



# Concentrating Solar Power Technologies: A Bibliometric Study of Past, Present and Future Trends in Concentrating Solar Power Research

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Bibliometric analysis is a key study in order to elucidate the relevance of a research field. This study will point out the main evolution of the research performed in a topic considering the significance of each sub-topic. This study aims to perform a bibliometric analysis in concentrating solar power (CSP) technology. CSP had a first commercial wave between 1984 and 1995. Between 1995 and 2005 there was a period of commercial inactivity. Nevertheless, since 2005 CSP commercial implementation has been accelerating. This topic accounts for almost 6,300 publications on relevant journals and conference proceedings. Regional analysis showed that China is becoming the most relevant country for CSP research. The European Union still leads the development and will continue that way at least in the short term. Authors' keyword evolution analysis has been useful as an indirect measure of technological maturity. It was found that conference proceedings have an important effect in the overall CSP publications and need to be considered when working within this field. However, the journal publications have more impact since they are more frequently cited. Funding analysis had shown a direct relationship between funding and research output. Finally, it was concluded that inside the CSP field, parabolic trough has shown to have great relevance in the research output.

**Keywords:** bibliometric, concentrating solar power, solar tower, parabolic trough, stirling dish, renewable energies index

## INTRODUCTION

Meeting the world energy demand constitutes one of the greatest challenges of our generation, it has grown constantly until 2019 with a 0.9% annual growth. Even with the 2020 pandemic, renewable energy growth achieved 1% during 2020. For developed countries as well as for developing ones, energy has a major role for achieving the desired wellness; 67% energy demand growth since 2000 has been driven by China, Russia, India, Brazil, and South Africa (Enerdata, 2020; International Energy Agency, 2020). During the last few decades, use of fossil fuels as main source of energy to reach energy demand has resulted in a continuous CO<sub>2</sub> emissions growth related to it. (Dincer, 2000; International Energy Agency, 2018a). However, the emissions concern has resulted in the implementation of renewable energy and low emissions policies for several decades and, as a consequence, has contributed toward the reduction of emissions per the amount of energy produced (Dincer, 2000; Ürge-Vorsatz et al., 2015).

Renewable energies have a main role in today's global energy strategy. Nowadays photovoltaic and wind power have become the main drivers on renewable energy implementation (International Energy Agency, 2018b). Nevertheless, their development is limited by the mismatch between resource availability and energy demand. This mismatch cannot be fully counteracted, for now, with economically and technically viable solutions (like energy storage or interconnection) (International Energy Agency, 2014a).

Solar thermal energy offers the advantage of storing heat and/or cold, which is much simpler than storing electricity, even if the thermal energy is converted later to electricity. Concentrating Solar Power (CSP) offers a solution for harvesting solar energy and integrating it with thermal storage for high enthalpy applications (such as industrial heat or electricity generation) (International Energy Agency, 2014b). CSP technologies have been under constant development in recent years; it is expected that, with the adequate support, thermal CSP can constitute up to 11% of electricity generation by 2050 (International Energy Agency, 2010; International Energy Agency, 2014b). Notice that 11 TWh were produced by CSP during 2017 compared with 1 TWh in 2000, and these numbers are expected to grow to 180 TWh in 2030 (International Renewable Energy Agency, 2016; International Energy Agency, 2018b; International Energy Agency, 2020).

Different strategies are in the research stage in order to make more technologically and economically viable thermal solar power, such as increasing the low and high temperatures (Ho and Iverson, 2014; Laughlin, 2017; Calderón et al., 2018), using latent heat on heat transfer fluid (HTF) and thermal energy storage (TES) media (Liu et al., 2012), studying thermochemical reactions for long term energy storage capabilities (Felderhoff et al., 2013), studying ways to improve current HTF-TES and power plant operation conditions (Casati et al., 2015; Liu et al., 2017), new supercritical power conversion cycles with improved efficiency, solar field components optimization for cost reductions (Cha et al., 2015; Guo et al., 2018), etc. Over the years, CSP progress has been closely related to scientific research, to finally impact CSP commercial applications, until each technology research has enough technological maturity (Liu et al., 2016; Hussain et al., 2017; Ahmadi et al., 2018). By studying research efforts and trends in order to monitor topic relevance and management of knowledge, Bibliometrics had become an important part of information sciences. Several studies have been made during years for several fields, such as health, marketing, entrepreneurship, production and operations management, innovation, etc. (Merigó et al., 2015). In the same way, bibliometric studies have been recently published for wind power price (Gao et al., 2016), for alternative energy research during 1994 and 2013 (Mao et al., 2015), and for TES technologies (Calderón et al., 2020). For CSP field, there are no deep bibliometric analysis that studied CSP technologies.

Bibliometrics use mathematical and statistical methods for measuring science output and relate it to quality. These methods can be applied to individuals, research groups, institutions, countries, and regions (Góngora Orjuela, 2010; Ellegaard and Wallin, 2015). These analyses have proven useful for

governmental and funding decision-makers, for building strategic plans on the long term, measuring research productivity, project potential evaluation, and for determining which research activities match the economic and political objectives of a region (Matcharashvili et al., 2014).

The aim of this bibliometric study is to provide an overview of CSP research and development evolution by using bibliometric methods. Finding research and development trends can be of great interest for CSP developers and researchers, for energy policy stakeholders, and for everyone involved in or starting in this field. Several regional efforts, policies, and financing options were identified over the years from the knowledge creation perspective. Finally, advancements and technological maturity were studied for the main CSP harvesting configurations: parabolic trough, solar tower, Stirling dish and Fresnel systems.

## SCOPE

Bibliometric methods are widely used in the social sciences for the analysis of the different outstanding research fields of which specific and objective information is required for their study. These methods are also used to determine potential strengths and weaknesses that a field of study has from an objective point of view. Bibliometrics had not been used extensively in technological or formal science fields, although in recent years they have been adapted to apply these methods to these fields. Currently, there are various scientific journals in the field of renewable energy and energy storage, among many others that have begun to publish bibliometric studies in high-impact scientific journals. The bibliometric methodology is used to discern from a specific technical field and find objective information to advance in the research associated with that field.

The current paper presents a bibliometric study of the technologies related to the power generation concentrating solar plants, trying to shed light on the present, past, and future trends in research related to CSP plants. Therefore, authors have developed the analysis of different key points that have been identified, once the bibliometric search that is explained in the methodology section has been done. The results have been analyzed from different points of view. The first is a global analysis of the publications produced per year that represents the importance that the field holds. The keywords used in the field are analyzed in order to discern the maturity of the technology. The location of the publications is relevant in order to understand where is more relevant to the field under study. In addition, the top 10 authors are of the CSP field listed in this paper as well as the communities and interaction between them to discern who is leading the research in this field. Finally, the configuration of the technologies are identified separately in order to understand which is the most important for CSP at the present time.

## METHODOLOGY

The procedures and tools used for performing the analysis of CSP research evolution are described in this section. Formally,

**TABLE 1** | CSP keyword map search.

Exclusion phrases		Main phrases			Complement phrases			Total				
pv	photovoltaic	Solar tower						797				
		Solar field			Concentrated			187				
		Parabolic trough						2,845				
		Concentrated solar			Power	Thermal			3,364			
		Fresnel reflector*						311				
pv	Photovoltaic	Polymer	Barrier	Lithium	Dish Stirling			244				
					Molten salt*			Solar	csp			1,466
					Heat transfer fluid			Concentrated			430	
					HelioStat*			Tower	csp	Solar	1,130	

Note that proceedings were included in the extraction because authors noticed the relevance that this kind of publication has in the field.

Note that phrases ending in \* use this symbol as a wildcard, it represents any character, group of characters, or no character.

Bibliometrics is a science dedicated to study the scientific publications of a specific research field by using statistical tools; these studies can be extended to a wide number of scientific fields (Pritchard, 1969). Bibliometrics had been considered to bring a general picture of the progress of a particular research field, detect the top researchers as individuals or as communities, find the most outstanding journals on that specific field, and the interactions between authors and countries, among other specific analyses (Bjork and Hedlund, 2015).

In order to use the most significant information sources and indicators, Web of Science (WoS) Core Collection was used as the source of data. This database includes more than 14,000 high-quality journals and provides enough information about the publications, such as authors name, affiliations, abstract, keywords, references, funding information, etc. All this information allowed us to extract high value analyses that could not be performed using other databases.

For creating the database, authors searched in the topic, abstract or keywords sections the research query: (“solar tower”) OR [“solar field” AND (“concentrated”)] NOT (“pv” OR “photovoltaic”) OR (“parabolic trough”) OR (“concentrated solar” AND [“power” OR “thermal”]) OR (“fresnel reflect OR \*”) OR (“dish Stirling”) OR [“molten salt\*” AND (“solar” OR “CSP”)] NOT (“pv” OR “photovoltaic” OR “polymer” OR “barrier” OR “lithium” OR “solar-cells”) OR [“heat transfer fluid” AND (“concentrated”)] OR [“helioStat\*” AND (“tower” OR “CSP” OR “solar”)].

A common problem for building up a database for bibliometric analysis is that terminology selected by authors is different according to the specific approach they are using. This occurs also in the CSP field. Therefore, a keyword map was used in order to build a more complex and inclusive search, allowing as well as omitting several keywords from the result to avoid all subjects not related to CSP. Establishing boundaries and selecting the best keyword combination was challenging, since there is no convention on CSP classification by stages or by components or even by the terminology.

Table 1 shows these keywords that were used to collect the CSP database. In this keyword map a main phrase search is only included if at least one of the complement phrases in the same row are present in the different searched sections (title, keywords, abstract, etc.), with the exception of those publications that have

at least one of the exclusion phrases in that same row. As a result, the keyword map allowed the procurement of, in an improved way, a reliable database of CSP publications. The total scientific articles selected by each row search are also shown in Table 1. It is remarkable that several publications were selected by more than one row search and the sum of all the articles selected per row is higher than the total publications.

Eight two thousand fiftysix publications were found between 1969 and 2020. For yearly analyses only periods until 2019 were considered, since the database was created at mid-2020.

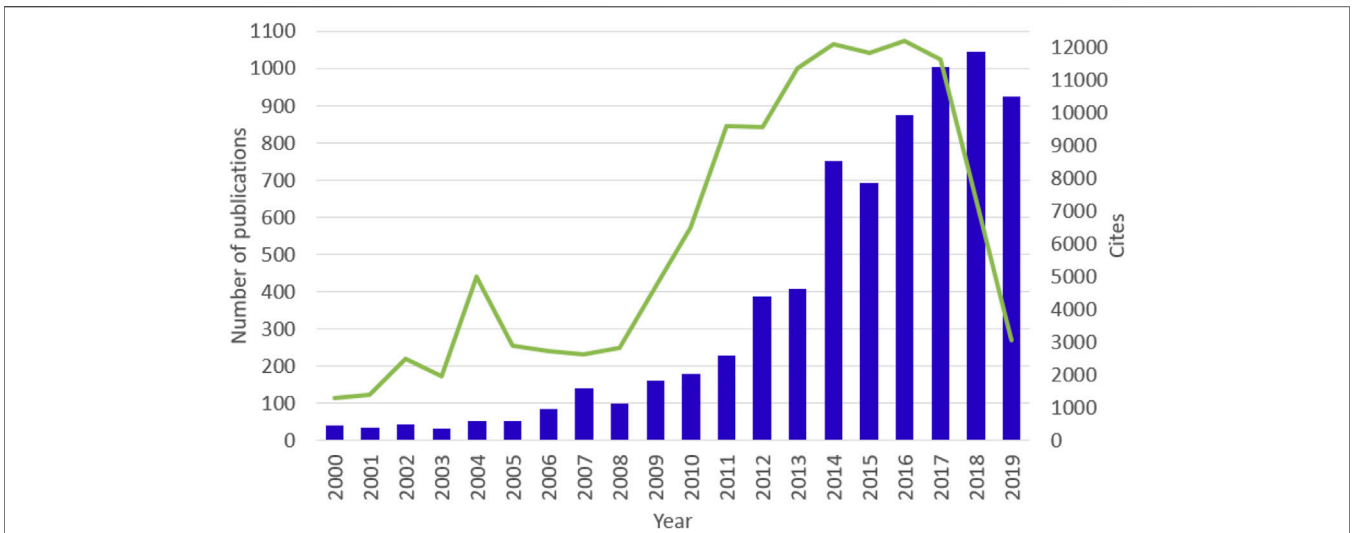
For deeper analysis, the database extracted from WoS was analyzed for studying specific CSP technologies which included parabolic trough, solar tower, Stirling dish, and Fresnel collectors. Most of the relevant authors, journals, regional cooperation and other relevant information was assessed and is presented in the following sections.

