Bibliometric analysis on supercritical CO_2 power cycles for Concentrating Solar Power applications

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Abstract: Over the last few years, supercritical CO_2 power cycles have received a massive interest due to the exceptional but theoretical conversion efficiency above 50% that is leading a revolution in power cycles research. High efficiency can be achieved at a moderated temperature level that suits well with concentrating solar power (CSP) applications that it is seen as one of the core businesses within supercritical technologies. In that context, hundreds of publications have recently appeared what requires a thorough analysis to detect research areas of interest and who are the main actors in this field. In this work, a bibliometric analysis on supercritical CO_2 for CSP applications has been performed considering all indexed publications in the Web of Science between 1990 and 2020. Main research actors and areas of interest have been discussed through networking mapping and text mining techniques. Results found are compared to the most recent research projects and programs on sCO_2 for CSP applications.

Keywords: sCO_2; supercritical CO_2; supercritical fluids; CSP; concentrating solar power; solar energy; power cycles; bibliometric; scientometrics

1. Introduction

The use of supercritical carbon dioxide (sCO_2) as a working fluid in electricity generation systems, based on fossil fuel, nuclear power or Concentrating Solar Power (CSP), offers several advantages compared to other conventional schemes. For nuclear or fossil energy, sCO_2 is employed in the power cycle, yielding to different supercritical Brayton layouts; in the case of CSP, sCO_2 can perform as the working fluid in the power block, the heat transfer fluid (HTF) in the solar field, or/and even in the thermal storage system. Because of that, this introduction analyses all these possibilities, as well as their integration in different schemes of Solar Thermal Power Plants (STPPs).

According to IRENA, the total global installed power of CSP has increased from 2010 to the present, also achieving a reduction in the levelized cost of electricity (LCoE) from 0.346 USD/kWh_e to 0.182 USD/kWh_e [1]. Nevertheless, this cost is still far away from the goal of 0.06 USD/kWh_e established by the SunShot Initiative of the US Department of Energy (DOE) [2]. In addition, it is important to note that the LCoE drop during the last decade has been mainly motivated by a reduction in solar field cost (that represents 40% of the STPP investment cost), due to a greater economy of scale. Although the LCoE can be reduced by lowering costs, there is a second approach to make CSP competitive: increasing the global thermal performance of the STPPs. This is the pathway established by the Gen3 CSP Roadmap [3], and in this line, the use of sCO_2 is a key element.

In the following sections, the state-of-art of the different subsystems of the STPP, employing sCO_2, is introduced. First, the sCO_2 cycles layouts that best integrated into CSP are described; second, a review on solar receivers employing sCO_2 is presented; and finally, the third part analyzes different integration schemes, as well as some proposals of thermal storage systems employed in these schemes.

1.1. Supercritical CO_2 Brayton cycles

Supercritical CO_2 cycles, following a closed recompression layout, present thermal efficiency higher than those of superheated or supercritical steam Rankine cycles, at the working temperature range of STPPs. This high efficiency is achieved thanks to the thermophysical properties of sCO_2 in the region near to the supercritical point (7.38 MPa, 31 °C); the sCO_2 density close and above the critical pressure is high, so the compressor power is reduced [4]; this involves that the turbine inlet temperature is also reduced for the same thermal efficiency; so efficiencies of 40% and above 50% are achieved for turbine inlet temperatures of 500 °C and 700 °C, respectively [5,6].

Besides that, sCO_2 cycles exhibit other technological advantages compared to conventional steam Rankine cycles: the size of turbomachinery, operating near the critical point, is smaller, which implies good operational flexibility and the possibility of a lower LCoE; and the sCO_2 is less corrosive than steam at high temperature. There are also significant drawbacks, including the development of components that withstand the demanding working conditions of supercritical cycles. In this sense, a key element is the primary heat exchanger, when the coupling between the solar field and the power cycle is indirect.

These sCO_2 cycles have been mainly developed for nuclear applications. The research on sCO_2 layouts integrated into STPPs is relatively recent. Turchi et al. [7] present a scheme of supercritical STPP based on modular towers and a conventional recompression supercritical layout; from the point of view of the power cycle, this configuration does not present new features, although it will be discussed in the last section of this introduction since it presents a complete integration scheme in a supercritical plant. In a later work, Neises and Turchi [8] analyses in deep the partial cooling and the recompression configurations, concluding that the partial cooling configuration offers important advantages for CSP applications, like a large temperature difference in the primary heat exchanger; this implies a smaller size of the solar receiver and higher efficiency, by reducing the average working temperature. At last, in [9], the efficiency of the sCO_2 power turbine and associated turbomachinery at the scale of operational CSP projects is assessed, to promote this new technology at a commercial level.

A few years later, two important review works were published. In [10], a general evaluation of sCO_2 cycles for power generation is presented. Wang et al. [11] identified and analysed 6 possible supercritical layouts that can be indirectly coupled to a central receiver working with molten salts: simple recovery cycle; recompression cycle; precompression cycle; intercooling cycle; partial-cooling cycle; and split expansion cycle. This analysis identifies different parameters for the comparison, highlighting the thermal efficiency; the complexity of the cycle. Compared to the simplest one, the recompression cycle; and the temperature difference of the sCO_2 in the primary heat exchanger which, as seen above, determines the molten salt temperatures and can yield to lower investment in the coupled solar subsystem. This study concludes that there is not any layout better than others. The choice of one or the other depends on the specific operating and ambient conditions, and it should account for the annual performance of the STPP.

A later work of NREL [12] analyses two sCO_2 cycles: the recompression and partial-cooling, based on the global performance of the STPP. They conclude that the partial-cooling cycle presents lower investment costs and generates more net electricity, because of the larger temperature difference in the primary heat exchanger.

To finalize this section, it is important to point out that one of the key elements for the feasibility of this technology is the design of the primary heat exchanger between the solar field and the power block, as the fluids are not the same in general (indirect integration scheme). This is the case of a molten salt central receiver coupled to a sCO_2 layout. There are several designs proposed in the literature for molten salts-to-CO_2 heat exchangers, for both nuclear and CSP applications [13–16]; the simplest one would be the Shell and Tube Heat Exchanger (STHX), in which the molten salt flows through the shell, while the sCO_2 circulates through the tubes. For this type of heat exchanger, a new sCO_2 layout is proposed in [17], in which the primary thermal energy is supplied through the low-pressure side of the layout, downstream of the turbine (85 bar approximately).

