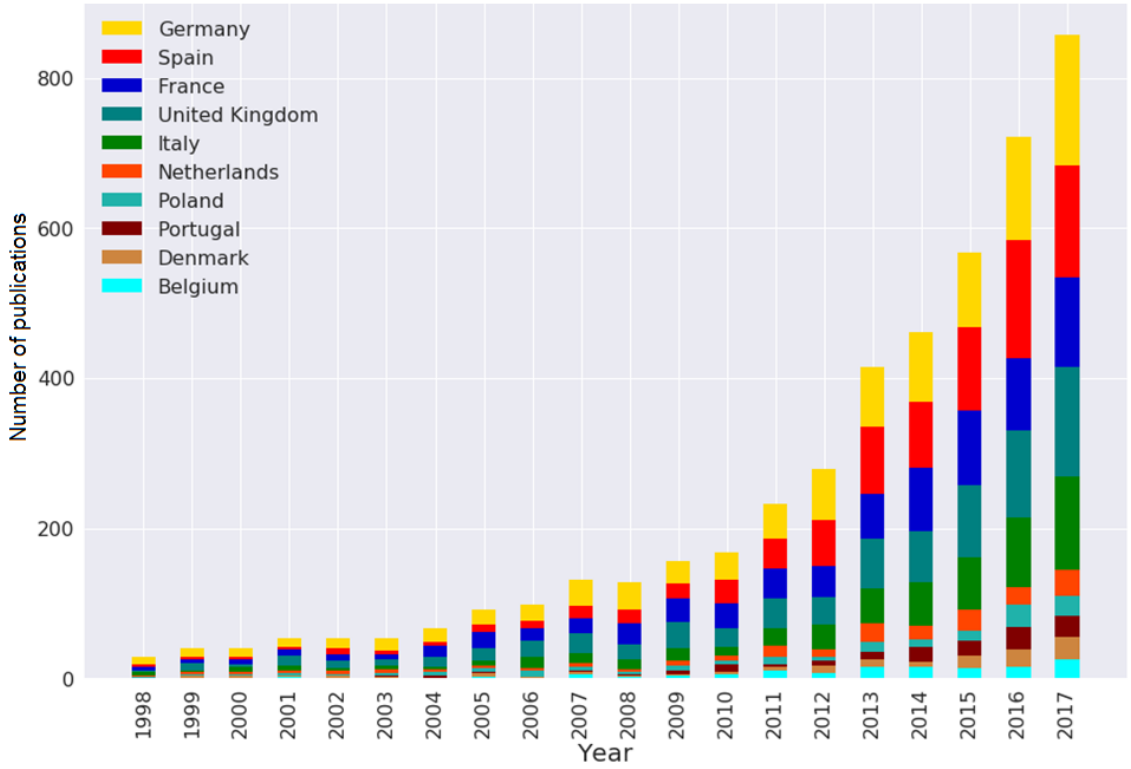


Figure 4. Publication evolution regarding TES field in the last 2 decades divided by top 10 European countries

Table 3 represents growing rates for the top 10 EU members on TES. It can be noted that Denmark, Italy and Germany constantly have been incrementing their research when compared to previous total publications. On the other hand, Spain constantly decreased their research output over the last years, having the lower one in 2017 since 2009.

Table 3. EU countries increment of TES publications compared to the accumulated from previous year.

Country	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
Germany	17.1%	16.2%	13.9%	15.1%	15.2%	15.5%	12.6%	11.4%	10.8%	14.4%
Spain	17.5%	22.5%	20.6%	20.6%	26.6%	24.3%	20.5%	20.5%	16.7%	17.0%
France	14.2%	13.2%	15.6%	15.8%	13.2%	10.8%	11.8%	11.1%	11.4%	11.6%
U K	17.9%	17.4%	17.5%	15.0%	17.1%	11.3%	14.1%	9.8%	15.9%	10.8%
Italy	20.9%	19.6%	18.8%	19.0%	18.5%	16.8%	13.7%	7.6%	12.7%	12.0%
Netherlands	15.4%	12.5%	16.1%	12.8%	21.1%	9.3%	17.0%	11.0%	9.2%	5.1%
Poland	15.6%	21.3%	11.7%	10.2%	14.8%	8.0%	13.0%	8.3%	10.9%	8.2%
Portugal	19.4%	25.9%	23.3%	30.3%	21.7%	16.7%	13.3%	34.6%	35.3%	9.1%
Denmark	22.2%	21.0%	20.5%	10.6%	15.3%	20.0%	12.5%	11.4%	6.5%	6.9%
Belgium	19.7%	15.1%	15.6%	19.7%	26.2%	15.6%	26.3%	17.9%	13.0%	10.0%

The interactions through joint publications by different countries where also identified in this bibliometric study based on the affiliations of the authors in the papers available in the database. Notice that there are countries that are not considered in this map since only the most publishing countries are highlighted in Figure 5 (top 15 TES publishing countries). Interaction strength is represented by the thickness of the line between the countries. Therefore, the main interaction of European countries is with China in the TES field (thicker blue). The second more remarkable interaction is between EU and USA, and both USA and China have a highlighted interaction too. In addition, Europe has remarkable interaction with Australia, Switzerland, and Canada. These countries form the first group of interaction in TES field (in blue). Moreover, there is a huge interaction between Japan, South Korea, Taiwan, which form the second group (in green). Last, India, Iran, Turkey, Malaysia, Egypt , Saudi Arabia and Canada form the third main group (in red).