Bibliometric analyses were carried out by python coding and graphic tools. Additional reports were done using VOS Viewer<sup>®</sup> scientific visualization tools (Center for Science and Technology Studies, 2018) used for bibliometric network analysis and Complexity Lab Barcelona (CLabB) (Department de Física Fonamental, 2019) software.

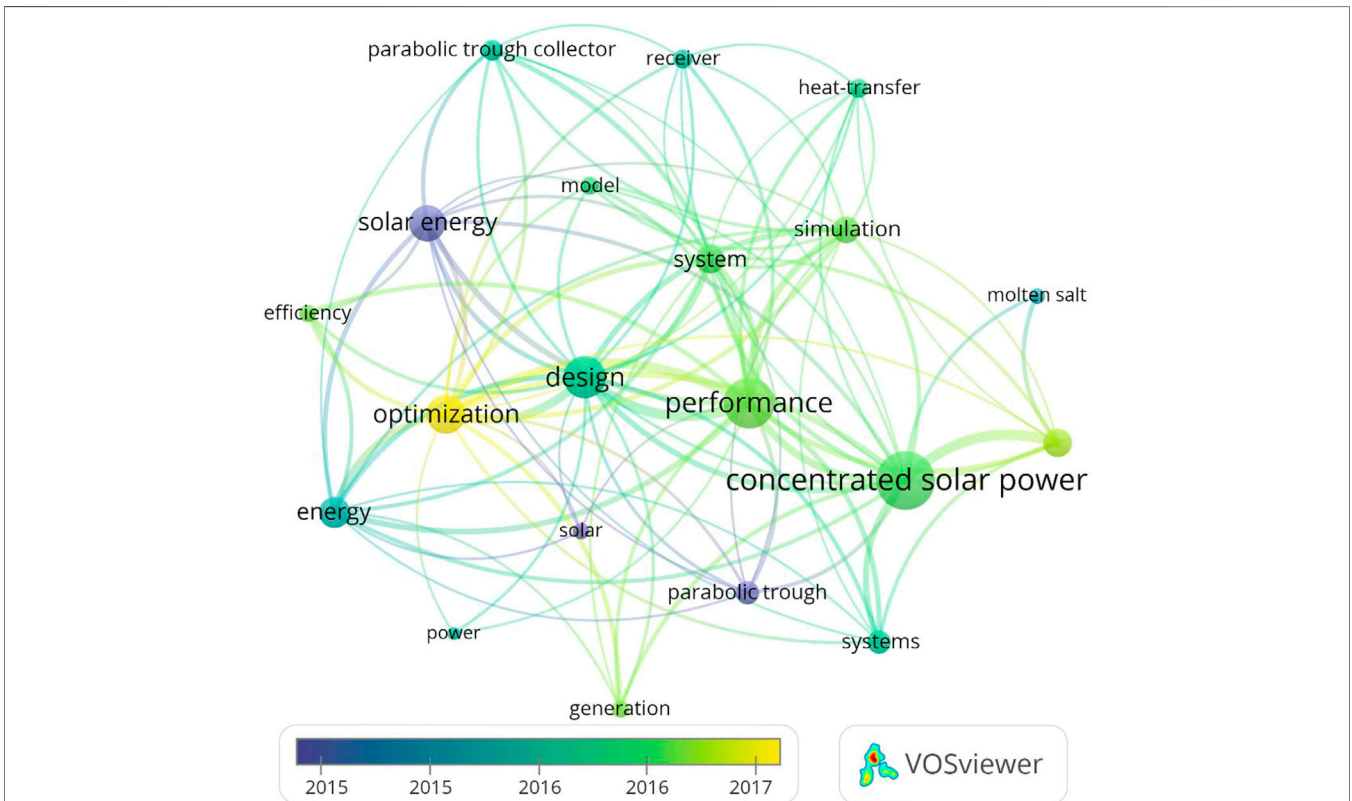
## RESULTS

### Publication Bibliometric Analyses

Based on the publications included in this new bibliometric database search, the total publications per year regarding the whole concentrating solar power field are presented as bars in Figure 1 for the last 20 years. Also, the number of citations can be appreciated by the green line in Figure 1. Therefore, the number of publications has grown considerably during the last decade, even though not every year increases the number of publications. Since proceeding papers have been included, they influenced the change of tendency from one year to another but not to the tendency on a greater time span. Citations of the publications are low for the few last years; nevertheless, this was expected since the most recent papers have not been cited yet. Indeed, publications will not reach their full citable potential until some years after their publication date. General tendency remarks that the CSP field is growing up along with its market development in the near future (International Energy Agency, 2018b).



**FIGURE 1** | CSP publications and citations during the last 2 decades.



**FIGURE 2** | Evolution of trend keywords on CSP publications.

**Figure 2** shows the top trend keywords for CSP field. It can be seen that the most used keywords are “performance”, “design”, “solar energy”, “energy”, “optimization”, “systems”, “parabolic trough”, and “concentrated solar power”. Moreover, “optimization” and “concentrated solar power” have been used

more recently in 2016 compared with “performance”, “design”, or “system” in 2014–2015; this reflects the maturity of the technology, since these keywords are most commonly used for optimization of commercial solutions. This is a visible example that optimization prevails over the design learning process, since

**TABLE 2** | CSP Most cited publications.

Authors	Title	Journal	Type	Cites	Year	Country
Kalogirou, SA	Solar thermal collectors and applications	Progress in energy and combustion science	Review	1405	2004	Cyprus
Gil, Antoni; Medrano, Marc; Martorell, Ingrid; Lazaro, Ana; Dolado, Pablo; Zalba, Belen; Cabeza, Luisa F	State of the art on high temperature thermal energy storage for power generation. Part 1- Concepts, materials and modellization	Renewable and sustainable energy reviews	Review	824	2010	Spain
Steinfeld, Aldo	Solar thermochemical production of hydrogen-a review	Solar energy	Review	817	2005	Switzerland
Jacobson, mark Z	Review of solutions to global warming, air pollution, and energy security	Energy and environmental science	Review	712	2009	United States
Tian, Y.; Zhao, C. Y	A review of solar collectors and thermal energy storage in solar thermal applications	Applied energy	Review	694	2013	United Kingdom, China
Jacobson, mark Z.; Delucchi, mark A	Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials	Energy policy	Article	690	2011	United States
Papageorgiou, N; Athanassov, Y; Armand, M; Bonhote, P; Pettersson, H; Azam, A; Gratzel, M	The performance and stability of ambient temperature molten salts for solar cell applications	Journal of the electrochemical society	Article	669	1996	France, Switzerland
Fernandez-Garcia, A.; Zarza, E.; Valenzuela, L.; Perez, M	Parabolic-trough solar collectors and their applications	Renewable and sustainable energy reviews	Review	568	2010	Spain
Kalogirou, SA	Artificial neural networks in renewable energy systems applications: a Review	Renewable and sustainable energy reviews	Review	551	2001	Cyprus
Kalogirou, SA	Applications of artificial neural-networks for energy systems	Applied energy	Proceeding	527	2000	Cyprus
Price, H; Lupfert, E; Kearney, D; Zarza, E; Cohen, G; Gee, R; Mahoney, R	Advances in parabolic trough solar power technology	Journal of solar energy engineering-transactions of the Asme	Article	519	2002	Spain, United States
Steinfeld, Aldo	Solar hydrogen production via a two-step water-splitting thermochemical cycle based on Zn/ZnO redox reactions	International journal of hydrogen energy	Article	480	2002	Switzerland
Mills, D	Advances in solar thermal electricity technology	Solar energy	Proceeding	470	2004	Australia
Zhang, H. L.; Baeyens, J.; Degreve, J.; Caceres, G	Concentrated solar power plants: Review and design methodology	Renewable and sustainable energy reviews	Review	432	2013	Belgium, United Kingdom, Chile
Kenisarin, Murat M.; Van Valkenburg, ME; Vaughn, RL; Williams, M; Wilkes, JS	Thermochemistry of ionic liquid heat-transfer fluids	Thermochemica acta	Proceeding	419	2005	United States
Liu, Ming; Saman, Wasim; Bruno, Frank	Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems	Renewable and sustainable energy reviews	Review	349	2012	Australia
Herrmann, U; Kelly, B; price, H	Two-tank molten salt storage for parabolic trough solar power plants	Energy	Proceeding	349	2004	Germany, United States
Selvakumar, N.; Barshilia, Harish C	Review of physical vapor deposited (PVD) spectrally selective coatings for mid- and high-temperature solar thermal applications	Solar energy materials and solar cells	Review	339	2012	India
['Behar, omar', 'khellaf, abdallah', 'mohammedi, kamal']	A review of studies on central receiver solar thermal power plants	Renewable and sustainable energy reviews	Review	331	2013	Algeria
Romero, Manuel; Steinfeld, Aldo	Concentrating solar thermal power and thermochemical fuels	Energy and environmental science	Review	317	2012	Spain, Switzerland

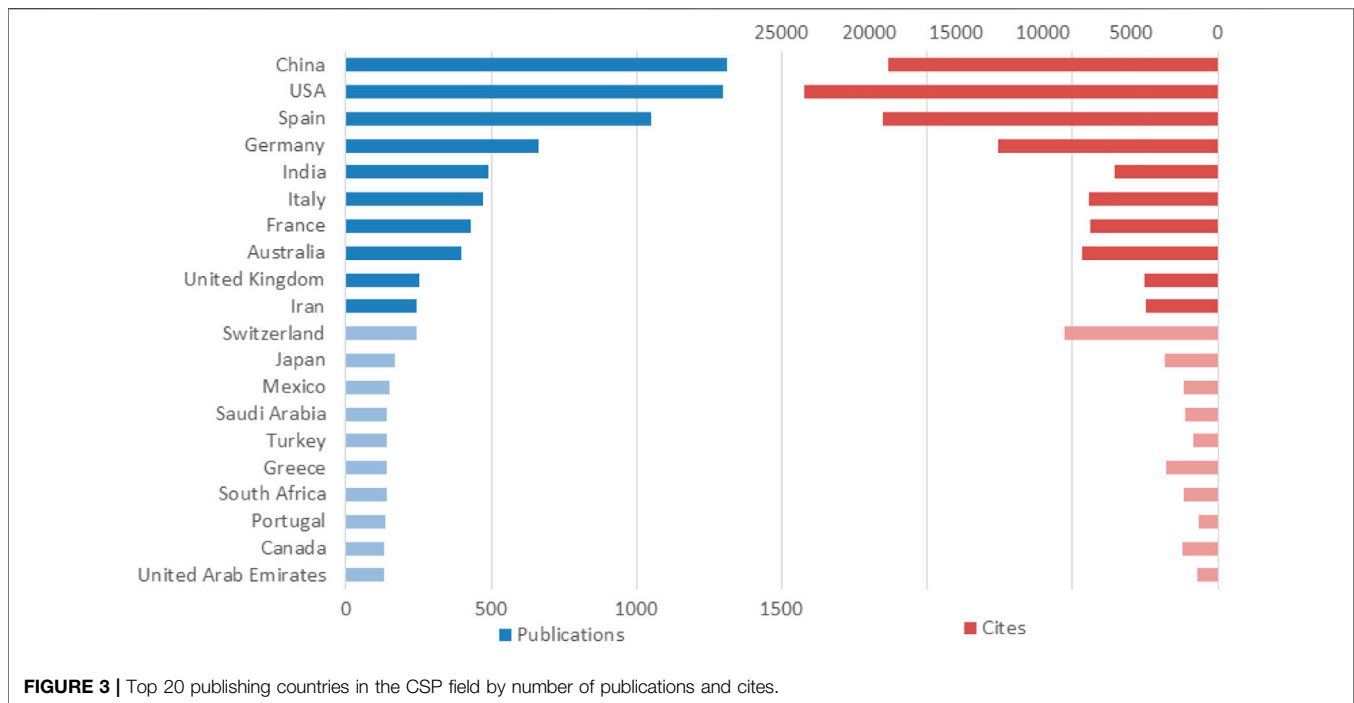
CSP is a mature technology, even though it is under constant improvement. The oldest top keywords are “solar energy”, “energy”, and “parabolic trough” which were more frequently used in 2013.

In **Table 2** the 20 most cited articles can be appreciated. It is understandable that 12 of the top 20 articles are reviews. Also, several molten salts publications are in the top 20 since this topic is very attractive as HTF and TES media for its high service temperature limit. Kalogirou also denotes as one of the most cited

authors as well as Steinfeld. This stays in line with the current CSP tendency to incorporate TES for optimizing CSP plants, which allows the consideration of the high manageability of CSP as a main attribute that adds flexibility to electric networks and to the energy mix.