1.2. Supercritical CO_2 solar receivers

As in the case of the supercritical CO_2 cycles for CSP, the research on sCO_2 solar receivers is relatively new, although there seems to be a growing interest nowadays. The review presented in this section is focused on sCO_2 solar Central Receivers (CRs). These are the solar receivers that better suit the high pressure of the sCO_2. As said in [7], the high pressure required for sCO_2 makes application to Parabolic Trough (PT) fields difficult, although there are some theoretical studies about it [18].

One previous and interesting study is the review on Compact Heat Exchanger (CHE) structures and the possibility of integrating them in pressurized solar receivers [19]. Although the authors claim that their work could be the starting point for further research, only a few studies are based on their conclusions, as exposed below.

One of the first supercritical CO_2 central receivers proposed is based on the external tubular receiver concept [20,21]. This design is intended to heat the air to 800 °C with a pressure of 5 – 7 bar, but the possibility of adapting this receiver to be directly coupled to a sCO_2 cycle working at 200 bar and 700 °C is considered. In this case, it would be necessary additional requirements to withstand the high pressure and temperature and to enhance the heat transfer to the supercritical phase.

In the study presented in [22], the CHE concept is used in a 3 MW_{th} cavity receiver for sCO_2. This receiver consists of several plates joined by diffusion, with rectangular fins between them, in such a way that square-shaped channels are formed. The optimal geometry of this CHE structure has been selected by an optimization process, explained in the same work.

Another interesting configuration is proposed in [23]. In this case, there is an intermediate fluid, pressurized air, which directly receives the radiation impinging a cavity receiver provided with a quartz window and a porous structure. This working fluid transfers its thermal energy to the sCO_2 that circulates through ducts embedded in the porous matrix itself.

At last, there is a recent and very interesting work by the National Renewable Energy Laboratory (NREL), which presents two concepts for sCO_2 central receiver designs [24]. The first one is a cavity receiver for a 2 MW_e power cycle, and the second one is a surround external receiver for 10 MW_e. For both designs, the sCO_2 circulates through a compact structure consisted of two attached plates with a wavy fin structure between them; these plates act as the absorber surfaces of the concentrated solar radiation. The main difference is that the absorber plates are arranged to form a cavity, in the first case, while they are arranged to form an external cylindrical receiver in the second one. As radiation losses would be very high in this last case, a radiation trap has been designed; this design consists of small quartz cylinders, perpendicular to the wall, which reduce radiation and convection losses. In this way, the receiver thermal efficiency remains high (80%) when working at temperatures of the order of 750 °C. For both designs, the objective of 0.06 USD/kWh_e established by the SunShot Initiative is attained.

1.3. Integration schemes and thermal storage systems in sCO_2 STPPs

Most of the supercritical STPP layouts presents an indirect coupling because the HTF in the solar field and the working fluid in the power cycle are different. This is the configuration selected by the above mentioned Gen3 CSP Roadmap [3], in which the power cycle is a sCO_2 cycle, and three different schemes are defined, depending on the HTF in the central receiver: molten salt, particles or gas. In all these schemes, it is necessary to incorporate a primary heat exchanger between both subsystems. As said in section 1.3, the design of this heat exchanger is a key issue for the technological feasibility of these plants, and several proposals are found in the literature, for both falling particles-to-sCO_2 and molten salt-to-sCO_2 [15,16,25].

The molten salt receiver scheme coupled to a sCO_2 cycle is the most conventional one, and there are several works in the literature about this configuration. In this scheme, the molten salts also perform as the thermal storage fluid, and the proposed configuration is usually a direct two-tank TES, although a thermocline could be also an option [11,16,26]. To achieve the objectives of the SunShot program, it is necessary to work at a higher temperature, compared to already commercial STPPs; the HTF temperature at the outlet of the solar receiver should be about 700 °C, which also implies the use of advanced ternary salts [27].

Regarding the pressurized air receiver coupled to a sCO_2 cycle, it is interesting to highlight the works of Li et al. [28] and Trevisan et al. [29]. A design and simulation model of a sensible-packed bed thermocline (PBT) for pressurized air is proposed in both works.

The STPP based on a particle receiver coupled to a sCO_2 cycle presents very few works in technical literature, although a global integration scheme is presented in [3,21], and there are several models developed for the falling particle receiver [30], the thermal storage system in particles [31] and the primary heat exchanger between the solar field and the power block [25].

Besides the schemes cited in Gen3 CSP Roadmap [3], there is another scheme integrated by a liquid metal solar receiver coupled to a sCO_2 cycle. This configuration is analyzed in [32], considering a tubular sodium receiver, a high-temperature Phase-Change Material (PCM) storage system, and a sCO_2 power block.

To finish this section, it is necessary to expose the direct integration schemes between the solar field and the power block, employing sCO_2 as the HTF / working fluid in both systems. Turchi et al. [7] present a scheme of supercritical STPP based on modular towers. Each modular tower is provided by its sCO_2 power block and, because of the turbine/compressor compactness, it is possible to allocate them in the tower; as a result, the piping is reduced, thus also pressure and heat loss, and the transient response is improved.

Although most of these direct integration schemes are intended to be coupled to indirect thermal storage in molten salts [7], some studies propose a direct coupling using a thermocline system. In this way, Kelly et al. [33] present a thermocline system based on a matrix of individual vessels of reduced dimensions to avoid a great wall thickness. A more theoretical model of the charge/discharge operation is presented in [34].

To summarize this introduction, the use of sCO_2 in CSP is a recent but very promising investigation, which is currently supported by several research programs. In this way, the number of research lines and new proposals has grown exponentially in recent years, always looking for more efficient and competitive STPPs. That makes challenging the process of reviewing the existing literature on supercritical CO_2 power cycles for CSP applications and it is where bibliometrics tools can shed some light regarding who are the main actors in the topic, the way they are connected, or what are the main research trends [35]. Table 1 gathers similar bibliometric analyses related to power cycle technologies and concentrating solar power applications. As it can be observed, a couple of bibliometric research works have been recently published about supercritical CO_2 power cycles [36,37]. However, both works covered the topic from a general perspective rather than analyzing the potential of that technology coupled to concentrating solar power applications. As it can be noted most of the existing bibliometric studies covered whether power cycle literature or solar energy topics but not the combined application of both technologies.