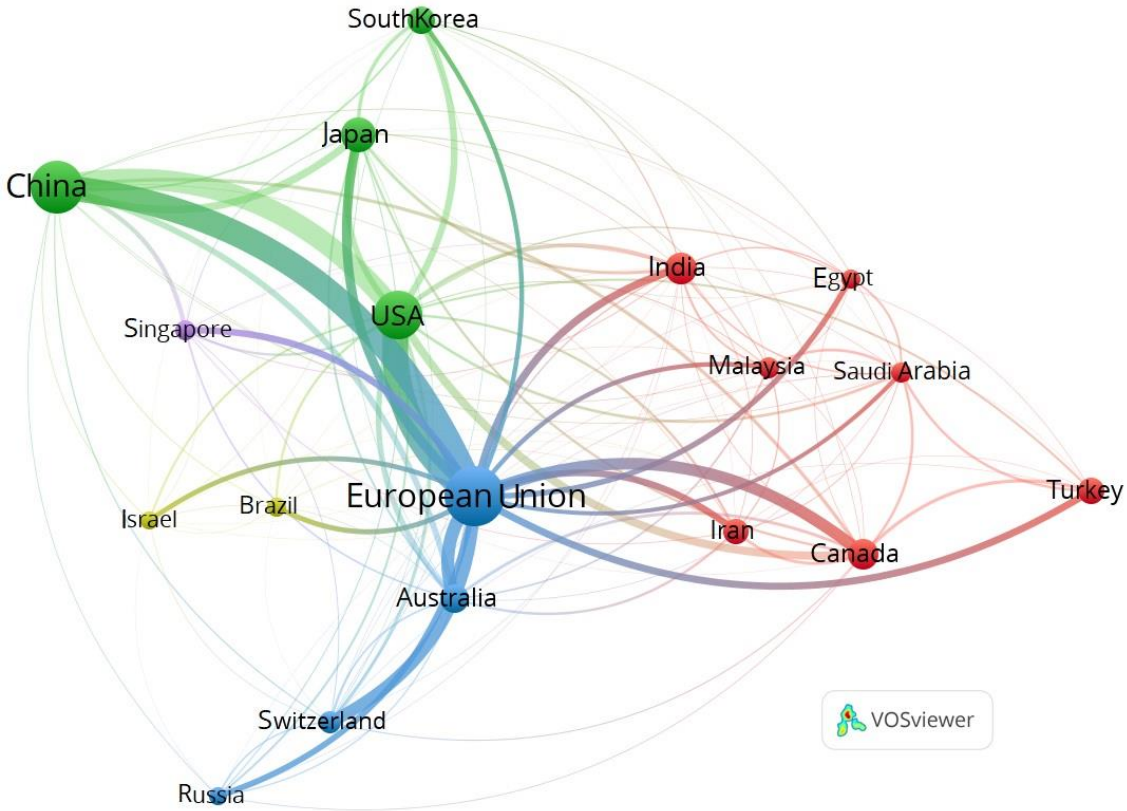


Figure 5. Affiliation and co-authorship interaction taking into account the countries collaboration of the Top15 countries and EU.

Note that countries from South America and Africa are not included in this interaction map since these countries are less active in publishing papers in TES field.

Figure 6 shows the interaction between European countries publishing in TES field. It can be seen that there are five main publishing countries in TES field, which are Germany, Spain, England, France and Italy. Indeed, these countries highly interact between them as this figure shows. Moreover, these five countries interact and share authorship with all the other countries of this figure.

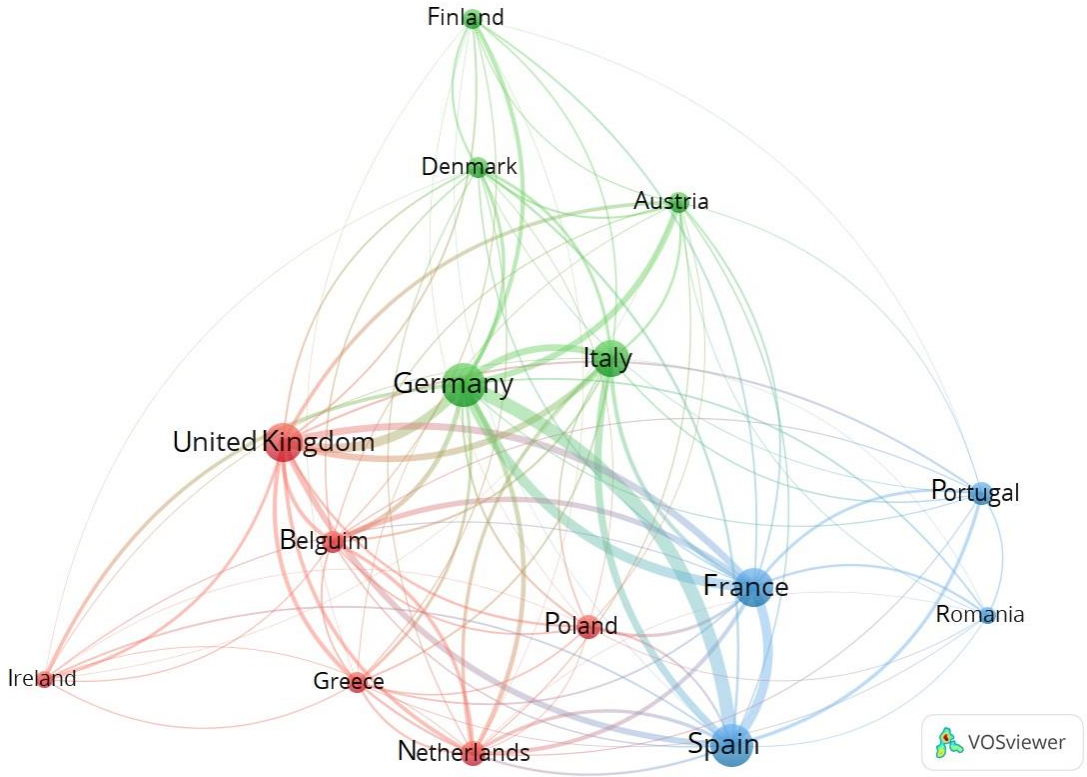


Figure 6. Affiliation and co-authorship interaction of EU countries.

3.3. Authorship bibliometric evolution

The cumulative author evolution by number of publications is shown in Figure 5. This takes into account the grouped publication of each author profile available in the web of science (WoS) - core collection database, and authors were checked for repeated WoS profiles although it is difficult to do this revision in every single profile. This analysis does not take into account in which order the authors appear on the articles, only that they participate on them. As Figure 7 shows, Prof. Luisa Cabeza is the top-one researcher publishing in TES field followed by Dr. Song, Dr. Sari and Prof. Farid, who are the most representative prestigious researchers in the TES field. Furthermore, the *h index* was calculated only taking into account papers published in

TES field for each of the top 10 authors and these indices are presented in Figure 7. Prof. J.E. Hirsch from University of California (San Diego) defined *h index* [13] as *"The number of papers with citation number higher or equal to h, as a useful index to characterize the scientific output of a researcher".* Thereby, all top 10 authors have *h index* higher than 15, being Prof. Cabeza the top one (*h=38*).

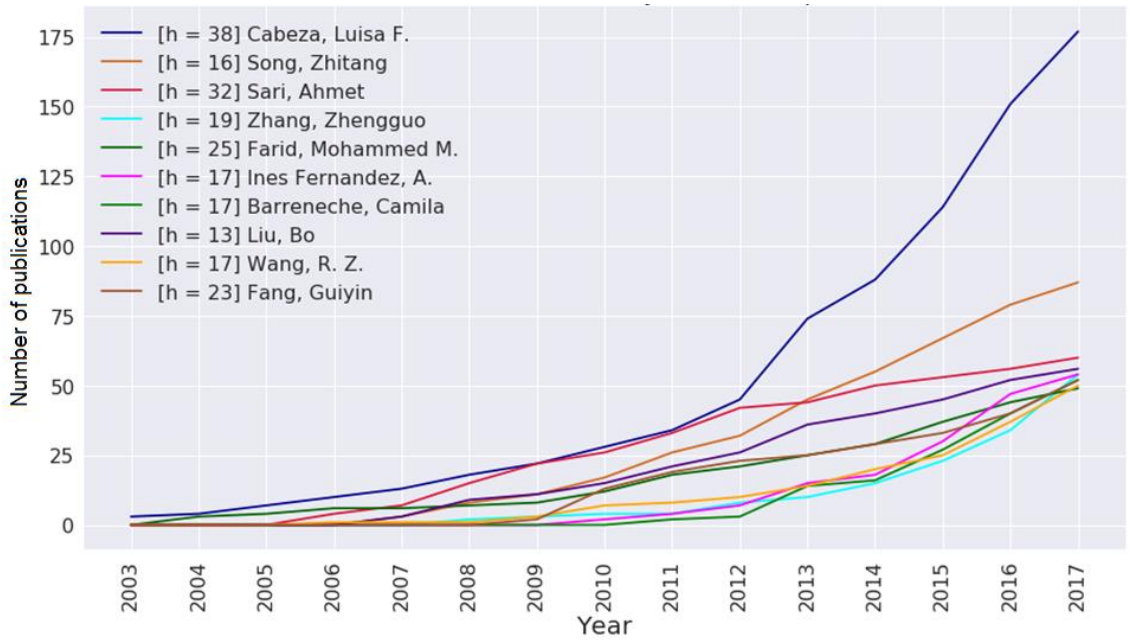


Figure 7. Cumulative author evolution by number of publications over the last two decades.