## Country Bibliometric Evolution

Regional evolution is of great interest for design and evaluation of research policies focused on particular technologies. In **Figure 3**,



total publications over time for the top 20 countries are presented. United States stands at the top as the country with the most publications, followed by China, Spain, and Germany. When considering regional efforts Spain, Germany, Italy, France, United Kingdom, Greece, and Portugal suggest that the biggest effort has been made by European Union. Also, emerging economies such as India and China outstand in this list.

**Figure 4A)** shows the publication evolution per country over the last 2 decades. Notice that a high number of publications per country does not imply that countries produce a high relevance output, as can be observed in the number of citations in recent years. United States and almost every European country's research literature was constant over the last five years, while growth during these years was mainly driven by China, India, United Kingdom, and Australia. This is related to different strong programs that have been implemented by the European Union, the Department of Energy (DoE) of United States, and the Chinese government (Visiongain Energy, 2018; National Renewable Energy Laboratory, n.d.).

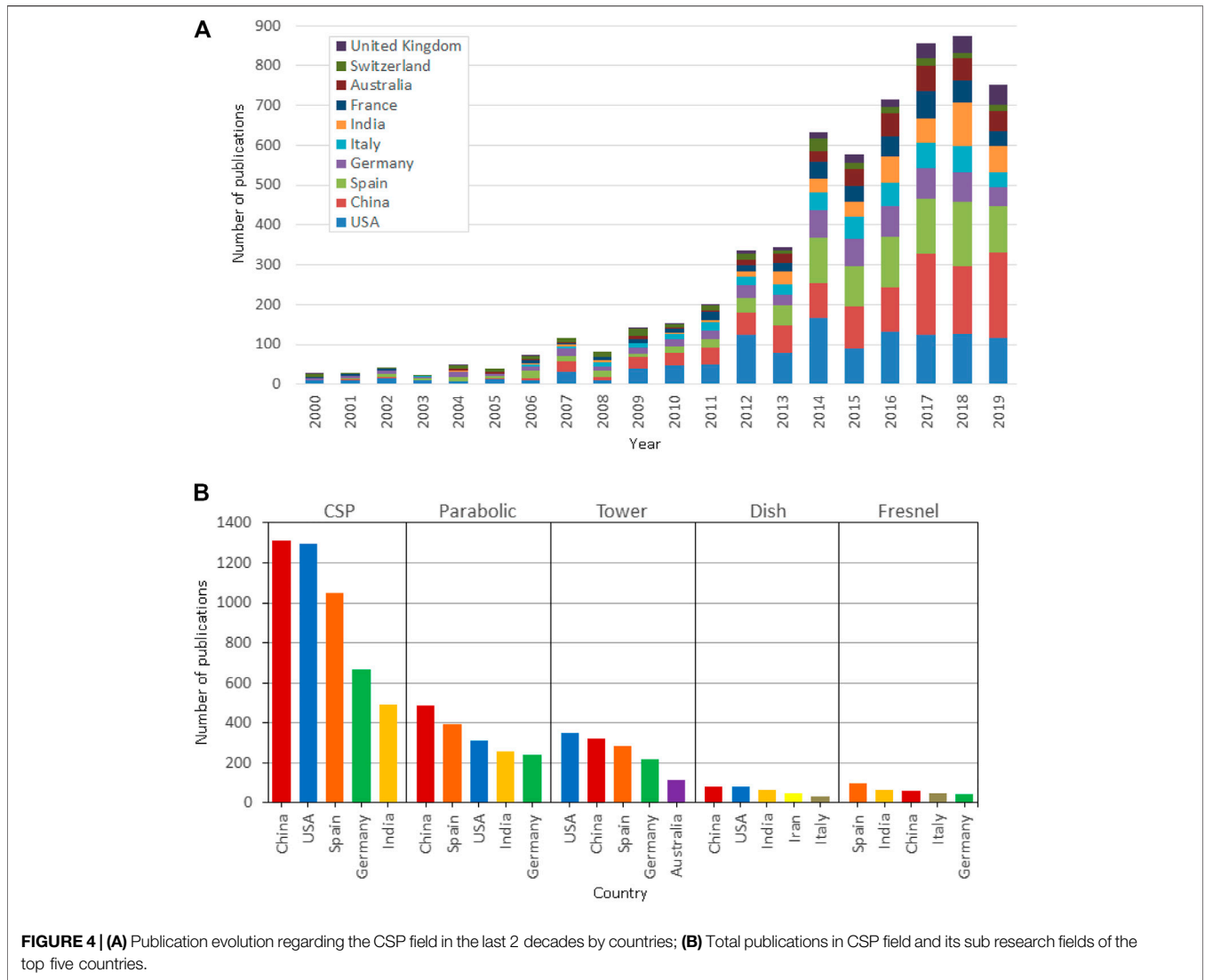
Furthermore, **Figure 4B)** presents the total publications for the top five countries divided by CSP technologies. The main ways that are considered to harvest concentrated sunlight are parabolic trough, solar tower, Stirling dish, and Fresnel lens. Total publications for each of these technologies are presented in **Figure 4B)** and compared to the total publications of CSP field. It can be observed that China leads the total publications for parabolic trough, solar tower, and Stirling dish, while Spain remains as the first one for Fresnel and second one in parabolic trough and solar tower.

**Figure 4B)** also reflects the higher interest on parabolic trough and solar tower compared to both remaining technologies. This is understandable since parabolic trough and solar tower are the

first and second most implemented CSP technologies, respectively.

Based on current trends, it is expected that China will lead CSP research over the next years, followed by a significant increase of India participation in CSP deployment. China technological development policy is being implemented in the CSP field as it has been implemented in other technological areas, which includes use of foreign experts in order to achieve expertise combined with strong and well-funded homeland research and innovation programs (European Commission, 2017; Kennedy, 2017). This, in the long-term, will potentially allow China to be the most developed country in CSP. This tendency is replicated in **Table 3** where publication rate is compared to their total papers accumulated up to the previous year. This information clearly elucidates that China, India, United Kingdom, and Australia were growing during recent years. Also, Spain, Italy, and France maintained their publications trend at a constant rate.

Citations are very interesting to analyze, since it can reflect the relevance of the published work. In **Table 4** the performance ratio, defined as the total number of citations divided by the number of publications, is presented for the top 20 countries. Again, the performance ratio is low for recent years' papers. Most productive period was registered for Spain between 2009–2011; nevertheless, it was reduced during recent year publications compared to other countries like Switzerland, Iran, or Greece. The case of Spain could be explained due to changes in the public regulations regarding solar energy in that country during 2013–2018 (Boletín Oficial del Estado, 2013; Boletín Oficial del Estado, 2015; Gabaldon-Estevan et al., 2018). In addition, the case of Switzerland's performance ratio over the last ten years is remarkable, since it was the most prolific one, achieving about 35 citations per paper for the whole decade. Together with Spain,



**TABLE 3 |** Country increment of CSP publications compared to the accumulated from previous year.

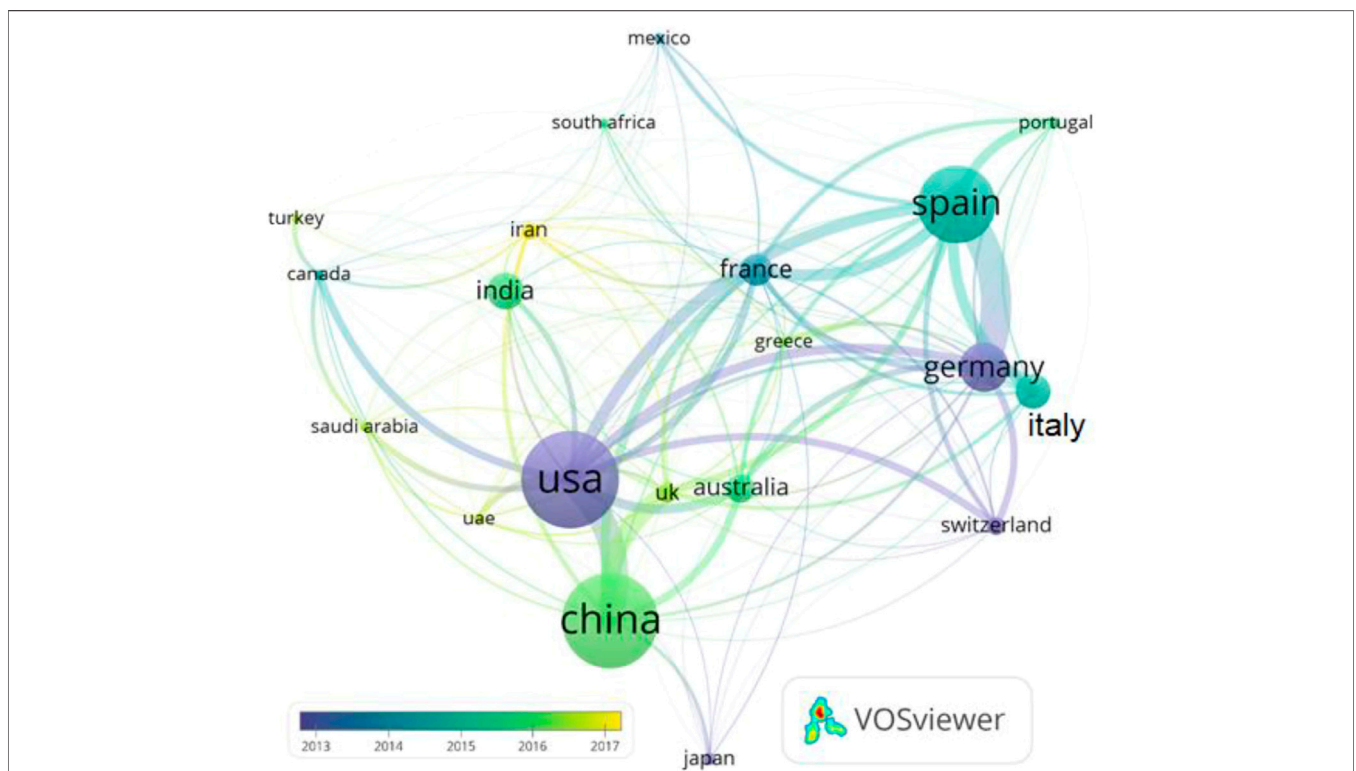
Country	2010 (%)	2011 (%)	2012 (%)	2013 (%)	2014 (%)	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)
China	44.0	38.9	38.0	34.3	32.4	29.1	23.4	34.8	21.3	22.4
United States	23.7	20.0	41.8	18.7	33.3	13.5	17.8	14.2	12.6	10.1
Spain	13.8	18.5	25.2	26.1	48.3	29.1	28.6	24.0	23.2	13.5
Germany	14.7	14.2	18.3	14.0	30.7	22.8	20.5	17.2	14.3	8.0
India	16.7	23.8	53.8	77.5	47.9	36.2	46.2	29.2	40.4	16.9
Italy	38.2	46.8	31.9	29.7	38.1	35.0	26.8	22.9	19.2	9.3
France	20.0	31.7	17.7	23.7	36.5	24.8	25.5	27.6	17.2	10.6
Australia	7.1	16.7	37.1	45.8	40.0	42.9	42.1	32.2	21.3	16.0
United Kingdom	50.0	55.6	57.1	36.4	53.3	43.5	27.3	46.4	34.1	30.9
Switzerland	9.4	11.8	16.3	7.4	24.6	9.9	9.6	9.2	6.1	6.6

The United States decreased citations per paper over the last decade. Finally, India’s performance ratio was the lowest during the last decade of all the top ten countries, caused mainly by the low citations during the 2014–2016 period.