Table 1. Related bibliometric analysis publications

Author	Manuscript title	Data Source	Year	Ref
Sultan, U. et al.	Qualitative assessment and global mapping of supercritical CO_2 power cycle technology	Scopus & Web of Science	2021	[36]
Yu, A. et al.	Recent trends of supercritical CO_2 Brayton cycle: Bibliometric analysis and research review	Scopus	2021	[37]
Reyes-Belmonte, M.A.	A Bibliometric Study on Integrated Solar Combined Cycles (ISCC), Trends and Future Based on Data Analytics Tools	Web of Science	2020	[38]
Calderon, A. et al.	Where is Thermal Energy Storage (TES) research going? – A bibliometric analysis	Web of Science	2020	[39]
David, T.M. et al.	Future research tendencies for solar energy management using a bibliometric analysis, 2000–2019	Scopus	2020	[40]
Saikia, K. et al.	A bibliometric analysis of trends in solar cooling technology	Web of Science	2019	[41]
Islam, M. et al.	A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends	Web of Science	2018	[42]
Imran, M. et al.	Recent research trends in organic Rankine cycle technology: A bibliometric approach	Scopus	2018	[43]
Paulo, A.F. et al.	Solar energy technologies and open innovation: A study based on bibliometric and social network analysis Alex	Web of Science	2017	[44]
Du, H. et al.	A bibliographic analysis of recent solar energy literatures: The expansion and evolution of a research field	Web of Science	2014	[45]
Dong, B. et al.	A bibliometric analysis of solar power research from 1991 to 2010	Web of Science	2012	[46]

In this paper, a bibliometric analysis is conducted on the existing literature about sCO_2 power cycles for CSP applications. In section 2, the working methodology is presented along with the publishing evolution. In section 3, several bibliometric indicators are investigated; who are the main contributors in the research field (authors, countries and organizations), those connections and publishing evolution. In section 4, text mining techniques are applied to identify research trends while project discussion is referred to in section 5 to connect current research trends and future topics for sCO_2 in CSP.

2. Materials and Methods

Table 2 summarizes the number of supercritical CO_2 related publications that can be retrieved attending to different question queries and consulted databases. Both Web of Science (WOS) and Scopus databases were consulted attending to topic field search. Publications including the question query whether at publication title, abstract, keywords or KeywordPlus® were retrieved. To account for most publications within the field, different expressions and search combinations were considered and the logical operator "or" was introduced to combine all of them what resulted in the total corpus data of the study. As it can be noticed, the number of sCO_2 power cycles indexed publications that also included the keyword "solar" was similar among Web of Science (441 publications) and Scopus (468) databases. In both cases, those publications accounted for one-third of total sCO_2 power cycles publications what indicates the relevance of CSP applications within sCO_2 technologies.

Table 2. Question query used for corpus data collection (1990 – 2020)

Question query	solar sCO_2		sCO_2	
	WOS	Scopus	WOS	Scopus
s-CO_2 power cycle	113	124	357	409
Supercritical CO_2 power cycle	373	341	1294	1295
Supercritical carbon dioxide power cycle	269	402	871	1441
sCO_2 power cycle	29	152	113	421
Total corpus data	441	468	1509	1710

The data set retrieved from the Web of Science (WOS) was preferred as it is claimed to contain journals with higher impact [47] and no previous studies were covering sCO_2 power cycles using this database [36,37]. Under that assumption, corpus data was formed of 441 WOS indexed publications whose metadata (including full record and cited references) were exported for processing and networking mapping visualization using VOSviewer software [48,49].

Figure 1 shows the publishing evolution of sCO_2 power cycle publications (sCO_2) between 1990 and 2020 according to the WOS. As it can be noticed, the first WOS sCO_2 power cycle indexed publication goes back to 1993 but the first one related to CSP applications appeared in 2005. Since then, the relevance of sCO_2 solar-related publications has kept growing and it accounts already for one-third of the annual sCO_2 publications. As it can be noted, 70% of the total number of publications have been published after 2015. It can also be noted that the ratio between sCO_2-CSP and sCO_2 publications is around 30% with a slight decrease during 2020 when sCO_2 publications achieved their maximum despite the decrease of sCO_2-CSP related publications compared to 2019.

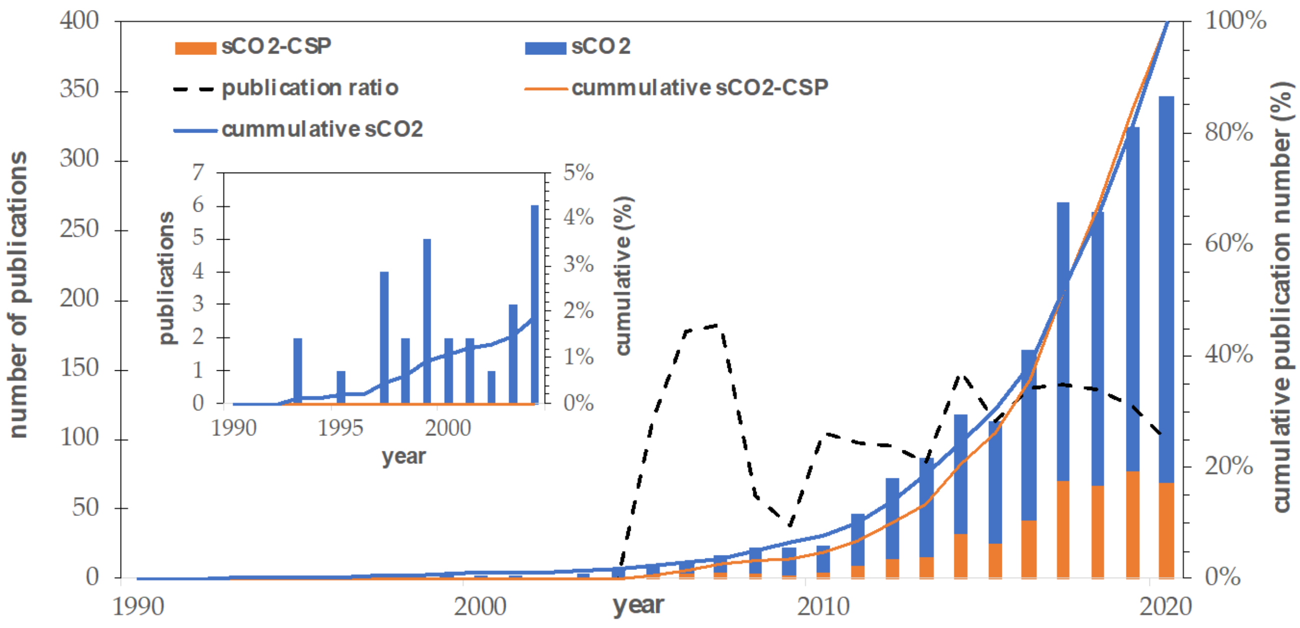

Figure 1. Publication evolution in sCO_2 for CSP and sCO_2

In terms of the number of citations, the contribution of sCO_2-CSP related publications is slightly higher compared to the publication ratio shown in Figure 1 as it accounts for almost 40% of the total citations what indicates the growing relevance of CSP applications for sCO_2 technologies. It can also be observed that 80% of sCO_2 power cycle citations have been received after 2016.