Besides, Table 4 shows the citations of the top 20 authors in TES field, what is even more important than the amount of publications since it is also a quality-publishing indicator, or the TES h index, which is calculated only for the TES field articles and reviews. The top one in citation is also Prof. Cabeza who accounts more than 8,000 citations, followed by Dr. Song and Dr. Sari. Notice that almost all top 10 authors of Figure 5 are also included in Table 4.

Table 4. Top 20 authors in TES field.

Author	Afiliation	TES publications	Total TES cites	TES h index
Cabeza, Luisa F.	Universitat de Lleida, Spain	196	8400	38
Song, Zhitang	Shanghai Institute of Microsystem & Information Technology, China	87	778	16
Sari, Ahmet	Gaziosmanpasa University, Turkey	66	3755	32
Zhang, Zhengguo	South China University of Technology, China	62	1178	19
Farid, Mohammed M.	University of Auckland, New Zealand	60	4079	25
Ines Fernandez, A.	Universitat de Barcelona, Spain	59	1284	17
Barreneche, Camila	Universitat de Barcelona, Spain	56	1139	17
Liu, Bo	National Institute of Advanced Industrial Science & Technology, Japan	56	558	13
Wang, R. Z.	Shanghai Jiao Tong University, China	54	1288	17
Fang, Guiyin	Nanjing University, China	54	1385	23
Velraj, R.	Anna University Chennai, India	53	1879	23
Feng, Songlin	Shanghai Institute of Microsystem & Information Technology, China	52	586	14
Dincer, Ibrahim	University of Ontario Institute Technology, Canada	49	762	16
Alkan, Cemil	Gaziosmanpasa University, Turkey	48	1972	25
Li, Wei	Peking University, China	48	1030	16
Rao, Zhonghao	China University of Mining & Technology, China	47	1019	18
Zhao, C. Y.	Shanghai Jiao Tong University, China	46	2228	20
Akiyama, Tomohiro	Hokkaido University, Japan	44	1545	20
Ding, Yulong	University of Birmingham, United Kingdom	43	1341	14
de Gracia, Alvaro	Universitat Rovira i Virgili, Spain	39	1355	17

Finally, one of the most highlighted analysis of the bibliometric analysis here presented is the Figure 8, where the authorship communities in TES field are shown. A list of the publications in the TES database was analyzed by CLabB software tool in order to define the attraction forces between the authors (represented by the circles) and order them, using an algorithm, to identify the communities they belong to.

Notice that the top 10 publishing authors (listed in Figure 7) are highlighted in Figure 8. Prof. Cabeza and Prof. Farid are members of the biggest research community (in olive green). Prof. Zhang leads the second one (in indigo), followed by Prof. Song and Prof. Bo who integrate the third one (in green). There are other 12 detected research communities in TES field (marked in different colors in Figure 8).

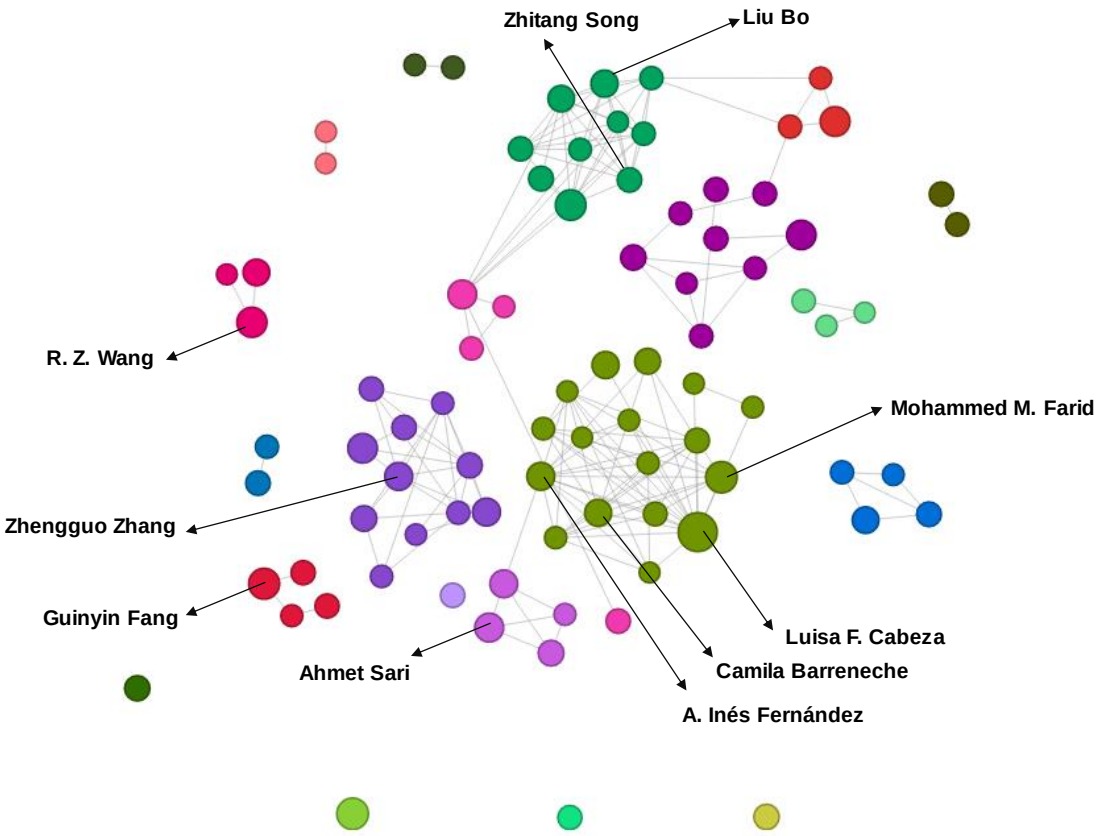


Figure 8. Authorship communities based on the affiliation interaction of published papers in TES field [14]**.**

3.4. Journal bibliometrics

The cumulative journal evolution that TES researchers use to publish their research is presented in Figure 9, by number of publications. Thereby, the journal that publish more TES papers is Applied Thermal Engineering, followed by Applied Energy, Solar Energy and Energy Conversion and Management.

This trend is the current but it has been changing over the years. For example, until 2000 the journal that published more TES papers was Energy Conversion and Management followed by Energy and International Journal of Heat and Mass Transfer, and the current trend is susceptible to be changed again.