Co-authorship between countries has also been studied in the CSP field (see **Figure 5**). Each country is represented by a circle in this figure; the size of the circle represents the number of publications, while thickness of the curved lines represents the

**TABLE 4 |** Country performance ratio of CSP publications per year for the last 10 years.

Country	2011	2011	2012	2013	2014	2015	2016	2017	2018	2019	Publications	Cites
China	34.8	39.3	21.1	28.7	17.8	16.1	17.1	17.4	10.3	4.1	1,311	18,881
United States	23.5	63.1	17.0	30.9	15.5	20.7	8.9	12.8	6.4	3.1	1,296	23,702
Spain	113.8	67.0	33.3	33.6	19.9	16.2	13.2	9.7	5.4	3.4	1,048	19,223
Germany	21.3	42.8	25.5	26.3	21.1	13.2	8.8	12.8	4.5	3.9	665	12,609
India	64.0	19.8	50.0	32.5	11.8	15.2	12.0	10.9	5.0	2.6	490	5,934
Italy	39.8	53.6	28.6	25.4	17.1	15.6	15.9	8.8	6.4	4.2	474	7,432
France	20.8	34.6	24.9	41.8	21.3	12.1	14.5	12.3	6.4	5.5	430	7,350
Australia	36.0	14.8	74.1	24.9	18.4	21.8	17.3	12.2	11.9	3.3	399	7,754
United Kingdom	25.7	58.6	26.3	157.5	15.5	19.2	22.2	13.9	10.5	3.9	253	4,232
Switzerland	46.1	46.8	62.4	25.0	18.4	25.1	13.4	7.8	9.5	3.9	245	8,803
Iran	57.7	0.0	36.0	46.8	34.9	47.3	28.5	15.8	14.8	5.3	245	4,104
Japan	10.0	41.7	6.2	9.2	7.8	12.1	10.3	5.9	5.2	2.4	168	3,053
Mexico	25.0	28.9	6.0	53.0	5.6	14.9	9.1	12.5	3.4	0.6	152	1,941
Saudi Arabia	0.0	50.3	34.0	33.0	15.9	22.0	14.6	13.0	6.4	4.1	141	1,894
South Africa	2.0	1.2	18.0	41.6	16.5	22.2	10.9	7.3	4.8	1.6	140	1,936
Greece	31.7	52.0	29.5	26.7	37.0	23.0	42.9	21.0	15.8	6.6	140	2,993
Turkey	0.0	20.7	18.0	12.8	17.8	8.7	18.5	13.5	9.8	2.7	140	1,378
Portugal	25.7	17.0	13.5	13.9	10.6	8.0	13.9	6.1	3.9	2.4	135	1,107
Canada	20.3	53.5	34.6	26.6	18.1	12.3	28.9	12.4	14.9	3.1	133	2,021
United Arab Emirates	23.5	11.0	4.0	12.0	7.2	17.7	6.6	5.0	13.8	4.9	130	1,162

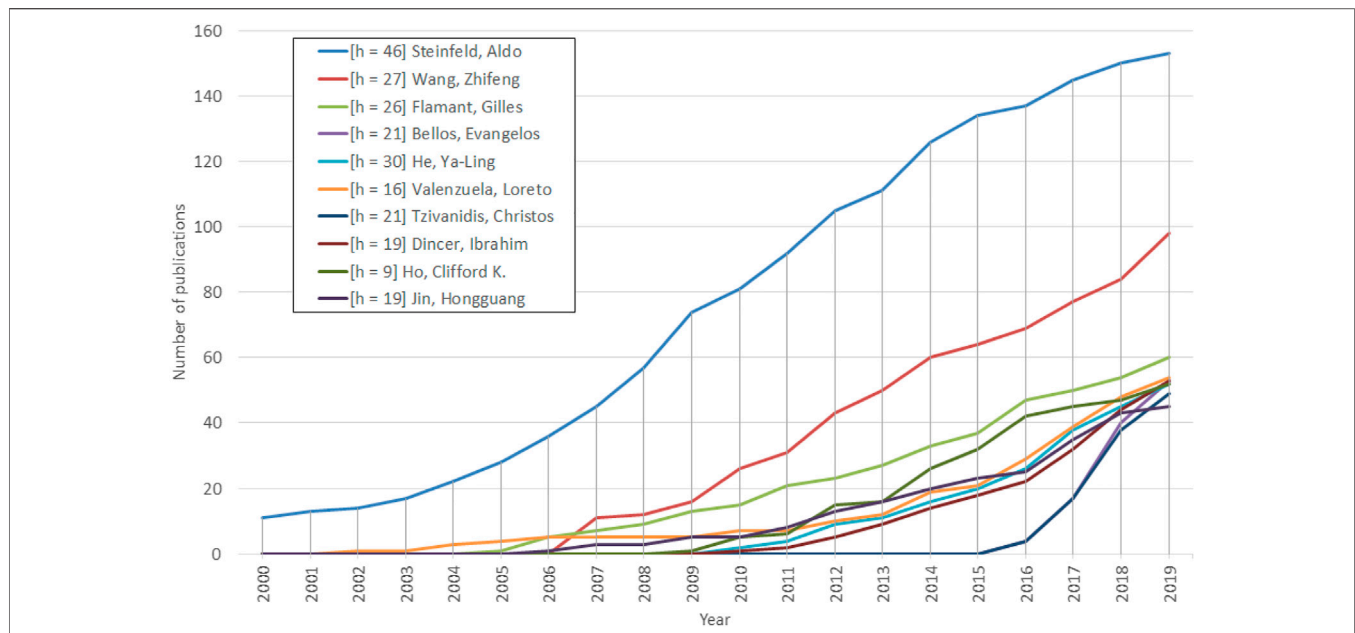


**FIGURE 5 |** Country co-authorship interaction collaboration of the Top20 countries.

interaction strength between countries. Colors represent the most relevant year of interaction between countries. Thereby, the oldest research cooperation exists between United States and Germany, followed by a newer relation between Spain and Italy. Also, Spain and Germany have the biggest relationship of all, leading the

European cluster; followed by the United States-China relationship. This is consistent with known research cooperation between CIEMAT (Spain) and DLR (Germany) with the PSA (Plataforma Solar de Almeria), and ENEA Group (Spain) and DLR molten slat trough projects. In





**FIGURE 6** | Cumulative author evolution by publications for the last 2 decades.

addition, China-United States co-authorship is in line with the NREL (United States) and Sandia National Laboratories (United States) cooperation with China. Other known cooperative projects that are coherent with the bibliometric data are the MIT (United States)–Masdar (UAE) projects as well as solid particle technologies for solar tower between DLR (Germany), Sandia National Laboratories (United States) and CNRS (France) (Calderón et al., 2018; National Renewable Energy Laboratory, n.d.; Calderón et al., 2019). One outstanding cooperation opportunity is the cooperation between China and the Germany-Spain cluster. Besides, Middle Eastern countries were the newest relevance and cooperation of the top countries, showing a growing relevance in the world's stage. Finally, the lack of African and South American countries shows an area of opportunity for deployment, since a lot of those countries can find CSP implementation very favourable (International Energy Agency, 2010). A special highlight is the case of Chile. This country did a huge step forward in renewables implementation around the country and built the biggest CSP plant in South America in 2018 (110 MW and 17.5 h of storage) being one of the most ambitious projects looking within the future regarding the CSP field (Cerro Dominador, n.d.).

### Authorship Bibliometric Evolution

The accumulated author publications profile is shown in **Figure 6** by taking into account the grouped publication of each author profile available in the 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 remark the authorship order, only if they are in the author list.

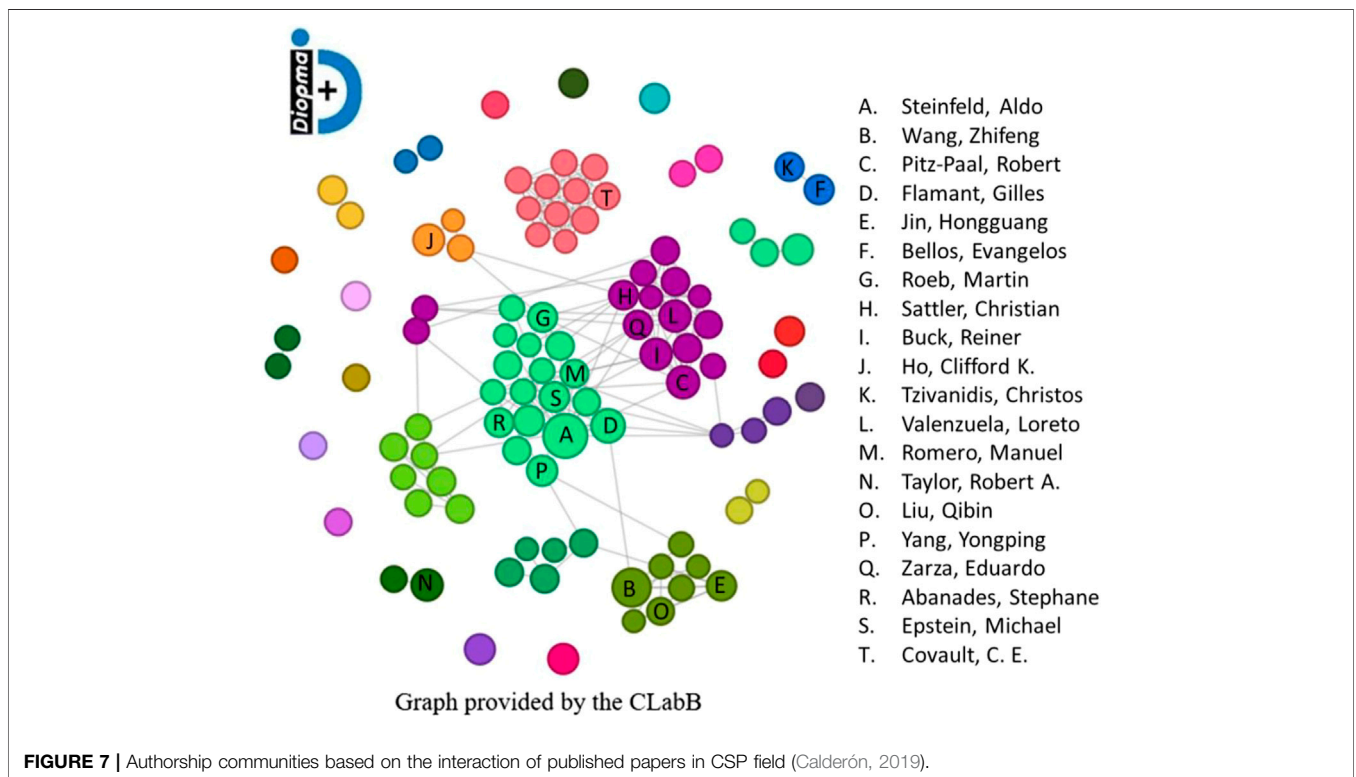
As **Figure 6** shows, Dr Aldo Steinfeld is the top-one researcher publishing in CSP field followed by Dr. Zhifeng Wang, Dr. Pitz-Paal,

and Dr. Flamant, who are the most representative prestigious researchers in the CSP field. The CSP h index can also be appreciated, this h index was calculated by taking into account only the CSP database. The H index was defined by Prof. J.E. Hirsch from University of California 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*” (Hirsch, 2010). In the CSP field, Dr. Aldo Steinfeld obtained an h index of 42, while Dr. Zhifeng Wang and Dr. Giles Flamant had 22 each. These results must be interpreted with caution, since some research centers include the scientific directors of the centers into the publication's author list. While in other centers only the persons involved directly in the projects are in the publication author list. Some known experts in the CSP field that are present in the current top 20-author list include Dr. Clifford Ho, Dr. Eduardo Zarza, among others.

The H-index has been used by academic societies for measuring and quantifying the scientific output. It has become a fundamental standard method to determine the efficiency of the researchers, scientists, institutions, departments, and universities based on their publications and citations (Pavlova, 2018; Youssef et al., 2021). There have been some efforts to develop other indicators for overcoming the flaws of the h-index, however, it is still the most used parameter for measuring author scientific output (Grech and Rizk, 2018). For this analysis, the h-index has been calculated, taking into account only the research area or sub-area under study. Therefore, the h-index reported in this paper only considers the CSP field. In **Table 5**, the top 20 authors by number of CSP publications are listed with the number of citations and the CSP h-index. The most cited author and the one with the highest CSP h-index is Dr. Aldo Steinfeld. Other relevant authors that can be denoted are Dr. Zhifeng Wang and Dr. Giles Flamant with a CSP h-index of 22. When considering countries of

**TABLE 5 |** Top 20 authors in the CSP field.

Author	Affiliation	CSP publications	Total CSP cites	CSP h-index
Steinfeld, Aldo	ETH Zurich, Switzerland	153	6,937	46
Wang, Zhifeng	Hebei University of technology, China	103	1,849	27
Flamant, Gilles	Center National de la Recherche Scientifique (CNRS), France	62	1,970	26
Bellos, Evangelos	National technical University of Athens, Greece	62	1,156	21
He, Ya-Ling	Xian Jiaotong University, China	58	2,413	30
Valenzuela, Loreto	Plataforma solar Almeria, Spain	56	1,516	16
Tzivanidis, Christos	National technical University of Athens, Greece	53	1,137	21
Dincer, Ibrahim	Ontario Tech University, Canada	53	1,009	19
Ho, Clifford K	Sandia National Laboratory, Department of energy, United States.	52	730	9
Jin, Hongguang	Institute of engineering Thermophysics, CAS, China	49	918	19
Roeb, Martin	German Aerospace Center (DLR), Germany	48	1,274	19
Pitz-Paal, Robert	German Aerospace Center (DLR), Germany	48	1,391	18
Ding, Jing	German Aerospace Center (DLR), Germany	46	610	14
Buck, Reiner	German Aerospace Center (DLR), Germany	45	1,075	15
Yang, Yongping	North China electric power University, China	42	545	14
Liu, Qibin	Institute of Soil science, CAS, China	41	871	18
Abanades, Stephane	Center National de la Recherche Scientifique (CNRS), France	39	1,196	19
Cabeza, Luisa F	University of Lleida, Spain	39	1,525	16
Taylor, Robert A	University of New South Wales Sydney, Australia	38	895	16
Zarza, Eduardo	CIEMAT, Spain	37	2,167	20