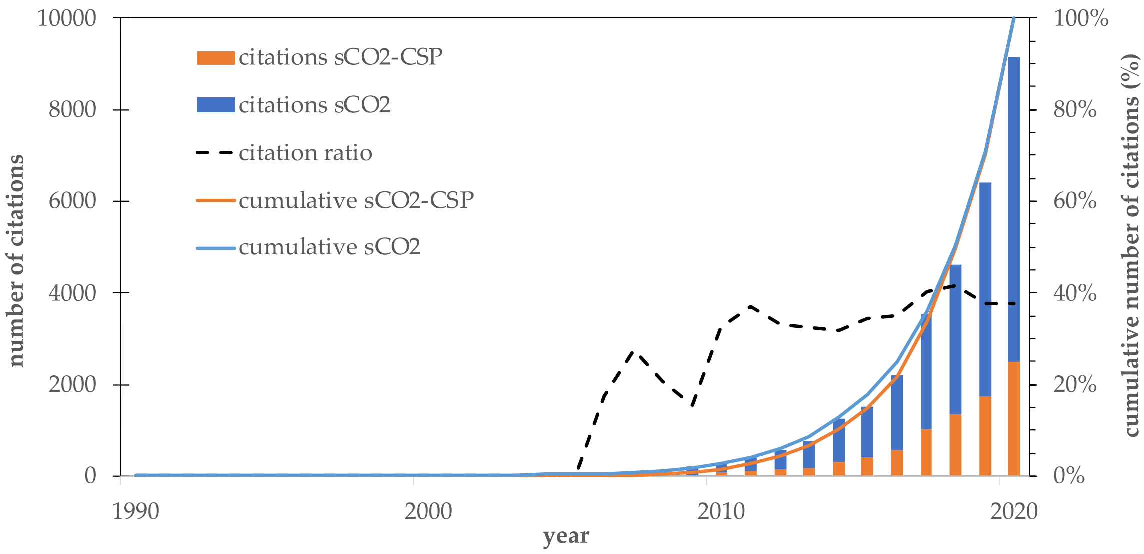

Figure 2. Citations' evolution in general sCO_2 publications and for CSP applications

3. Results

In this section, several bibliometric indicators are presented and discussed to analyze the main actors in sCO_2 research with a focus on CSP applications and to shed some light on technology trends.

3.1. Main publishing countries

As it can be observed in Figure 3, the most productive countries in terms of WOS indexed publications are the United States and China that both together account for 43% of all sCO_2-CSP documents.

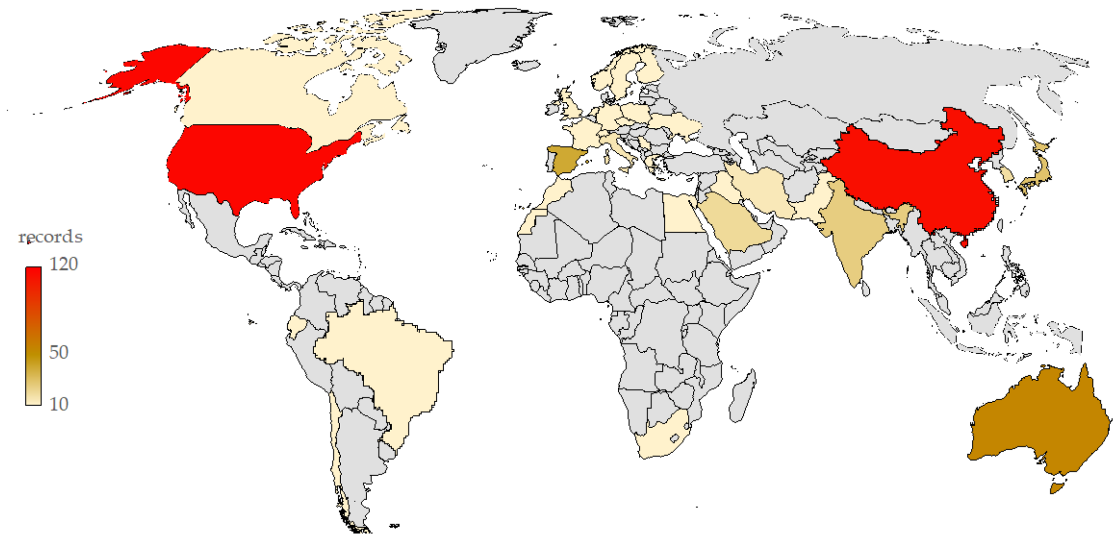

Figure 3. Publishing distribution in sCO_2 for CSP applications topic (accumulative distribution until 2020)

As it can be read in Table 3, the 10 most productive countries in sCO_2-CSP account for 82.6 % of publications in cumulative terms. A closer look at the scientific production of the year 2020 indicates a clear growth in Chinese and Spanish publications and the cumulative production of the 10 most productive countries slightly increased up to 86.5% of the annual publications.

Table 3. Worldwide publishing distribution in sCO_2 for CSP applications topic

Rank	1990 – 2019	2020

	Country	Number of publications	% of publi-cations	Country	Number of publica-tions	% of pub-lications
1	United States	117	21.7 %	China	31	34.8 %
2	China	113	20.9 %	Spain	11	12.4 %
3	Australia	55	10.2 %	United States	9	10.1 %
4	Spain	40	7.4 %	Australia	5	5.6 %
5	Japan	29	5.4 %	United King-dom	5	5.6 %
6	India	25	4.6 %	Iran	4	4.5 %
7	Saudi Arabia	29	3.7 %	Turkey	4	4.5 %
8	South Korea	18	3.3 %	Germany	3	3.4 %
9	Italy	15	2.8 %	India	3	3.4 %
10	Iran	14	2.6 %	Italy	2	2.2 %
	Total		82.6%	*Total*		86.5 %

Figure 4 shows a clearer picture regarding the most productive countries in terms of publishing evolution. As it can be observed, Chinese production has grown quickly over the last 3 years while the Japanese production has gradually been reduced even though it was the most productive country before 2010. It can also be observed the growing relevance of Italy, Iran and Saudi Arabia in recent years.