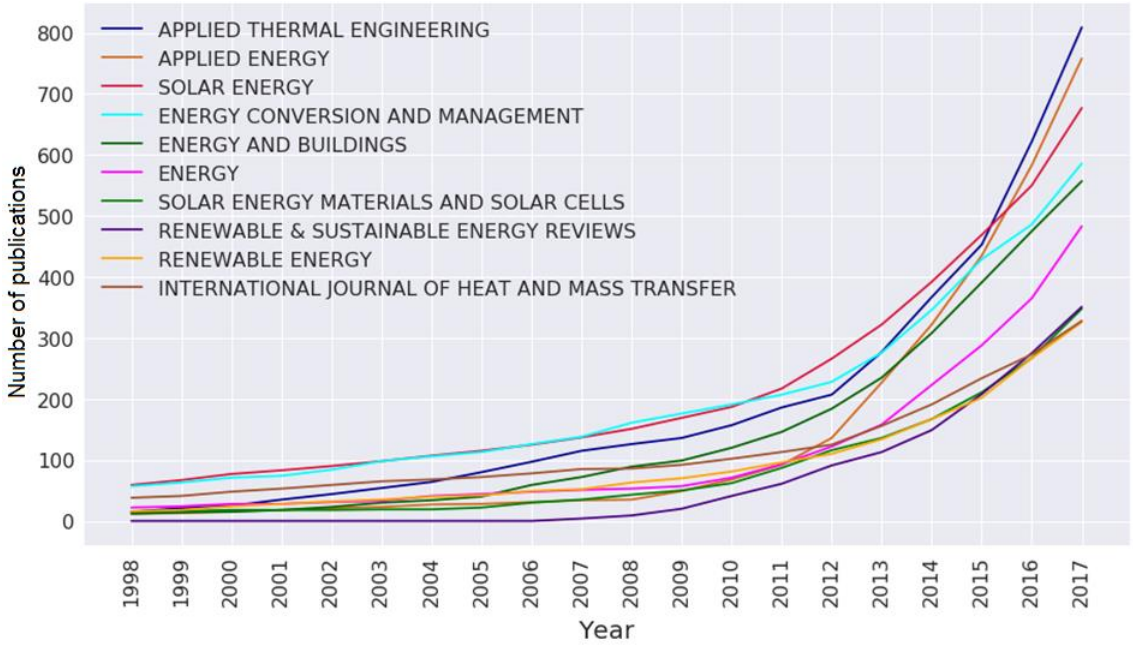


Figure 9. Cumulative journal evolution, by number of publications

In Table 5, TES performance ratio is shown, as well as journal impact factor and quartile score for each of the top 20 TES journals. The performance ratio is calculated by dividing the number of TES cites over the total TES publications. Renewable & Sustainable Energy Reviews journal has the better performance ratio, which was expected since it's a reviews journal. Other journals such as Solar Energy, Energy Conversion and Management, Applied Energy, and Solar Energy Materials and Solar Cells, have a higher impact factor regardless that they are not leading on number of publications. This suggests a greater quality on their contents.

Table 5. Top 20 journals in TES field.

JOURNAL	TES publications	TES Cites	Performance Ratio	Impact factor	Quartile scores
APPLIED THERMAL ENGINEERING	876	16262	18.6	3.77	Q1-Q2
APPLIED ENERGY	829	19619	23.7	7.90	Q1
SOLAR ENERGY	703	16219	23.1	4.37	Q1
ENERGY CONVERSION AND MANAGEMENT	608	16824	27.7	6.38	Q1
ENERGY AND BUILDINGS	589	13522	23.0	4.46	Q1
ENERGY	513	9595	18.7	4.97	Q1
SOLAR ENERGY MATERIALS AND SOLAR CELLS	397	10577	26.6	5.02	Q1
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	393	20194	51.4	9.18	Q1
RENEWABLE ENERGY	360	6601	18.3	4.90	Q1
INTERNATIONAL JOURNAL OF HEAT AND MASS TRANSFER	352	9031	25.7	3.89	Q1
JOURNAL OF SOLAR ENERGY ENGINEERING-TRANSACTIONS OF THE ASME	223	3677	16.5	1.37	Q3
INTERNATIONAL JOURNAL OF ENERGY RESEARCH	199	3098	15.6	3.01	Q2
THERMOCHIMICA ACTA	169	3623	21.4	2.19	Q2-Q3
INTERNATIONAL JOURNAL OF REFRIGERATION-REVUE INTERNATIONALE DU FROID	149	2737	18.4	3.23	Q1
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	141	1608	11.4	4.23	Q1-Q2
ENERGIES	130	478	3.7	2.68	Q2
JOURNAL OF THERMAL ANALYSIS AND CALORIMETRY	112	1198	10.7	2.21	Q2-Q3
INTERNATIONAL JOURNAL OF THERMAL SCIENCES	96	1948	20.3	3.36	Q1
RSC ADVANCES	92	641	7.0	2.94	Q2
JOURNAL OF HEAT TRANSFER-TRANSACTIONS OF THE ASME	88	1100	12.5	1.6	Q3

3.5. Funding

Special programs to encourage research performance include funding efforts. These fundings have been properly reported on the last decade. In Figure 10 the relation between the special fundings and research publications is shown. It is undeniable that fundings have a main role on current TES research exponential growth; the main two world TES actors, EU and China, have strong funding programs (by EU Commission and Chinese Academy of Sciences, respectively).

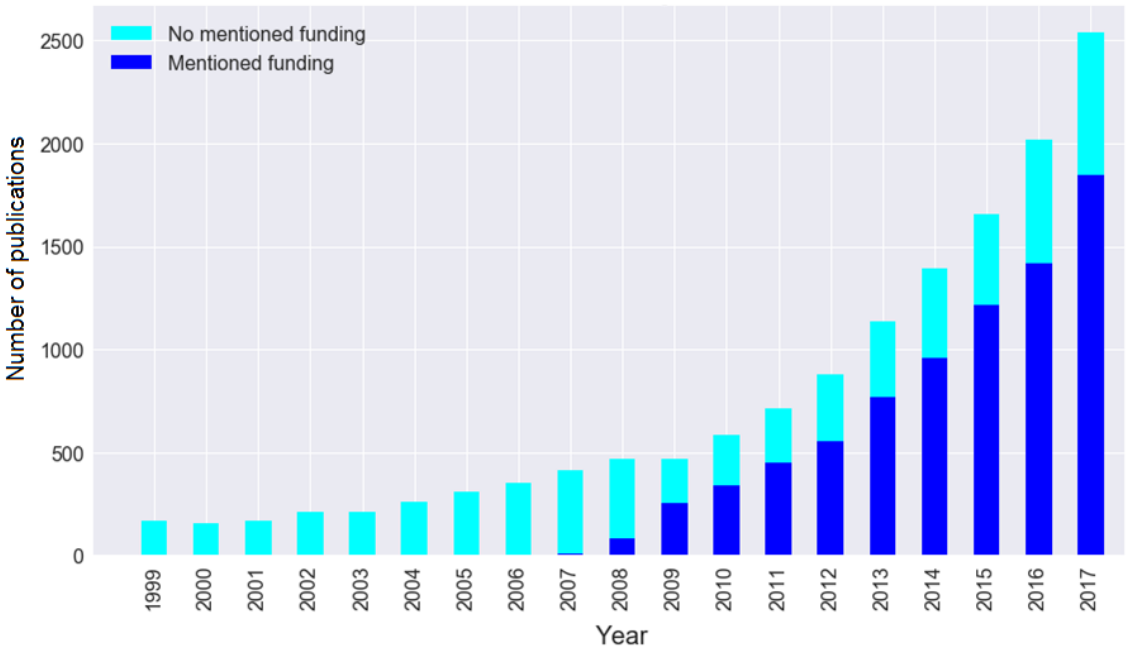


Figure 10. Funding evolution for TES publications.