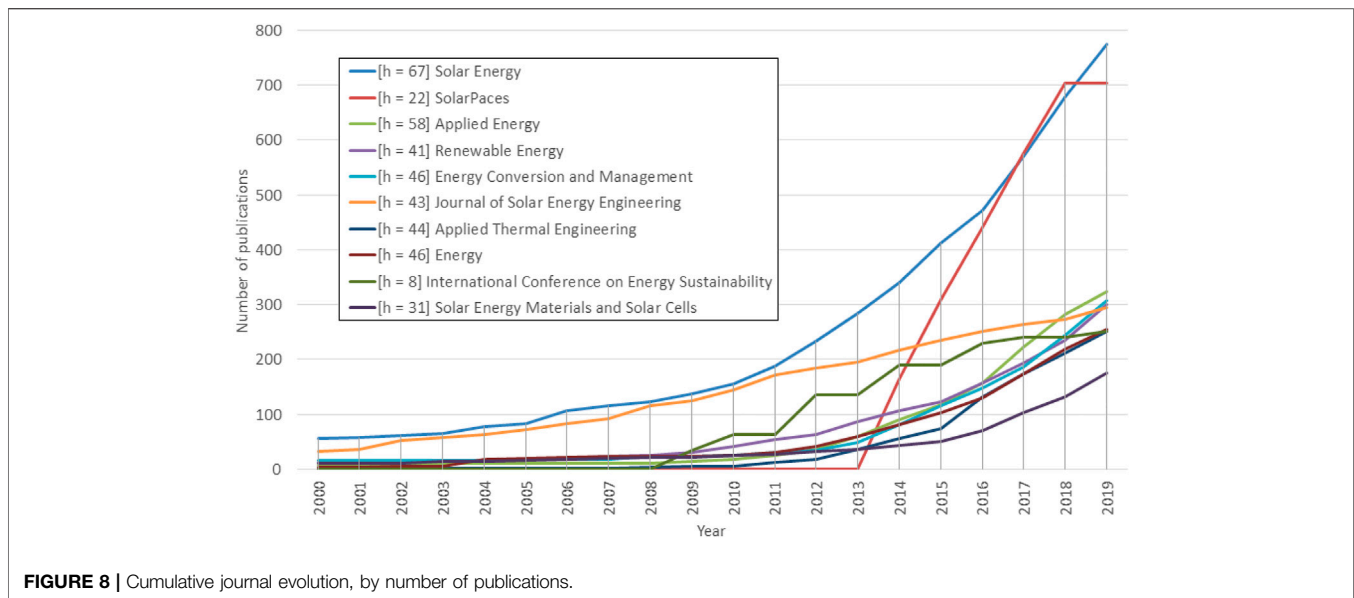


the top 20 authors, Germany, Spain, United States, and China are shown to be the most relevant. Finally, German Erospace Center (DLR) stands out since four of the top 10 authors are affiliated there.

Identifying the author communities besides their affiliation or geographical location can be very useful. **Figure 7** shows groups of authors based on the number of co-authorship. Top 100 authors were analyzed and the top 20 are identified in the

figure. This analysis was performed by using CLabB software tool which defines the attraction forces between the authors to order them into communities.

International cooperation is outstanding in the two main groups showing a strong link of cooperation between them. The first group include organizations such as ETH Zurich, CNRS, DLR, IMDEA (with thermochemical solar tower and solid particle solar tower), and University of Nebraska and



groups 7 of the top 20 authors. In the second group, organizations such as DLR, Plataforma Solar de Almeria, and CIEMAT are represented by 5 of the top 20 authors. Between these two groups, 12 of the top 20 authors had cooperated actively. Another group, led by Dr. Wang from the Chinese Academy of Sciences, had some cooperation with other communities but not with such intensity as others. This can be explained because of Dr. Wang's role as government technical advisor for commercial CSP projects. Finally, a strong cooperation opportunity outstands with the community led by Dr. Covault, which shows no co-authorship with any other group, even though they have 11 of the top 100 authors in CSP field.

### Journal Bibliometric Study

The evolutions of the main journals in the CSP field are presented in **Figure 8** by number of publications. Journals and conference proceedings are included together in this analysis. Also, an h-index was calculated for the CSP field only. The Solar Energy journal had been leading by far for CSP publications during the last decade with the highest h-index of 55. Other journals such as Applied Energy, Energy Conversion and Management, and Energy had been increasing their publications during the last years, while Renewable Energy and Journal of Solar Energy Engineering had stagnated during more recent years.

Conference proceedings have shown to be of big relevance, especially Solar Paces Conference with a number of publications similar to Solar Energy journal. Nevertheless, the h-index is significantly low for conference proceedings compared to journals. This can be explained since the availability of conference proceedings is more limited compared to journal publications.

In **Table 6**, the top 20 journal and conference proceedings of the CSP performance ratio are presented, as well as impact factor and quartile score (only for journals). The performance ratio is obtained by dividing the number of CSP citations over the total

publications. Energy Policy journal has the better performance ratio followed closely by Renewable and Sustainable Energy Reviews journal, which was expected since it is a reviews journal. Applied Energy journal has the third better performance ratio, reflecting more relevance in their publications in the CSP field. Other journals such as Solar Energy, Energy, and International Journal of Hydrogen Energy, have a higher impact factor regardless of the fact that they are not leading on number of publications. This suggests a good quality on their content.

In **Figure 9**, journal citation relevance is showed graphically. This analysis was performed using the VOS Viewer<sup>®</sup> software tool. It can be appreciated that the Applied Energy journal has the higher citation relevance even with their small amount of publications. The Solar Energy journal is clearly the most relevant and influential in the CSP field. Also the importance of the Solar Paces conference is confirmed even though citations are low.

### Funding

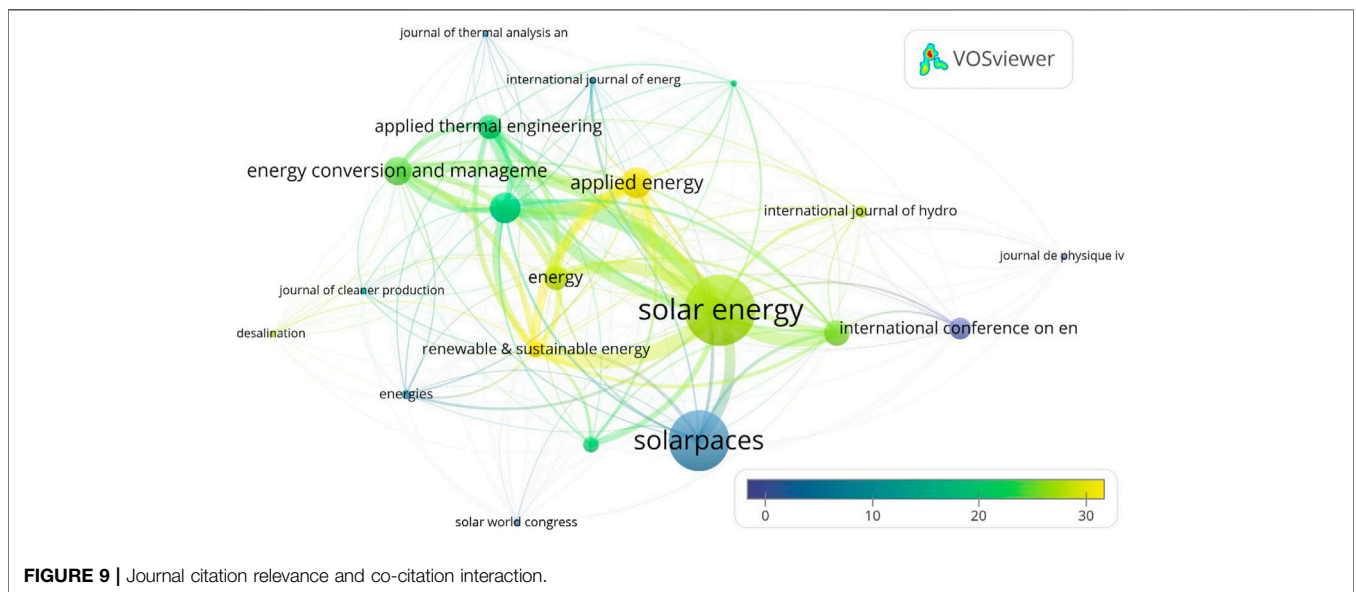
The funding achieved to perform research in the CSP field was properly reported over the last decade, therefore, this information is highlighted in **Figure 10**. Thereby, the relationship between the special funding and research publications is shown in this Figure. Half of the works regarding the CSP field mentioned any funding agent. United States, China, and the European Union countries have strong funding programs (by Department of Energy, EU Commission, and Chinese Academy of Sciences, respectively).

### Concentrating Solar Power Technology Bibliometric Evolution

CSP plants have several plant configurations. These are the following: parabolic trough, solar tower (Zhang et al., 2013), Stirling dish (Kaliakatsos et al., 2017), and Fresnel reflector (Baharoon et al., 2015) within others that are not considered to be in commercial or pilot scale as the open receiver curtain

**TABLE 6 |** Top 20 journals in CSP field.

Journal	CSP publications	Total CSP cites	Performance ratio	Impact factor	Quartile scores
Solar energy	823	21,442	26	4.608	Q2
SolarPaces	703	3,547	5	N/A	N/A
Applied energy	357	12,504	35	8.848	Q1
Renewable energy	357	6,861	19	6.274	Q1
Energy conversion and management	331	7,699	23	8.208	Q1
Journal of solar energy engineering	295	7,240	25	1.641	Q4
Applied thermal engineering	286	5,867	21	4.725	Q2
Energy	282	7,642	27	6.082	Q1
International conference on energy Sustainability	251	273	1	N/A	N/A
Solar energy materials and solar cells	190	3,865	20	6.984	Q1
Renewable and Sustainable energy reviews	183	11,171	61	12.11	Q1
International journal of Hydrogen energy	144	3,819	27	4.939	Q2
Energies	116	644	6	2.707	Q3
Solar world Congress	84	320	4	N/A	N/A
International journal of energy research	79	654	8	3.741	Q2
International journal of heat and Mass transfer	68	1,336	20	4.947	Q1
Desalination	47	1,229	26	7.098	Q1
Journal de Physique Iv	43	96	2	N/A	N/A
Journal of Cleaner production	42	524	12	7.246	Q1
Journal of thermal analysis and Calorimetry	36	211	6	2.731	Q2



**FIGURE 9 |** Journal citation relevance and co-citation interaction.

(Ho, 2017). All of these CSP configurations are analyzed in this section. **Figure 11** shows the number of publications in the CSP field divided by CSP configurations published over the last 2 decades. This is one of the most important parts of the bibliometric analyses shown in this study since elucidating the importance of each technology in the research field. Therefore, the most important to the least in order are as follows: parabolic trough, solar tower, Stirling dish, and Fresnel reflectors. However, it is well known that the most commercially installed configuration is the solar tower one (Fernández et al., 2019). Therefore, the publishing trend does not follow the market trend in this case.

The evolution of the papers is, in general, exponential but there are some peaks in recent years such as 2017 and 2014.

### Parabolic Trough

Parabolic trough configuration papers per year are presented in **Figure 12A**. These papers represent almost half of the total papers published in the CSP field when the CSP configuration is mentioned in the paper. The evolution is similar to the one shown in **Figure 11**, therefore, in general it follows an exponential growth pattern but there is a peak in 2014. Thereby, this trend is still growing after 20 years, becoming more and more highlighted during the last decade.

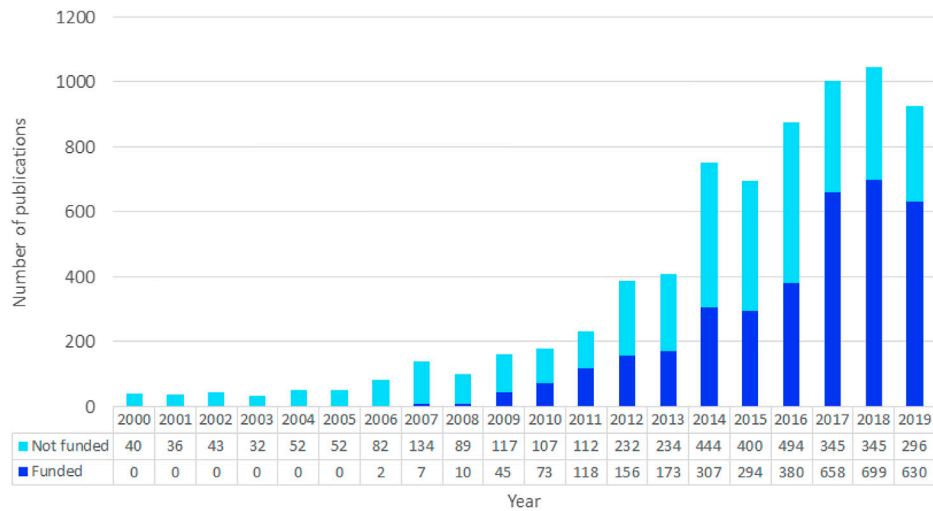


FIGURE 10 | Funding evolution for CSP publications.