Figure 4. Publishing evolution of the most productive countries

3.2. *Main publishing institutions*

Table 4 shows the most productive organizations regarding the number of indexed publications on sCO_2 power cycles for concentrating solar power applications. Research institutions are ranked according to the number of publications. The number of authors that have published in sCO_2-CSP topic under the organization affiliation is reported as well as the accumulated number of citations (including self-citations). The publishing ratio (PC ratio) is determined as the ratio between the number of citations and publications for a given organization. The h-index of the institution is also provided considering only the number of publications and citations for the analyzed topic [50]. As it can be noted, the ten most productive organizations fit most productive countries with a clear dominance of United States having four institutions in the top 10 rankings (United States Department of Energy, Sandia National Laboratory, National Renewable Energy

Laboratory and State University System of Florida). Regarding the number of citations received to the total publications, the higher PC ratios are found for Xi’an Jiaotong University (China) and Doshisha University (Japan).

Table 4. Most productive organizations in sCO_2 - CSP related publications

rank	Organization	Country	Number of publications	Number of authors	Number of citations	PC ratio	h-index
1	United States Department of Energy DOE	United States	54	128	1311	24.28	15
2	Xi’an Jiaotong University	China	32	70	1121	35.03	15
3	Doshisha University	Japan	26	23	1010	38.85	14
4	Sandia National Laboratory	United States	25	53	767	30.68	8
5	University of Queensland	Australia	25	39	348	13.92	10
6	Commonwealth Scientific Industrial Research Organisation CSIRO	Australia	22	39	643	29.23	13
7	North China Electric Power University	China	18	50	164	9.11	8
8	National Renewable Energy Laboratory NREL	United States	17	38	382	22.47	8
9	State University System of Florida	United States	16	24	511	31.94	7
10	Indian Institute of Science IISC Bangalore	India	15	27	243	16.20	8

3.3. Main publishing authors

Table 5 gathers the 10 most productive authors in sCO_2-CSP topics in terms of the number of publications. It is also given the number of cites received in this topic, the PC ratio and the equivalent h-index considering only sCO_2-CSP publications. Author most common affiliation of those publications has been provided as well. As it can be observed, most of the relevant authors belong to the most productive organizations (show in Table 4) and most productive countries (gathered in Table 3) except for Zhang, XR. from Peking University who exhibits the highest PC ratio, Liu, M. from University of South Australia and Sanchez, D. the last two with 10 research publications on sCO_2-CSP each.

Table 5. Most productive authors in sCO_2-CSP

rank	Author	Institution	Country	Topic documents	Topic	PC ratio	h-index

					cites		
1	Yamaguchi, H.	Doshisha University	Japan	25	985	39.4	14
2	Zhang, XR.	Peking University	China	21	1018	48.48	15
3	Ho, CK.	Sandia National Laboratory	United States	16	429	26.81	6
4	Gurcenci, H.	University of Queensland	Australia	13	93	7.15	5
5	Guan, ZQ.	University of Queensland	Australia	10	95	9.5	5
6	Liu, M.	University of South Australia	Australia	10	150	15.0	6
7	Mcnaughton, R.	Commonwealth Scientific Industrial Research Organisation CSIRO	Australia	10	242	24.2	7
8	Sanchez, D.	University of Seville	Spain	10	339	33.9	5
9	Wang, JF.	Xi'an Jiaotong University	China	10	463	46.3	7
10	Albrecht, KJ.	Sandia National Laboratory	United States	9	46	5.11	4

3.4. Most cited publications in sCO_2-CSP

Table 6 gathers the most cited publications in sCO_2-CSP topics together with the publishing source, first author, country and year of publication. Other relevant indicators such as the total number of citations and the average citations per year are included for comparison purposes.

Table 6. Most cited publications in sCO_2-CSP

rank	Publication	Publishing Source	Author	Institution	Country	year	Cites	Cites/ year	Ref
1	Review of Supercritical CO_2 power cycle technology and current status of research and development	Nuclear Engineering and Technology	Ahn, Y. et al.	Korea Advanced Institute of Science and Technology	South Korea	2015	371	53.0	[51]
2	Review of high-temperature central receiver designs for concentrating solar power	Renewable and Sustainable Energy Reviews	Ho, CK. and Iverson, BD.	Sandia National Laboratory	United States	2014	344	43.0	[20]
3	Supercritical CO_2 Brayton cycles for solar-thermal energy	Applied Energy	Iverson, BD. et al.	Sandia National Laboratory	United States	2013	265	29.44	[13]

4	Thermodynamic Study of Advanced Supercritical Carbon Dioxide Power Cycles for Concentrating Solar Power Systems	Journal of Solar Energy Engineering	Turchi, CS. et al.	National Renewable Energy Laboratory	United States	2013	224	24.89	[52]
5	Solar energy powered Rankine cycle using supercritical CO_2	Applied Thermal Engineering	Yamaguchi, H. et al.	Doshisha University	Japan	2006	172	10.75	[53]
6	Supercritical carbon dioxide cycles for power generation: A review	Applied Energy	Crespi, F. et al.	University of Seville	Spain	2017	171	34.2	[10]
7	Parametric optimization design for supercritical CO_2 power cycle using genetic algorithm and artificial neural network	Applied Energy	Wang, J. et al.	Xi'an Jiaotong University,	China	2010	147	12.25	[54]
8	Alternative cycles based on carbon dioxide for central receiver solar power plants	Applied Thermal Engineering	Chacartegui, R. et. al	University of Seville	Spain	2011	137	12.45	[55]
9	Exergetic analysis of supercritical CO_2 Brayton cycles integrated with. solar central receivers	Applied Energy	Padilla, R.V. et al.	CSIRO	Australia	2015	136	19.43	[56]
10	Thermodynamic analysis and optimization of a molten salt solar power tower integrated with a recompression supercritical CO2 Brayton cycle based on integrated modeling	Energy Conversion and Management	Wang, K. and He, Y.	Xi'an Jiaotong University,	China	2017	134	26.80	[26]

As it can be noted, all publications belong to the most productive countries and institutions except for the most cited publication from Korea Advanced Institute [51] and two publications from the University of Seville [10,55]. Despite the recent years of those publications, they exceed 50 citations per year.

3.5. Publication distribution by publishing source

Regarding the document type distribution, Figure 5 shows that most sCO_2-CSP publications belong to articles (63 %) followed by proceedings papers (31 %) and both categories together accounted for 94 % of corpus data.