3.6. TES technology bibliometrics evolution

The publications classified by TES technologies (SHTES, LHTES, TCS) are analysed in this section.

One of the most important analyses of this bibliometric study is the one shown in Figure 11. This figure displays the total number of publication per years and per TES technology during the last 20 years.

The publishing evolution over years is clearly exponential. The technology that accounts for the highest amount of publications per year is LHTES. Moreover, the technology whose publication increment per year is higher during the last year is SHTES, accounting for a 43% increment. The amount of publications regarding TCS is increasing although following a slow trend. This is highlighted for TES field since it is

the most promising technology that allows achieving compact storage systems to be implemented in several fields as renewables, heating and cooling for buildings, etc.

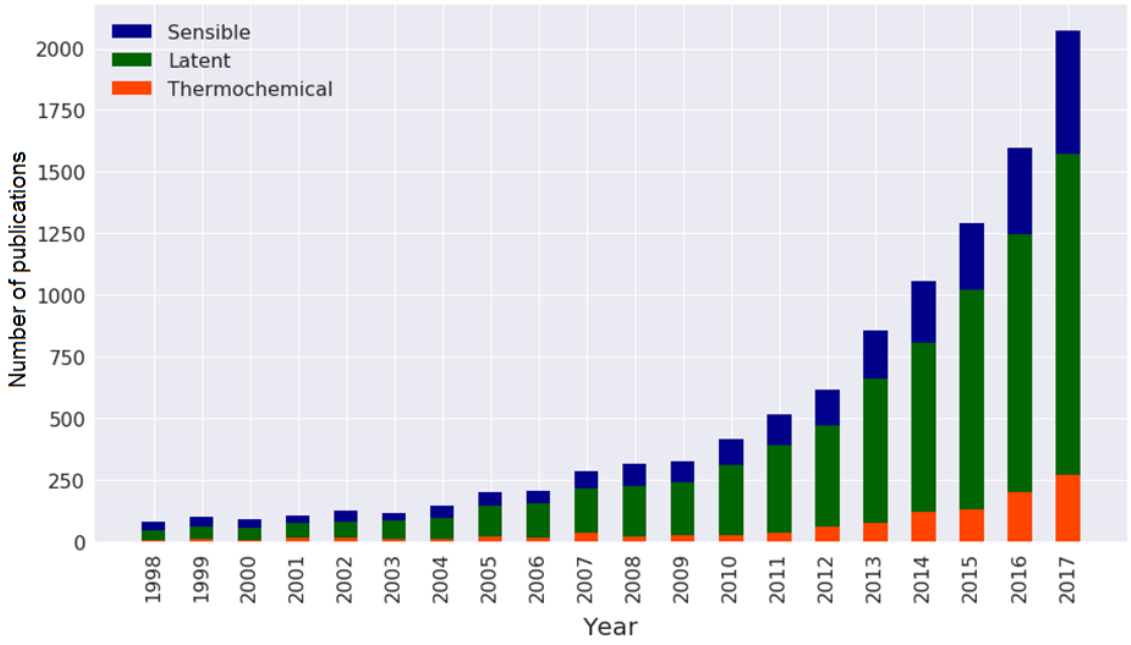


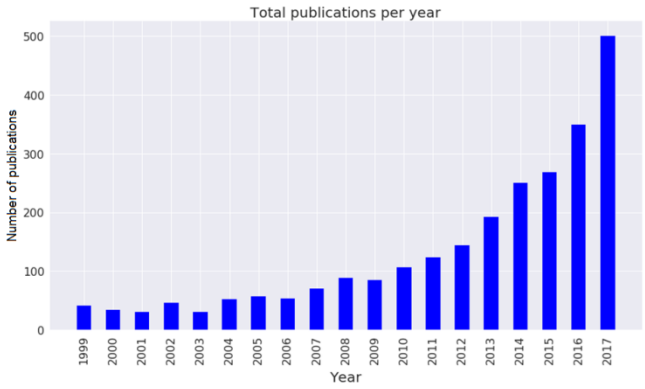
Figure 11. Number of publications per year for each TES technology and forecast technology calculation for 2017

SHTES publications per year are presented in Figure 12.a. The trend has passed over some attempt of stagnation during the last 20 years but it is still increasing every year.

Figure 12.b. shows the total SHTES publications by countries and Europe. Europe is by far the most publishing zone in the worldwide accounting around 1,000 publications in SHTES, followed by China and USA, and Germany is the most publishing country in Europe.

Figure 12.c. shows publication evolution over the last 20 years and the very high increase trend for China in the last 3 years is remarkable. The increment of publishing is in accordance with the economic growth that China is showing in the last years.

Figure 12.d. and Table 6 present the top 10 authors publishing in SHTES sub-field and their cumulative evolution by number of publications. Again, Prof. Cabeza is the author with highest amount of publications in SHTES.



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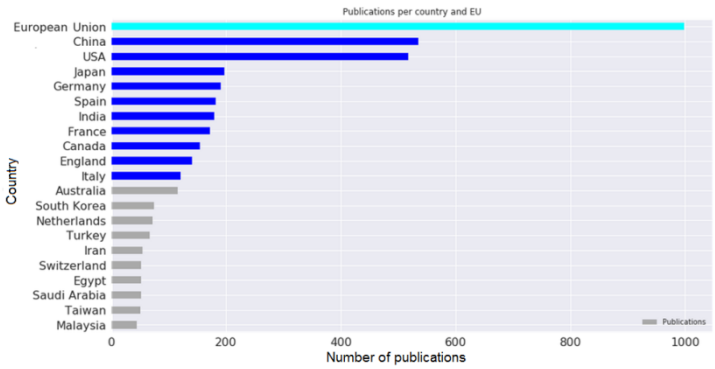

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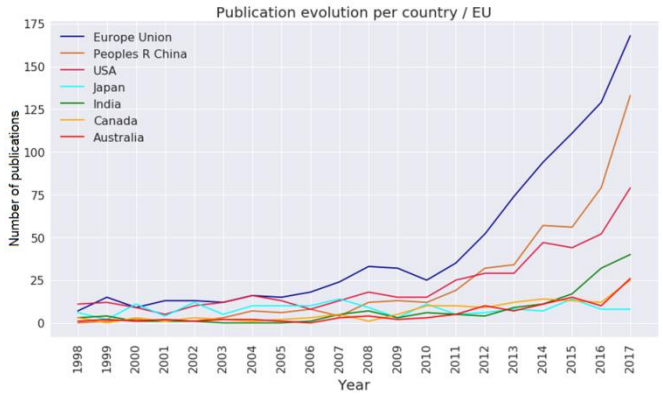