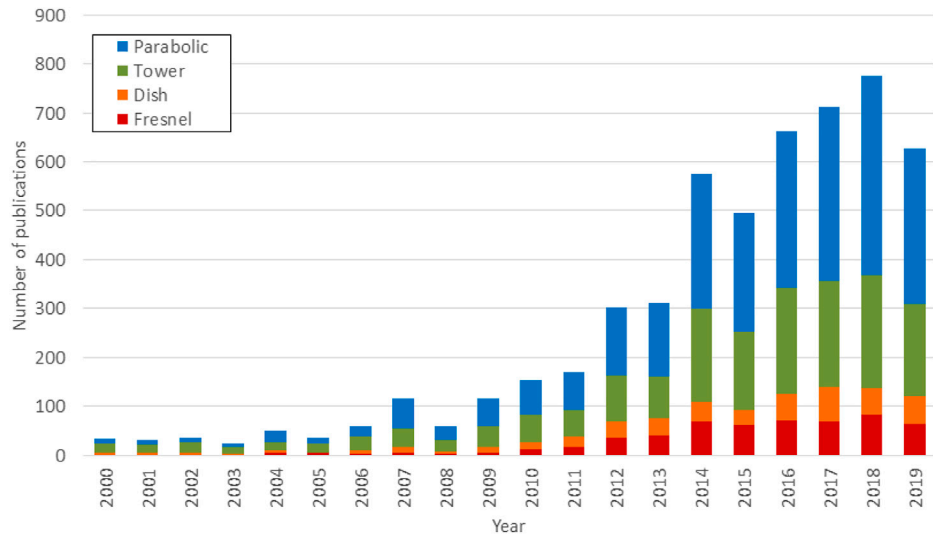


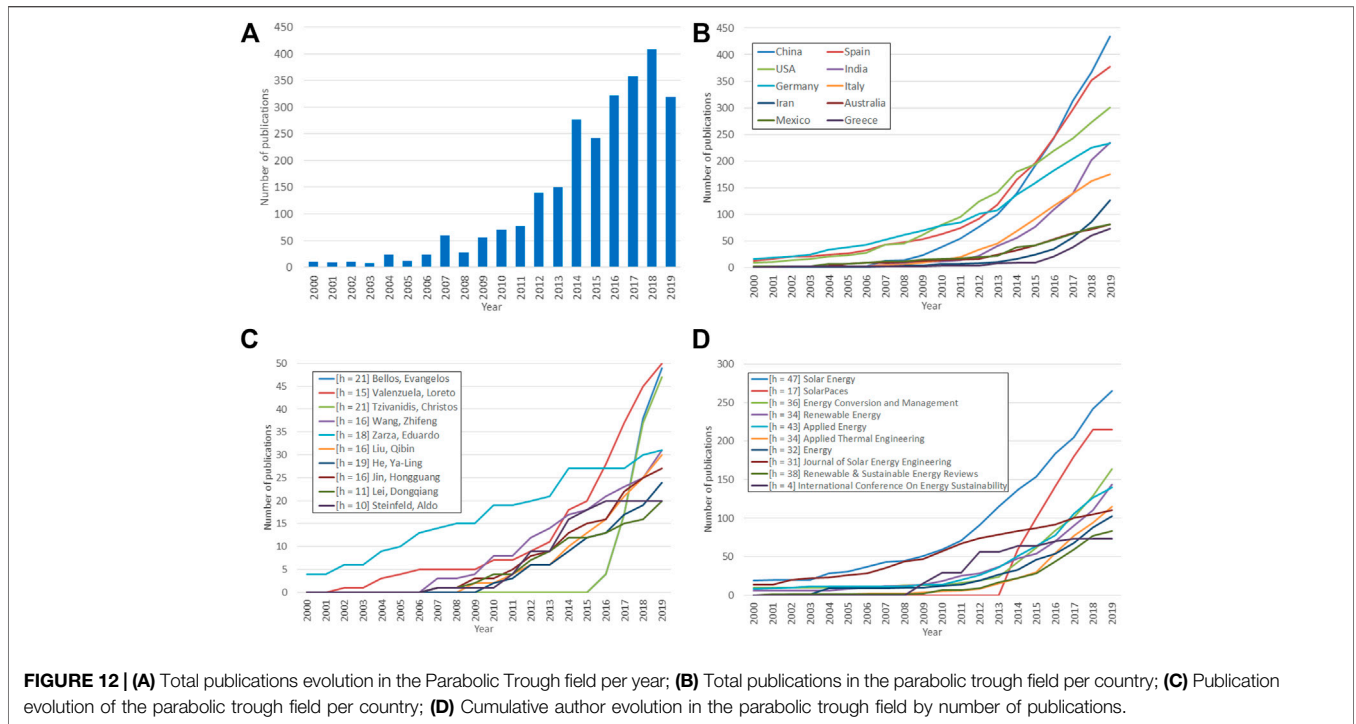
FIGURE 11 | Number of publications per year for each CSP technology.

Figure 12B presents the total parabolic trough configuration publications per country (top ten countries) and Table 7 lists all the data regarding this information for the top ten countries. Since, in 2015, the country publishing the most about parabolic trough CSP configuration was China, the increment of publishing is in agreement with the economic growth that China is performing in the last few years. Before this year, this position was occupied by Spain together with United States. Moreover, it is remarkable that countries as Algeria and Mexico are within the top 10 publishing countries in this field.

Figure 12C; Table 8 show the evolution of the last 20 years of the top 10 authors publishing papers regarding parabolic trough configuration in CSP plants. The author with the highest number of publications is Evangelos Bellos. Moreover, the h index was

calculated for each author in the parabolic trough CSP field and the h index of each author is also listed in Figure 12C.

Figure 12D presents the evolution of the published papers over the last 2 decades considering the journal where these papers were published and Table 9 summarizes this data. Thereby, the journal that has more publications about parabolic trough in CSP configuration is Solar Energy followed by the Solar Paces proceedings (<https://www.solarpaces-conference.org/home/>). This is very remarkable since a conference is the second largest publishing source in the field. That means that the conference is the most highlighted scenario related with this field and all people working on this field are presenting their works in it.



**FIGURE 12 | (A)** Total publications evolution in the Parabolic Trough field per year; **(B)** Total publications in the parabolic trough field per country; **(C)** Publication evolution of the parabolic trough field per country; **(D)** Cumulative author evolution in the parabolic trough field by number of publications.

**TABLE 7 |** Country increment of the parabolic trough field publications compared to the accumulated ones from the previous year.

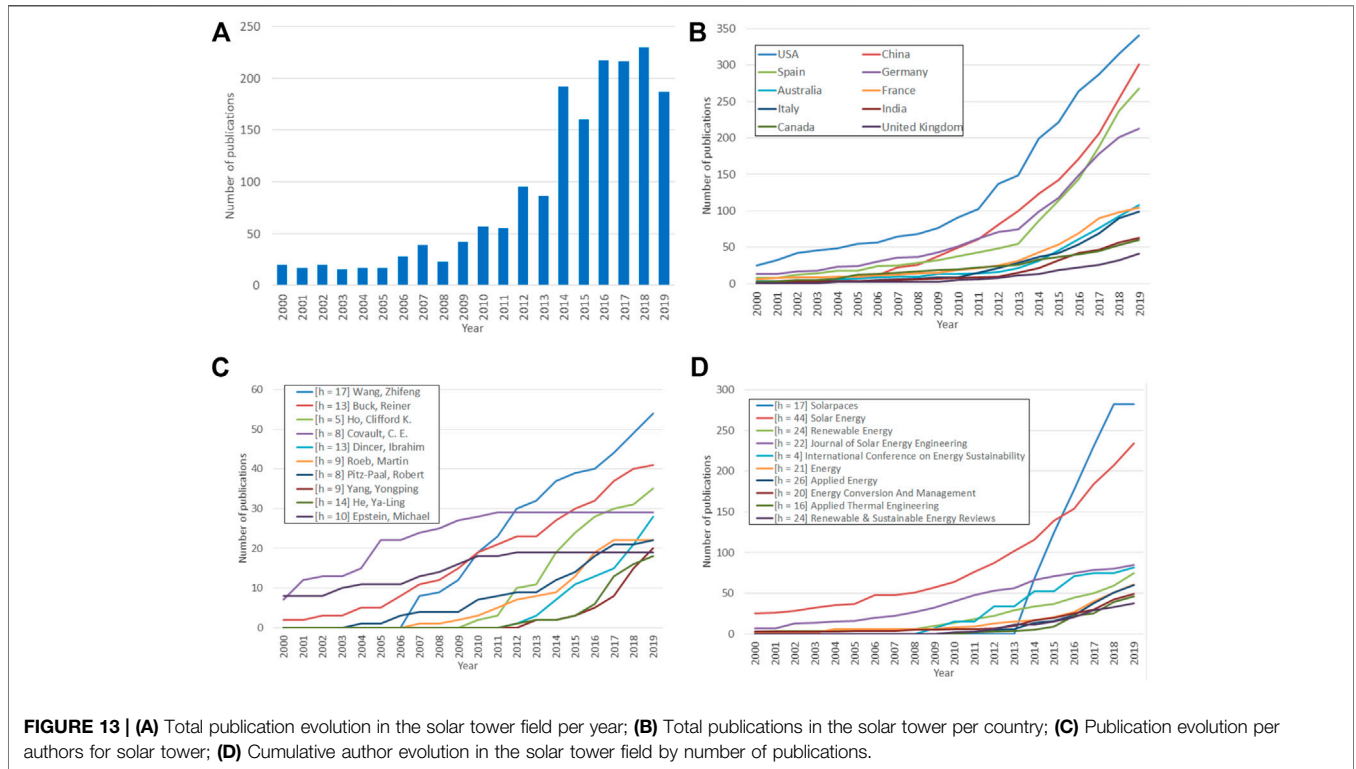
Country	2010 (%)	2011 (%)	2012 (%)	2013 (%)	2014 (%)	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)
China	69.6	41.0	40.0	29.9	39.0	38.1	26.6	28.8	17.3	18.3
Spain	16.7	19.0	22.7	28.3	39.8	18.8	24.5	21.7	18.5	7.1
USA	29.0	18.8	30.5	14.5	26.8	7.8	13.4	10.5	12.3	10.3
India	9.1	16.7	57.1	86.4	36.6	37.5	41.6	27.5	45.3	16.3
Germany	12.9	7.6	18.8	6.9	26.9	16.1	14.5	12.1	10.3	4.0
Italy	40.0	42.9	70.0	32.4	53.3	33.3	26.1	20.7	16.4	7.4
Iran	75.0	0.0	14.3	37.5	54.5	41.2	45.8	62.9	50.9	47.7
Australia	7.7	7.1	13.3	47.1	32.0	27.3	28.6	20.4	10.8	12.5
Mexico	6.7	12.5	11.1	10.0	72.7	10.5	26.2	20.8	17.2	8.0
Greece	33.3	0.0	0.0	100.0	12.5	11.1	110.0	81.0	57.9	21.7

**TABLE 8 |** Top 10 authors in the Parabolic Trough field.

Author	Affiliation	Parabolic publications	Total parabolic cites	CSP h-index
Bellos, Evangelos	National technical University of Athens. Greece	38	337	12
Tzivanidis, Christos	National technical University of Athens. Greece	36	327	12
Valenzuela, Loreto	Plataforma solar Almeria. Spain	35	808	10
Zarza, Eduardo	CIEMAT. Spain	25	1,663	16
Wang, Zhifeng	Hebei University of technology. China	24	340	12
Luepfert, Eckhard	German Aerospace Center (DLR). Germany	21	135	7
Steinfeld, Aldo	ETH Zurich. Switzerland	20	320	9
Pitz-Paal, Robert	German Aerospace Center (DLR). Germany	19	345	8
Eck, Markus	German Aerospace Center (DLR). Germany	19	610	9
He, Ya-Ling	Xian Jiaotong University. China	18	875	15

**TABLE 9 |** Top 10 journals or publishing sources for the parabolic trough field.

Journal	Parabolic publications	Total parabolic cites	Perf. Ratio	Impact factor	Quartile scores
Solar energy	189	4,662	25	4.374	Q1
Solarpaces Conference (Proceedings)	107	515	5	N/A	N/A
Energy conversion and management	106	1,834	17	6.377	Q1
Applied energy	102	3,264	32	7.9	Q1
Renewable energy	85	1,543	18	4.9	Q1
Applied thermal engineering	79	1,211	15	3.771	Q1
Journal of solar energy engineering	72	2,279	32	1.367	Q2
Energy	72	1,740	24	4.968	Q1
Renewable and sustainable energy reviews	67	3,758	56	9.184	Q1
Energy sustainability conference (Proceedings)	59	58	1	N/A	N/A



**Solar Tower**

In the case of solar tower configuration, the evolution over the last 2 decades is shown in **Figure 13A**. The trend is clearly exponential since 2018 where a decrement is shown. There is not a clear stagnation but the evolution needs to be followed in order to understand if it is changing or it is just an exception. Solar tower technology was expected to be the best CSP technology driver. However, problems in current commercial plants and the cost reduction of parabolic trough has slowed down solar tower growth. This also has consequences in the research output, leaving solid particle solar tower and thermochemical solar tower as the main research.