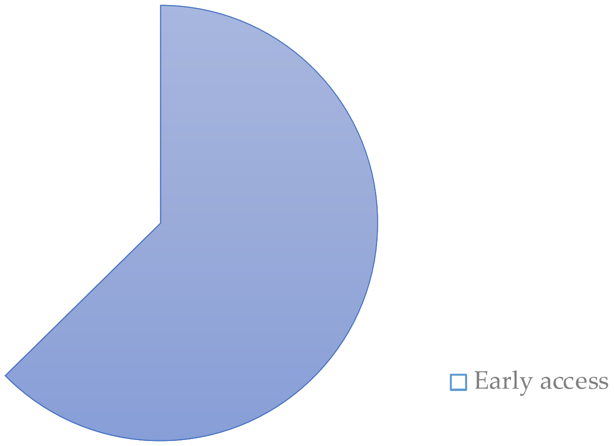

Figure 5. Document type distribution on sCO_2-CSP publications

Within article publications, the most relevant publishing sources for sCO_2-CSP are Energy Conversion and Management and Energy journals with 40 publications followed by Applied Thermal Engineering with 30 as can be noted in Figure 6. Among the 10 most common publishing sources for sCO_2-CSP publications, it can be found dedicated solar-related sources such as Solar Energy and the Journal of Solar Energy Engineering Transactions of the ASME. It can also be found sources for proceedings papers such as the ones from the SolarPACES conference that used to be published at Energy Procedia until 2014 and that are collected under AIP Conference Proceedings since the 2015 edition.

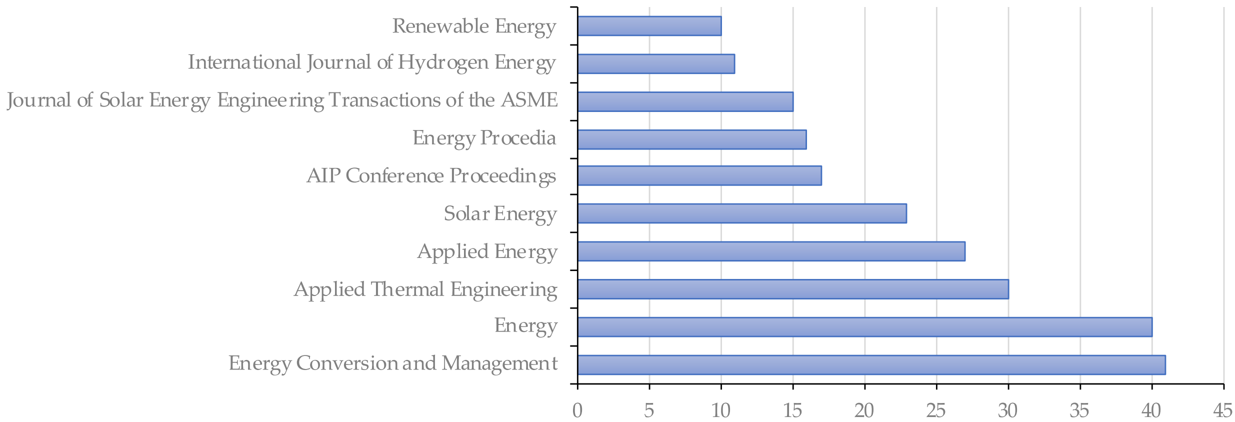

Figure 6. Most relevant publishing sources for sCO_2 CSP publications

It is also analyzed the distribution between open source and not open source sCO_2-CSP publications in Figure 7. As it can be observed, both publishing sources have been following the same trend in terms of publication records as the cumulative lines indicate. That is translated into an average contribution of open access sources around 20% for the recent years where the spike in the year 2005 corresponds to one open-source publication out of two publications that year.

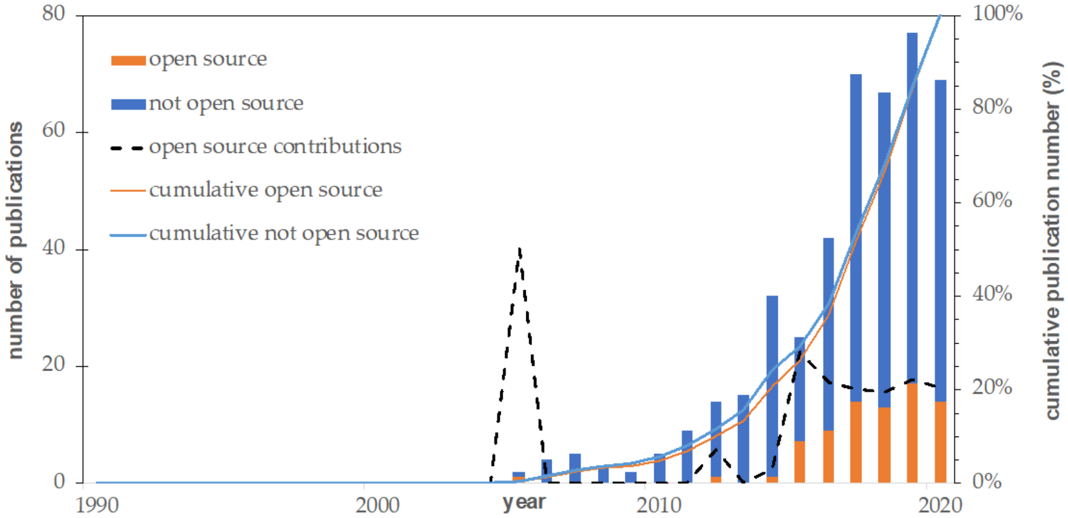

Figure 7. Most relevant publishing sources for sCO_2-CSP publications

3.6. Authorship networking map

Table 7 shows the number of authors from retrieved publications that are meeting a minimum number of citations and publications criteria on the sCO_2-CSP topic. As it can be observed, 1006 authors have ever published on this topic no matter the citations received. That number drastically reduces to 208 authors having two sCO_2-CSP related publications and 10 citations.

Table 7. Number of authors meeting citations and publications criteria

Minimum number of publications	Minimum number of citations						
	0	1	10	25	50	100	200
1	1006	859	489	281	163	84	44
2	278	263	208	152	113	63	38
5	66	66	66	62	53	35	26
10	9	9	9	9	9	6	5

Figure 8 shows the authorship networking map for those authors accomplishing the two sCO_2-CSP publications and 25 citations requirement. That criterion resulted in 152 authors, but only 66 were connected in terms of collaborative publications that also met the minimum number of publications and citations criteria. For representation purposes, only connected authors have been represented to explore their collaborations. A thesaurus was used to avoid duplicities in authors names.