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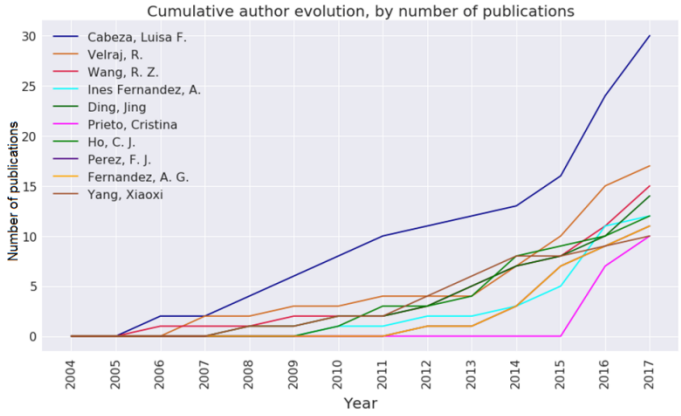


d)

Figure 12. a) Total publications evolution in SHTES field per year; b) Total publications in SHTES per country and EU; c) Publication evolution per country and EU for SHTES; d) Cumulative author evolution in SHTES field by number of publications.

Table 6. Top 10 authors in SHTES field.

Author	Afiliation	SHTES publications	Total SHTES cites	SHTES h index
Cabeza, Luisa F.	Universitat de Lleida, Spain	35	1004	16
Velraj, R.	Anna University Chennai, India	17	379	8
Wang, R. Z.	Shanghai Jiao Tong University, China	15	455	8
Ines Fernandez, A.	Universitat de Barcelona, Spain	15	225	7
Ding, Jing	Sun Yat Sen University, China	14	179	6
Prieto, Cristina	Abengoa Solar New Technologies S.A., Spain	14	85	6
Ho, C. J.	Sandia National Laboratories, USA	12	173	8
Perez, F. J.	Complutense University of Madrid, Spain	11	154	6
Fernandez, A. G.	Complutense University of Madrid, Spain	11	159	7
Yang, Xiaoxi	Dongguan University of Technology	10	189	6

Increment of the number of publications on SHTES compared to the previous year is presented in Table 7, showing that China, India and Iran are making important growing efforts, while the other top 10 countries are making slightly but constant progress.

Table 7. Country/region increment of SHTES publications compared to the accumulated from previous year.

Country	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
EU	21.8%	20.1%	20.9%	21.5%	20.3%	16.7%	12.6%	9.9%	14.5%	17.6%
China	38.1%	29.3%	26.2%	36.3%	27.6%	35.2%	26.4%	20.0%	27.7%	34.3%
USA	18.5%	13.9%	13.3%	16.5%	11.4%	12.8%	12.4%	8.1%	8.8%	11.8%
Japan	4.4%	4.6%	8.7%	4.5%	5.5%	4.3%	3.7%	8.9%	2.5%	8.0%
India	33.3%	36.4%	23.9%	18.3%	17.6%	8.5%	11.9%	16.7%	9.1%	26.9%
Canada	20.7%	11.0%	13.5%	17.1%	17.1%	14.8%	19.6%	24.4%	13.9%	2.9%
Australia	30.6%	13.3%	25.0%	22.4%	16.7%	31.3%	18.5%	12.5%	9.1%	22.2%
South Korea	18.6%	9.3%	17.4%	21.1%	15.2%	22.2%	22.7%	46.7%	7.1%	16.7%
Turkey	6.8%	13.5%	8.3%	4.3%	12.2%	7.9%	18.8%	10.3%	7.4%	22.7%
Iran	74.1%	28.6%	10.5%	26.7%	50.0%	11.1%	125.0%	33.3%	0.0%	-

Finally, Table 8 shows the most relevant journals for SHTES along with their TES performance ratio, showing Applied Energy and Energy Conversion and Management as a non-review journal leaders on this area from this point of view.

Table 8. Top 10 journals in SHTES field.

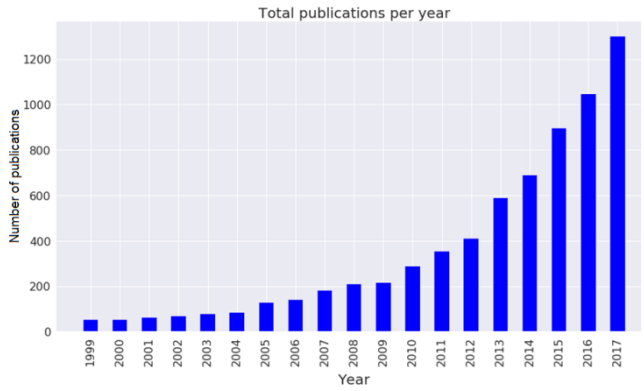
JOURNAL	SHTES publications	SHTES Cites	Performance Ratio	Impact factor	Quartile scores
APPLIED THERMAL ENGINEERING	171	2543	14.9	3.77	Q1-Q2
SOLAR ENERGY	164	3358	20.5	4.37	Q1
APPLIED ENERGY	144	3141	21.8	7.90	Q1
ENERGY CONVERSION AND MANAGEMENT	109	2372	21.8	6.38	Q1
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	93	3367	36.2	9.18	Q1
ENERGY	83	1603	19.3	4.97	Q1
SOLAR ENERGY MATERIALS AND SOLAR CELLS	75	1147	15.3	5.02	Q1
ENERGY AND BUILDINGS	63	837	13.3	4.46	Q1
RENEWABLE ENERGY	63	838	13.3	4.90	Q1
JOURNAL OF SOLAR ENERGY ENGINEERING-TRANSACTIONS OF THE ASME	56	868	15.5	1.37	Q3

In the case of LHTES publications, the evolution per year during the last 20 years is presented in Figure 13.a. The trend is clearly exponential without stagnation during the last 2 decades.

Figure 13.b. shows the total LHTES publications by countries and Europe. Europe is by far the most publishing zone in the worldwide accounting around 2,300 publication in LHTES, followed by China and USA and France is the most publishing country in Europe.

Figure 13.c. shows publication evolution over the last 20 years and again, it, the very high increase trend that followed China between 2014 and 2016 is remarkable in concordance with the high economic growth that China is showing the last years.

Figure 13.d. and Table 9 present the top 10 authors publishing in LHTES sub-field and their cumulative evolution by number of publications. Again, Prof. Cabeza is the author with the highest amount of publications in LHTES.