**Figure 13B** shows the total solar tower configuration papers by countries over the last 2 decades. The top 10 countries are represented and the evolution country in percentage per year is

listed in **Table 10**. China, Spain, United States, and Germany are publishing the most papers and their publishing trends have changed a lot since 2012.

**Figure 13C** shows the cumulative evolution of published papers over the last 20 years and again considering the top 10 authors. **Table 11** listed this information. The most published author is Dr. Wang followed by Dr. Buck and Dr. Ho. The h index of each author in the solar tower in CSP field is calculated and listed in this figure as well.

**Figure 13D** shows the journal evolution of publications in solar tower CSP configuration. The source publishing the most is Solar PACES conference followed by Solar Energy journal. Again, the Solar PACES conference is the most important scenario where authors present their papers related to solar tower in the CSP field.

**TABLE 10** | Country/region increment of solar tower publications compared to those accumulated from the previous year.

Country	2010 (%)	2011 (%)	2012 (%)	2013 (%)	2014 (%)	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)
United States	19.7	13.2	33.0	8.8	33.6	11.6	18.9	9.1	9.7	7.9
China	28.9	24.5	32.8	23.5	23.0	15.4	20.4	20.5	23.3	18.5
Spain	18.8	13.2	11.6	14.6	56.4	32.6	25.4	31.5	26.1	13.1
Germany	18.6	21.6	14.5	5.6	32.0	19.2	26.3	19.5	12.9	6.0
Australia	0.0	7.7	14.3	31.3	47.6	48.4	32.6	24.6	22.4	16.1
France	26.7	10.5	19.0	24.0	38.7	25.6	27.8	30.4	8.9	6.1
Italy	0.0	66.7	40.0	38.1	27.6	13.5	28.6	27.8	30.4	10.0
India	14.3	12.5	11.1	50.0	40.0	52.4	31.3	11.9	21.3	10.5
Canada	5.3	10.0	9.1	8.3	26.9	12.1	8.1	12.5	17.8	13.2
United Kingdom	150.0	20.0	33.3	37.5	18.2	46.2	15.8	18.2	23.1	28.1

**TABLE 11** | Top 10 authors in Solar Tower field.

Author	Affiliation	Total publications	Total cites	h-index
Wang, Zhifeng	Hebei University of technology. China	37	649	15
Buck, Reiner	German Aerospace Center (DLR). Germany	25	582	10
Ho, Clifford K	Sandia National Laboratory, Department of energy. United States	16	29	3
Kribus, Abraham	Tel Aviv University. Israel	14	192	6
Pitz-Paal, Robert	German Aerospace Center (DLR). Germany	12	238	6
Santana, Domingo	Universidad Carlos III de Madrid. Spain	11	87	5
Romero, Manuel	IMDEA energy Institute. Spain	11	329	6
Roeb, Martin	German Aerospace Center (DLR). Germany	10	149	6
Yang, Yongping	North China electric power University. China	10	46	4
Arancibia-Bulnes, Camilo A	Universidad Nacional Autonoma de Mexico. Mexico	10	40	4

**TABLE 12** | Top 10 journals in solar tower field.

Journal	Total publications	Total cites	Perf. Ratio	Impact factor	Quartile scores
Solarpaces conference (Proceedings)	137	333	2	N/A	N/A
Solar energy	118	2382	20	4.374	Q1
Journal of solar energy engineering	45	809	18	1.367	Q2
Renewable energy	37	831	22	4.9	Q1
Energy	30	414	14	4.968	Q1
Energy sustainability conference (Proceedings)	28	19	1	N/A	N/A
Applied energy	28	304	11	7.9	Q1
Renewable and sustainable energy reviews	23	1,215	53	9.184	Q1
Applied thermal engineering	20	379	19	3.771	Q1
Solar world congress (Proceedings)	18	26	1	N/A	N/A

The increment of the number of publications of solar tower compared to the total from previous years is presented in **Table 10**.

The most relevant authors in the solar tower CSP configuration field and their affiliations are listed in **Table 11** where the total publications, the total cites, and the h-index of these top 10 authors are also included.

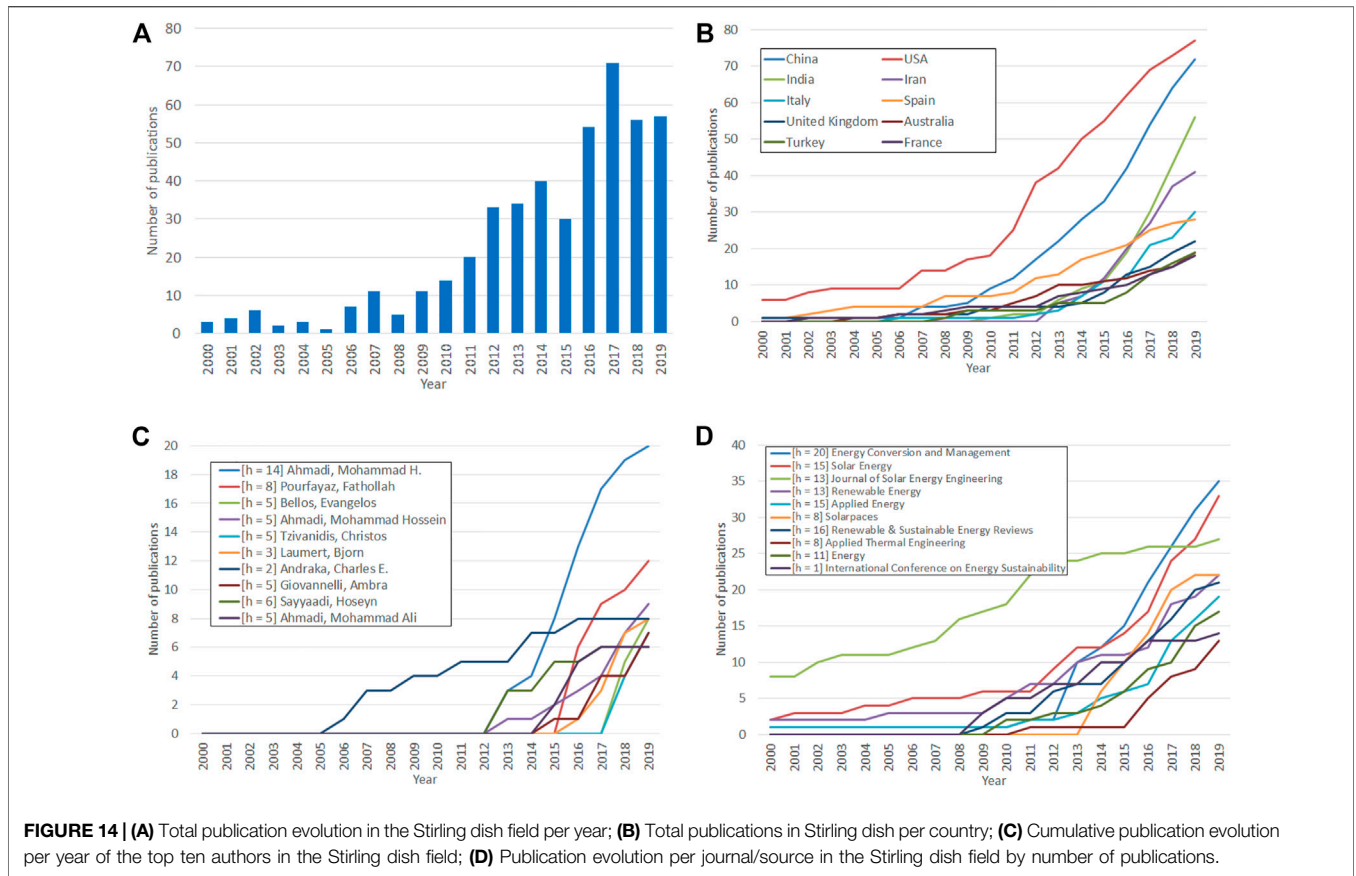
Finally, **Table 12** shows the most relevant journals in the solar tower topic along with the total publications per journal, the total citations, the performance ration, the impact factor of each journal, and the quartile scores.

### Stirling Dish

In the case of the Stirling dish, the evolution per year over the last 20 years is presented in **Figure 14A**. The trend is exponential until

2018 where a decrement is accounted. The trend needs to be studied in the next years in order to understand if it is an exception or if it is stagnation in the field. **Figure 14B** shows the total Stirling dish papers by country over the last 20 years. China, India, and Iran are standing out since 2014–2015. This is remarkable since before this period United States or Spain occupied these top positions. **Table 13** summarizes the country increment in the Stirling dish field over the last decade in percentages. **Figure 14C** shows publication evolution over the last 20 years by authors in the Stirling dish CSP field. The publication evolution was linear since Charles E. Andraka started detaching in 2005. However, the most significant standing up author is Mohammad Hossein Ahmadi that started in 2013 the scaling up until today. **Figure 14D** shows the most prolific publishing resources regarding the Stirling





**TABLE 13 |** Country/region increment of Stirling dish publications compared to those accumulated from the previous year.

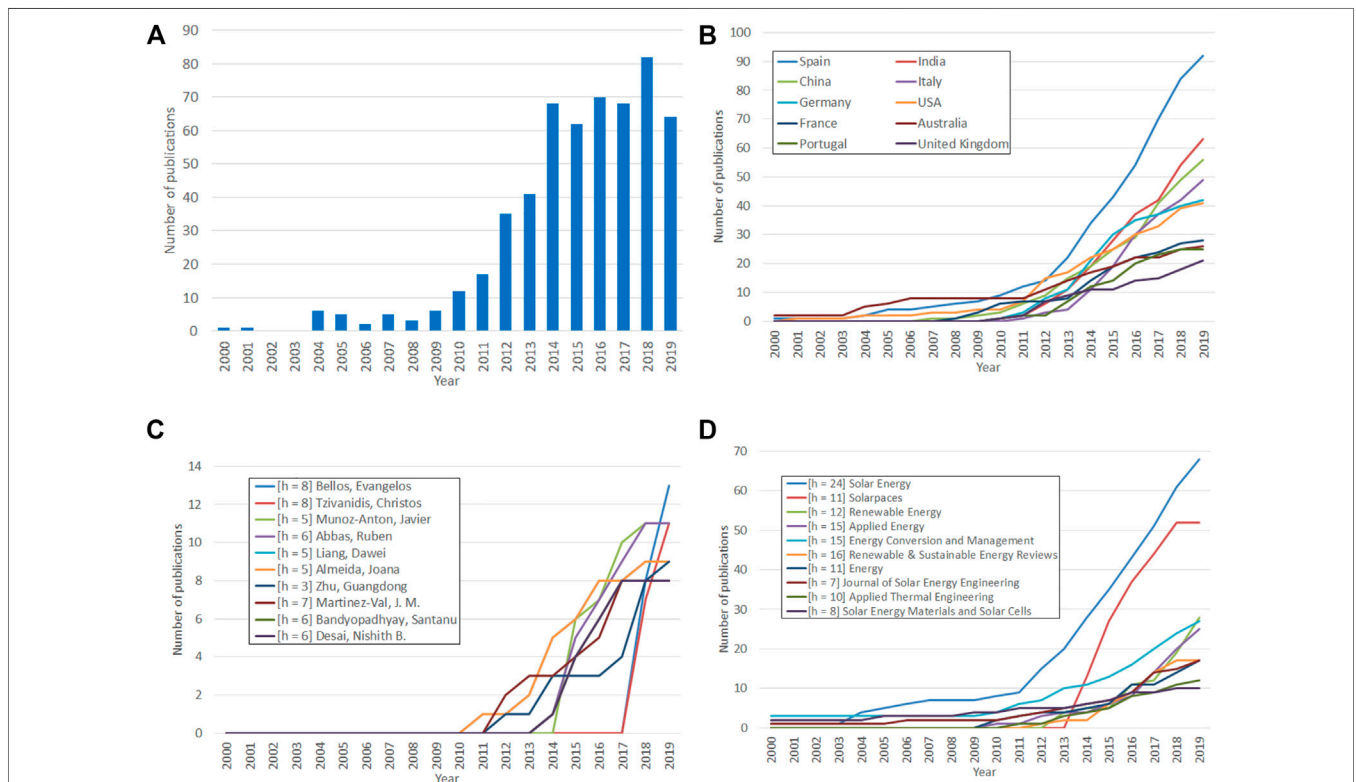
Country	2010	2011	2012	2013	2014	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)
China	80.0%	33.3%	41.7%	29.4%	27.3%	17.9	27.3	28.6	18.5	12.5
United States	5.9%	38.9%	52.0%	10.5%	19.0%	10.0	12.7	11.3	5.8	5.5
India	-	-	0.0%	-	50.0%	22.2	72.7	57.9	43.3	30.2
Iran	-	-	-	-	40.0%	71.4	66.7	35.0	37.0	10.8
Italy	0.0%	0.0%	-	50.0%	-	57.1	9.1	75.0	9.5	30.4
Spain	0.0%	14.3%	50.0%	8.3%	30.8%	11.8	10.5	19.0	8.0	3.7
United Kingdom	100.0%	0.0%	0.0%	0.0%	25.0%	60.0	62.5	15.4	26.7	15.8
Australia	0.0%	66.7%	40.0%	42.9%	0.0%	10.0	9.1	16.7	7.1	26.7
Turkey	0.0%	0.0%	0.0%	66.7%	0.0%	0.0	60.0	62.5	23.1	18.8
France	0.0%	0.0%	0.0%	75.0%	14.3%	12.5	11.1	30.0	15.4	20.0