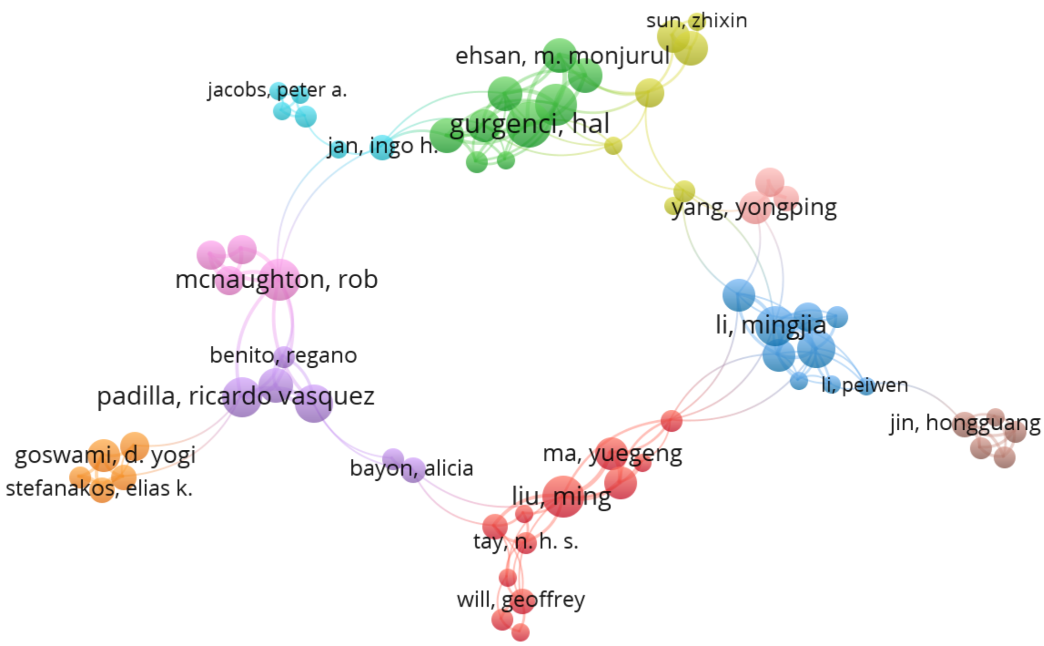

Figure 8. Authorship networking mapping that are meeting minimum publication and citation criteria

As it can be noted in the map, authors are grouped under different clusters what indicates common collaboration among them. Furthermore, a repulsion representation scheme has been chosen that implies authors appearing closer to each other in the map have a closer relationship (in terms of collaborative publications) rather than those that appear far in the map. In addition, the node's size is directly related to the number of authors' publications. Table A1 from the annexe gathers author clusters from Figure 8 indicating their affiliation.

Table 8 shows the number of institutions that are meeting the minimum number of citations and documents criteria attending to sCO_2-CSP related publications.

Table 8. Number of institutions meeting citations and publications criteria

Minimum number of publications	Minimum number of citations						
	0	1	10	25	50	100	200
1	300	263	166	101	67	34	18
2	114	110	94	65	53	27	17
5	31	31	31	29	27	18	15
10	11	11	11	11	11	10	9

Figure 9 shows the authorship networking map for those institutions accomplishing at least 2 co-authored publications related to the studied topic and 5 minimum citations. That criterion resulted in 107 institutions, but only 47 were connected and have been represented on the map. Nodes' sizes indicate the number of documents for each represented institution, the existence of connecting lines indicates collaborative publications among connected institutions while the line thickness designates the number of collaborative publications. Table A2 in the Annex lists the organizations forming each cluster.

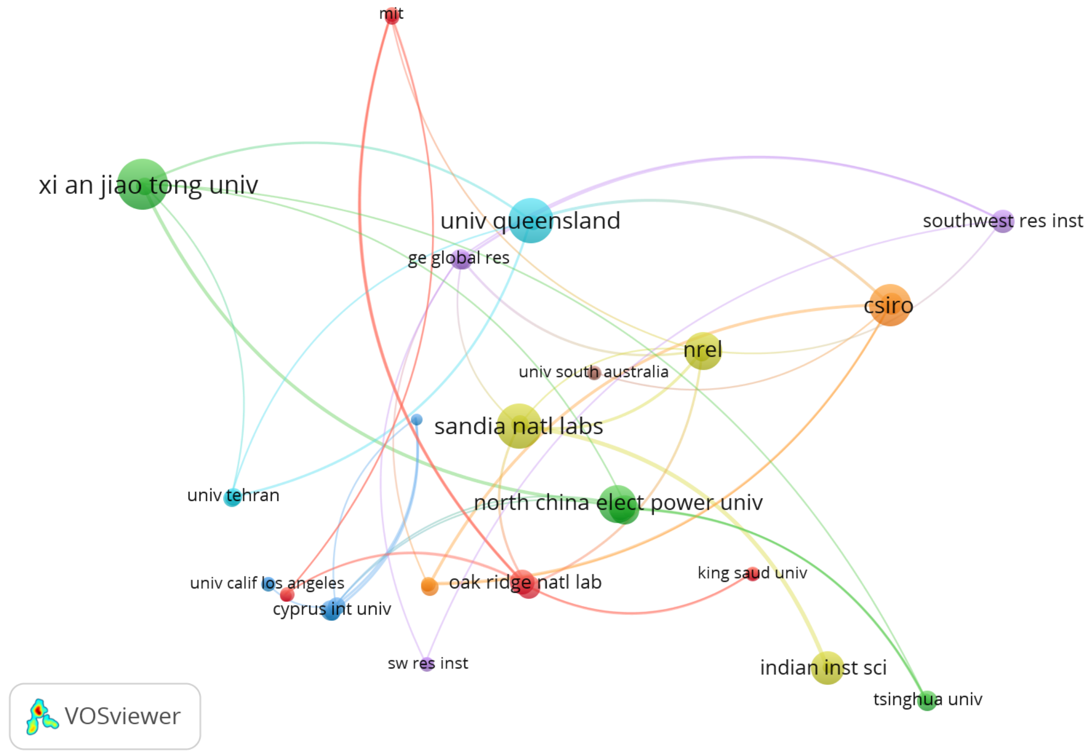

Figure 9. Authorship networking mapping in terms of authors affiliation that are meeting minimum publication and citation criteria

3.7. Publishing sources networking map

Regarding publishing sources and their connections, Table 9 summarizes the different number of sources attending to the minimum number of hosted publications and received citations. As it can be noted, sCO_2-CSP related publications have been published in 105 different sources, but only 11 sources gather 10 or more publications on this topic as was shown in Figure 6.