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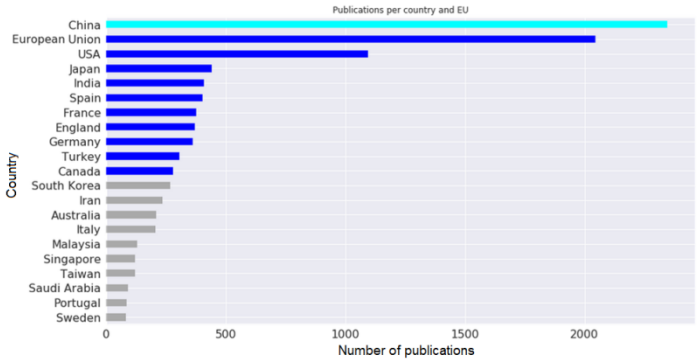

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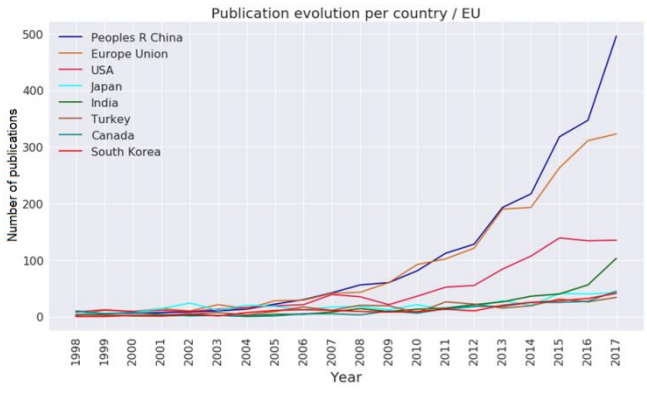

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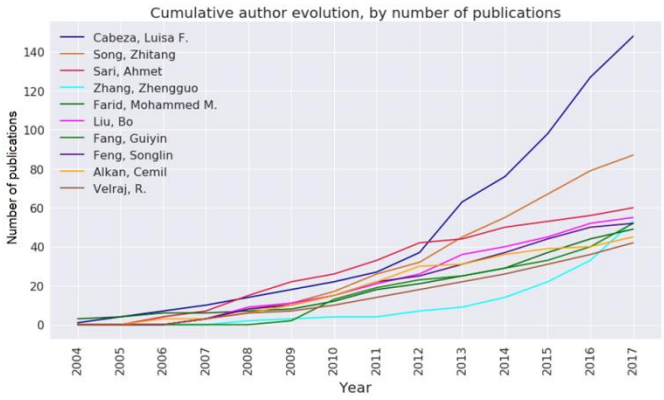

d)

Figure 13. a) Total publications evolution in LHTES field per year; b) Total publications in LHTES per country and EU; c) Publication evolution per country and EU for LHTES; d) Cumulative author evolution in LHTES field by number of publications.

Table 9. Top 10 authors in LHTES field.

Author	Afiliation	LHTES publications	Total LHTES cites	LHTES h index
Cabeza, Luisa F.	Universitat de Lleida, Spain	167	7306	36
Song, Zhitang	Shanghai Institute of Microsystem & Information Technology, China	87	778	16
Sari, Ahmet	Gaziosmanpasa University, Turkey	66	3755	32
Zhang, Zhengguo	South China University of Technology, China	61	1154	18
Farid, Mohammed M.	University of Auckland, New Zealand	57	4020	25
Liu, Bo	National Institute of Advanced Industrial Science & Technology, Japan	55	554	13
Fang, Guiyin	Nanjing University, China	54	1385	23
Feng, Songlin	Shanghai Institute of Microsystem & Information Technology, China	52	586	14
Alkan, Cemil	Gaziosmanpasa University, Turkey	48	1972	25
Velraj, R.	Anna University Chennai, India	48	1797	21

Increment of the number of publications of LHTES compared to the total from previous year is presented on Table 10, showing that EU, USA and Japan are slowing down their research growth, while the other, mainly China, India, Iran and Australia are still on a strong growing rate.

Table 10. Country/region increment of LHTES publications compared to the accumulated from previous year.

Country	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
China	29.9%	26.5%	32.0%	28.0%	33.1%	28.1%	32.7%	30.9%	29.7%	38.4%
EU	20.2%	24.1%	25.6%	23.2%	29.5%	23.2%	24.3%	28.0%	22.4%	19.1%
USA	14.9%	17.4%	22.0%	20.3%	19.0%	14.2%	15.5%	12.0%	7.6%	14.4%
Japan	10.8%	11.5%	13.4%	7.0%	10.8%	7.0%	5.2%	10.0%	6.1%	10.1%
India	38.0%	26.0%	22.9%	25.9%	23.0%	22.8%	19.5%	20.3%	16.4%	34.1%
Turkey	13.4%	11.5%	15.8%	10.7%	9.3%	15.7%	22.8%	6.5%	21.6%	29.4%
Canada	20.5%	14.1%	15.0%	17.6%	14.5%	17.0%	15.2%	7.0%	13.2%	4.1%
South Korea	19.2%	17.6%	18.2%	19.4%	18.3%	10.1%	15.1%	11.7%	11.6%	15.0%
Iran	43.7%	45.2%	30.0%	50.9%	51.4%	59.1%	69.2%	85.7%	40.0%	0.0%
Australia	35.2%	29.1%	34.1%	49.1%	44.7%	46.2%	36.8%	18.8%	0.0%	14.3%

Finally, Table 11 shows the most relevant journals for LHTES along with their TES performance index, showing that Applied Energy, and Energy Conversion and Management journals have the highest performance ratio, as defined in this work, as non-review journal leaders on LHTES.

401 **Table 11. Top 10 journals in LHTES field.**

JOURNAL	LHTES publications	LHTES Cites	Performance Ratio	Impact factor	Quartile scores
APPLIED THERMAL ENGINEERING	566	11948	21.1	3.77	Q1-Q2
APPLIED ENERGY	419	11771	28.1	7.90	Q1
ENERGY AND BUILDINGS	386	9482	24.6	4.46	Q1
ENERGY CONVERSION AND MANAGEMENT	371	13089	35.3	6.38	Q1
SOLAR ENERGY MATERIALS AND SOLAR CELLS	284	8750	30.8	5.02	Q1
INTERNATIONAL JOURNAL OF HEAT AND MASS TRANSFER	266	6732	25.3	3.89	Q1
SOLAR ENERGY	244	7461	30.6	4.37	Q1
ENERGY	198	4003	20.2	4.97	Q1
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	191	14417	75.5	9.18	Q1
RENEWABLE ENERGY	149	3853	25.9	4.90	Q1

402

403 In the case of TCS publications, the evolution per year during the last 20 years is
404 presented in Figure 14.a. The trend is clearly exponential without stagnation during the
405 last 7 years.

406 Figure 14.b. shows the total TCS publications by countries and Europe. Europe is
407 also by far the most publishing zone in the worldwide accounting around 550
408 publications in TCS, followed by China and USA and Germany is the most publishing
409 country in Europe.

410 Figure 14.c. shows publication evolution over the last 20 years. The publication
411 evolution was linear until 2012 when Europe started a high increment trend that is still
412 growing. China started this growth trend in 2015 and it has a remarkable increment
413 during this last period (2015-2017).

414 Figure 14.d. and Table 12 present the top 10 authors publishing in TCS sub-field
415 and their cumulative evolution by number of publications. In this case, Prof. Wang is
416 who has published more articles in TCS sub-field, and Prof. Cabeza has the 10th
417 position in this sub-field.