**TABLE 14 |** Top 10 authors in Stirling Dish field.

Author	Affiliation	Dish publications	Total dish cites	Dish h-index
Ahmadi, Mohammad Hossein	University of Derby. United Kingdom	25	655	13
Pourfayaz, Fathollah	University of Tehran. Iran	10	185	7
Laumert, Bjorn	Royal Institute of technology. Sweden	8	31	3
Andraka, Charles E	Sandia National Laboratory, Department of energy. United states	7	28	2
Bellos, Evangelos	National technical University of Athens. Greece	7	27	3
Sayyaadi, Hoseyn	K. N. Toosi University of technology. Iran	6	284	6
Ahmadi, Mohammad Ali	Amirkabir University of technology. Iran	6	164	5
Tzivanidis, Christos	National technical University of Athens. Greece	5	17	2
Bidi, Mokhtar	Shahid Beheshti University. Iran	5	47	3
Wang, Fuqiang	Harbin Institute of technology, China	4	136	4

**TABLE 15 |** Top 10 journals in the Stirling Dish field.

Journal	Total publications	Total cites	Perf. Ratio	Impact factor	Quartile scores
Energy conversion and management	25	648	26	6.377	Q1
Journal of solar energy engineering	16	336	21	1.367	Q2
Renewable energy	14	230	16	4.9	Q1
Solarpaces conference (Proceedings)	13	56	4	N/A	N/A
Solar energy	12	168	14	4.374	Q1
Energy	11	149	14	4.968	Q1
Renewable and sustainable energy reviews	11	438	40	9.184	Q1
Applied thermal engineering	10	160	16	3.771	Q1
Applied energy	7	193	28	7.9	Q1
Energy sustainability conference (Proceedings)	6	2	0	N/A	N/A



**FIGURE 15 |** (A) Total publication evolution in the Fresnel reflector field per year; (B) Total publications in the Fresnel reflector field per country; (C) Cumulative publication evolution per authors of the top ten authors in the Fresnel reflector field; (D) Publication evolution per year of journals publishing in the Fresnel reflector field.

dish CSP configuration. Thesource publishing the most is the Energy Conversion and Management journal, since 2015. The second one again is Solar PACES proceedings followed by the Journal of Solar Energy Engineering.

The top 10 authors in the Stirling dish field are listed in Table 14. Moreover, the total publication of each author as well as the citations and calculated h-index for the Stirling dish field are also included in this table.

Table 15 lists the most relevant journals for the Stirling dish field. Moreover, this table includes the total publications per journal, the total citations of each journal, the performance ration, the impact factor, and the quartile of each journal.

### Fresnel Reflector

In the case of Fresnel reflector, the evolution per year since 1999 is presented in Figure 15A. The trend was clearly exponential until 2014 and a stagnation trend followed until 2017. This was mainly caused because the development and advantages of parabolic trough collectors. Nevertheless, in 2018, linear Fresnel gained interest for the process of steam generation.

Figure 15B shows the total number of publications per country over the last 20 years. It has shown a growth by China since 2011 in concordance with China’s gross domestic product (GDP) growth.

**TABLE 16** | Country/region increment of Fresnel publications compared to those accumulated from previous year.

Country	2010	2011	2012	2013	2014	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)
Spain	28.6%	33.3%	16.7%	57.1%	54.5%	26.5	25.6	29.6	20.0	9.5
India	-	-	-	83.3%	72.7%	47.4	32.1	13.5	28.6	16.7
China	50.0%	-	50.0%	66.7%	26.7%	31.6	16.0	41.4	19.5	14.3
Italy	-	-	-	33.3%	-	72.7	57.9	23.3	13.5	16.7
Germany	-	-	-	37.5%	90.9%	42.9	16.7	5.7	8.1	5.0
United States	0.0%	75.0%	-	13.3%	29.4%	13.6	20.0	10.0	18.2	5.1
France	100.0%	16.7%	0.0%	14.3%	75.0%	35.7	15.8	9.1	12.5	3.7
Australia	0.0%	0.0%	37.5%	27.3%	21.4%	11.8	15.8	0.0	13.6	4.0
Portugal	-	-	0.0%	-	71.4%	16.7	42.9	15.0	8.7	0.0
United Kingdom	-	-	-	28.6%	22.2%	0.0	27.3	7.1	20.0	16.7

**Figure 15C** shows the publication evolution over the last 20 years regarding the top 10 authors in the Fresnel reflector field. The most published author is Ruben Abbas who has an outstanding publication trend, followed by Jose M. Martínez-Val. The h-index of each author is also listed in this figure.

The journal publishing the most in the Fresnel reflector field is Solar Energy followed by Solar PACES proceeding. Solar Energy journal has an outstanding trend for the last 10 years. **Figure 15D** shows the journal publication evolution over the last 2 decades considering the h-index of each journal.

Increment of the publications in the Fresnel reflector field compared to the previous 10 years is presented in **Table 16**. The amount of publications are presented in percentages and the country publishing the most papers in 2018 was India, followed by Spain and the United Kingdom.

Leaders like the EU, China, or the United States 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.

The top ten authors in the Fresnel reflector field are listed in **Table 17** as well as their affiliations. The most published authors are from the Polytechnic University of Madrid, Spain. In addition, the total publication, the total citations, and the h-index of each author calculated in the Fresnel reflector field is also listed in **Table 17**.

**Table 18** shows the most relevant journals for the Fresnel reflector field along with their Fresnel reflector performance index, showing that the Solar Energy journal is the leader with a good performance. Nevertheless, Renewable and Sustainable Energy Reviews has the highest performance for non-review journals showing higher quality on their publications in Fresnel reflector. In addition, the total publication, the total citation, the performance ration, the impact factor of the journal as well as the quartile score are listed in **Table 18**.

## CONCLUSION

This CSP scientific research field bibliometric revision has studied almost 6,300 publications on relevant journals and conference proceedings. This is the first time a bibliometric study of CSP has been performed with current scope and detail.

This study presents the publication evolution in the CSP field over the last 2 decades. Several metrics were used to analyze regional efforts, relevant authors, author communities, relevant journals, keywords evolution, and funding effort effects on the research output. Different parameters were used to measure the grade of cooperation between countries/authors and the relevance of authors/journals (h-index and impact factor). Some of these metrics were applied also within the main four CSP technologies: parabolic trough, solar tower, Stirling dish, and linear Fresnel.

Regional analysis showed that China is becoming the most relevant country for CSP research. Nevertheless, the European Union still leads the development and will continue that way at least in the short term. Also, the United States have an important role in CSP development, as it has occurred in the past, in the

**TABLE 17** | Top 10 authors in the Fresnel field.

Author	Affiliation	Total publications	Total cites	h-index
Abbas, Ruben	Polytechnic University of Madrid. Spain	18	293	8
Martinez-Val, Jose M	Polytechnic University of Madrid. Spain	13	257	8
Munoz-Anton, Javier	Polytechnic University of Madrid. Spain	8	56	3
Desai, Nishith B	Pandit Deendayal Petroleum University. India	7	104	5
Bandyopadhyay, Santanu	Indian Institute of technology (IIT)-Bombay. India	7	107	5
Bellos, Evangelos	National technical University of Athens. Greece	7	19	2
Kedare, Shireesh B	Indian Institute of technology (IIT)-Bombay. India	6	82	5
Singh, Suneet	Indian Institute of technology (IIT)-Bombay. India	6	76	5
Dai, Yanjun	Shanghai Jiao Tong University. China	6	92	3
Reddy, K. S	Indian Institute of technology (IIT)-Madras. India	6	50	3

**TABLE 18** | Top 10 journals in the Fresnel field.

Journal	Total publications	Total cites	Perf. Ratio	Impact factor	Quartile scores
Solar energy	42	929	22	4.374	Q1
Solarpaces conference (Proceedings)	18	96	5	N/A	N/A
Applied energy	16	351	22	7.9	Q1
Energy conversion and management	16	319	20	6.377	Q1
Renewable energy	14	117	8	4.9	Q1
Journal of solar energy engineering	11	103	9	1.367	Q2
Applied thermal engineering	10	245	25	3.771	Q1
Energy	10	187	19	4.968	Q1
Renewable and sustainable energy reviews	9	310	34	9.184	Q1
Solar world congress (Proceedings)	7	24	3	N/A	N/A

foreseen future. Due to their energy needs it is expected that China and India will become the main boosters for CSP development for the years to come. The main interest in CSP research development is expected to continue more vigorously in regions with good solar resources.

A research communities study allowed the identification of cooperation opportunities. Also, cooperation between regional and research communities is in line with known cooperation agreements between countries and institutions. Author analysis helped to identify individual CSP research stakeholders. However, each author should be considered individually, since several institutions add center managers into the author lists. This is actually not a negative issue, since usually these managers are important technology stakeholders, but it gets mixed with the technological and technical experts. Authors keyword evolution analysis has been useful as an indirect measure of technological maturity. China and India driven research communities can be expected to gain relevance during the following years due to the increase in scientific output in recent years.

Main journals and conferences were identified and contrasted. It was found that conference proceedings have an important effect in the overall CSP publications. However, the journal publications used to have more impact since they were more frequently cited. High quality journals (mainly Q1 and Q2) specializing in renewable energy, solar energy, and energy engineering and applications are expected to continue leading CSP research publications.

Funding analysis had shown a direct relationship between funding and research output. This first approach could help to

make deeper analysis in the future to measure the effectiveness by country or by funding agency.

Inside the CSP field, parabolic trough has shown to have great relevance in the research output. This also has been reflected in the cost reductions achieved by this technology. Solar tower technology is under constant research evolution. Nevertheless, it needs to be optimized to compete with parabolic trough, as well to solve current technical difficulties. New approaches on this technology like the solid particle solar tower are currently under very active research activity. Finally, Stirling dish and linear Fresnel are still emerging within the CSP research field with an accelerated research output. These results are coherent with CSP scalability, since utility size power generation from CSP are the ones expected to grow. Parabolic trough and solar tower have shown viability in utility-scale power plants and its research is related to increasing its performance and TES and HTF materials for increasing service temperature and energy density.

It can be expected that in the following decades CSP research development will boost green energy transition by making utility-scale power more competitive and viable, especially for the countries with more solar resources.

## AUTHOR CONTRIBUTIONS

AC created the data base where all the information required from the papers in the literature. In addition, he developed the software and produced the first files. He led the writing of the original draft of this

paper. CB improved the information of the files and graphs this paper has and produce the information collected in this paper as well as help to write specific parts of the paper and the conclusions section. She revised the draft to improve it, and writing review and editing of the final manuscript. IF organizes the data to be included, supervised the paper, and did the project administration and funding acquisition. CP did the validation of the data collected in this paper from the industrial point of view and conceptualization of the information stated in this paper. MS organizes all the information required to produce the files. In addition, she supervised the work produced in this paper and did a data curation in order to improve the quality of this paper.

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## SUPPLEMENTARY MATERIAL

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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