418

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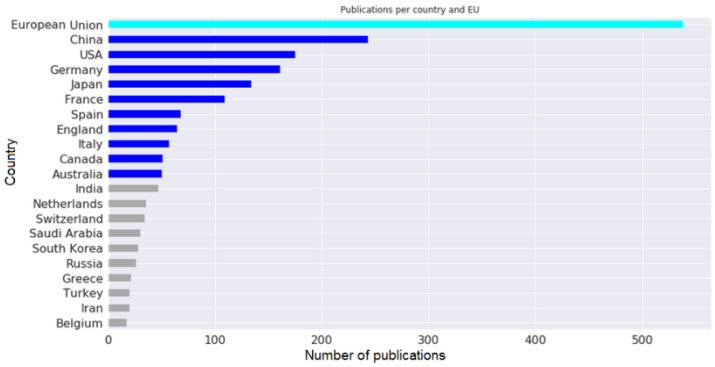

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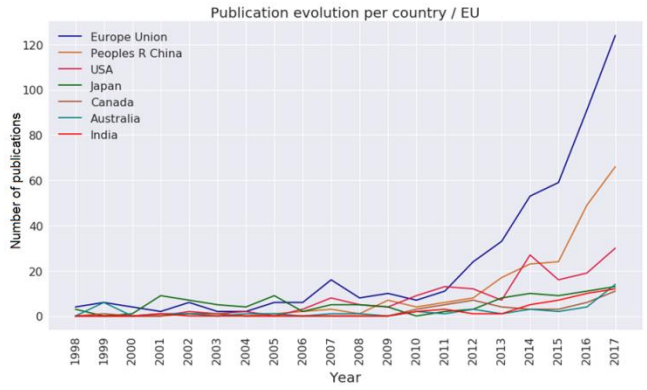

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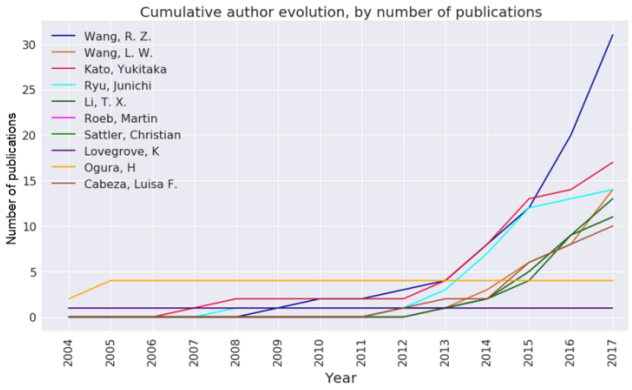

d)

Figure 14. a) Total publications evolution in TCS field per year; b) Total publications in TCS per country and EU; c) Publication evolution per country and EU for TCS; d) Cumulative author evolution in TCS field by number of publications

Table 12. Top 10 authors in TCS field.

Author	Afiliation	THTES publications	Total THTES cites	THTES h index
Wang, R. Z.	Shanghai Jiao Tong University, China	35	553	12
Wang, L. W.	Hebei University of Science & Technology, China	18	274	7
Kato, Yukitaka	Tokyo Institute of Technology, Japan	17	155	7
Ryu, Junichi	Chiba University, Japan	14	129	6
Li, T. X.	Shanghai Jiao Tong University, China	14	143	7
Roeb, Martin	German Aerospace Centre (DLR), Germany	11	228	7
Sattler, Christian	German Aerospace Centre (DLR), Germany	11	228	7
Lovegrove, K	IT Power, Australia	11	267	8
Ogura, H	Chiba University, Japan	11	143	7
Cabeza, Luisa F.	Universitat de Lleida, Spain	10	269	9

Increment of the publications on TCS compared to the previous year is presented in Table 13, showing that every country in the list is making a remarkable effort to

develop TCS technology. Leaders like EU, China or USA are growing at important rates. Other minor leaders such as Canada, India, Australia and Saudi Arabia are growing at rates that can make them top leaders in the following years.

Table 13. Country/region increment of TCS publications compared to the accumulated from previous year.

Country	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
EU	33.1%	32.0%	26.2%	30.8%	23.7%	20.9%	10.6%	7.2%	11.5%	10.1%
China	44.9%	50.0%	32.4%	45.1%	50.0%	30.8%	30.0%	25.0%	77.8%	12.5%
USA	22.2%	16.4%	16.0%	37.0%	10.6%	22.2%	31.7%	28.1%	14.3%	21.7%
Japan	11.1%	10.4%	9.3%	11.5%	10.1%	3.9%	2.7%	0.0%	5.7%	7.7%
Canada	28.9%	18.8%	10.3%	11.5%	18.2%	46.7%	50.0%	42.9%	0.0%	0.0%
Australia	41.2%	13.3%	7.1%	12.0%	4.2%	14.3%	5.0%	11.1%	0.0%	5.9%
India	38.7%	47.6%	50.0%	55.6%	12.5%	14.3%	75.0%	100.0%	0.0%	0.0%
Switzerland	22.2%	28.6%	16.7%	12.5%	6.7%	15.4%	0.0%	0.0%	0.0%	8.3%
Saudi Arabia	31.8%	83.3%	71.4%	40.0%	25.0%	100.0%	0.0%	100.0%	0.0%	0.0%
South Korea	25.0%	53.8%	30.0%	25.0%	60.0%	66.7%	50.0%	0.0%	0.0%	0.0%

Table 14 shows the most relevant journals for TCS along with their TCS performance index, showing that Solar Energy journal is the leader with a good performance. Nevertheless, Solar Energy Materials and Solar Cells journal has the highest performance for non-review journals showing higher quality on their publications in TCS.

Table 14. Top 10 journals in TCS field.

JOURNAL	LHTES publications	LHTES Cites	Performance Ratio	Impact factor	Quartile scores
SOLAR ENERGY	89	1686	18.9	4.37	Q1
APPLIED ENERGY	89	1264	14.2	7.90	Q1
APPLIED THERMAL ENGINEERING	88	1022	11.6	3.77	Q1-Q2
ENERGY CONVERSION AND MANAGEMENT	53	538	10.2	6.38	Q1
ENERGY	51	822	16.1	4.97	Q1
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	46	419	9.1	4.23	Q1-Q2
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	44	1878	42.7	9.18	Q1
SOLAR ENERGY MATERIALS AND SOLAR CELLS	28	758	27.1	5.02	Q1
JOURNAL OF PHYSICAL CHEMISTRY C	20	368	18.4	4.48	Q1-Q2
ENERGY AND BUILDINGS	20	294	14.7	4.46	Q1

4. Conclusions

TES scientific research field is a very important one accounting for more than 14,000 publications on relevant journals during the last decades. It is the first time that bibliometric analysis tool is applied in TES field.

This study presents the publication evolution in TES field over the last two decades, per year, per country, per authors, per journal, and per TES technology taking into account SHTES, LHTES, and TCS. Moreover, the interaction between co-authorship countries have been studied as well as author's community based on the co-authorship connections.

Furthermore, 14 research communities in TES field were detected by this bibliometric analysis, and the top 10 authors in this field leading most of these research communities.

Europe is leading the research in TES field since is the zone of the world that accounts for more amount of publications, more authors, and the main interactions are between Europe and all the countries of the world. In addition, China has suddenly increased the amount of TES publications per year, and this fact is directly related to the economic growth of this country. Therefore, the maturity of this technology is high but there is still place to continue performing research in TES field. Especially in TCS, this accounts for the lowest amount of published papers. Besides, the growth of number of publications, in this sub-field has appeared during the last years of this decade.

Acknowledgements

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