Table 9. Number of publishing sources meeting citations and publications criteria

Minimum number of publications	Minimum number of citations						
	0	1	10	25	50	100	200
1	105	87	51	27	21	15	10
2	40	37	32	20	17	13	9
5	18	18	18	15	15	12	9
10	11	11	11	11	11	9	8

For representation purposes, Figure 10 shows networking mapping connections among publishing sources having at least 2 publications on this topic and 10 citations. Nodes' sizes indicate the number of documents of each journal while line thickness represents the strength in terms of citations between publications from connected journals. As it can be noted, not all journals are connected among them what reflects that sCO_2-CSP documents did not cite the other journal documents. A thesaurus has been used to avoid duplicities among different publishing sources, especially for those from conference proceedings that have been grouped no matter the year edition. Table A3 gathers publishing sources of each cluster.

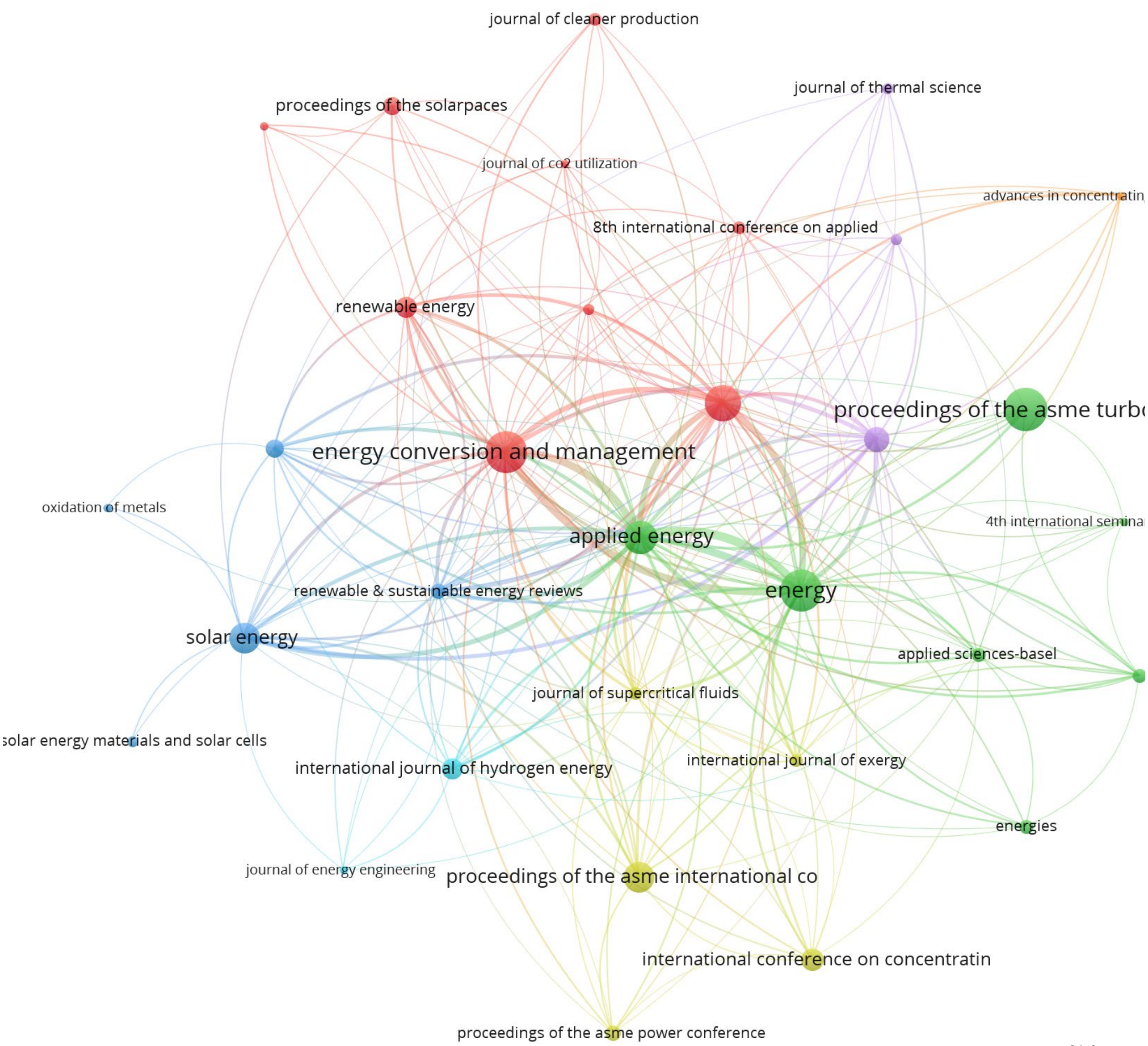

Figure 10. Publication sources connection networking map (at least 2 publications and 10 citations).

3.8. Bibliometric summary data

Table 10 summarizes the main bibliometric indicators presented in this section.

Table 10. Main bibliometric indicators for sCO_2-CSP WOS indexed publications

Field	Value
Total number of publications	441
Total number of authors	1006
Total number of research institutions	300
Total number of publishing sources	105
Total number of countries	35
Sum of times cited	8855
Sum of times cited (without self-citations)	6693
Citing articles	4107
Citing articles (without self-citations)	3747
h-index	47
Average citations per item	20,08

4. Discussion

In this section, technology trends for supercritical CO_2 power cycles within Concentrating Solar Power (CSP) applications are addressed both from a semantic point of view (attending to most common keywords extracted from publications) and how they are connected to most recent research projects both in Europe and in the United States.

4.1. Technology trends

Text mining analysis has been applied by extracting documents' keywords from publication titles, abstracts and the ones being provided by authors from the retrieved sCO_2-CSP publications. Table 11 shows the number of keywords attending to its occurrence number, as it can be observed, the 100 most common keywords appeared in at least 5 different publications.

Table 11. The minimum number of occurrences of a keyword.

Minimum number of occurrences	Number of keywords
1	1259
2	302
5	103
7	81
10	62
20	30
50	10

Figure 11 shows how the 100 most common keywords within sCO_2-CSP publications relate to each other. Similar repulsion and clustering scheme has been followed in keywords representation what can be summarized as follows:

- Keywords located in the centre of the map are the most relevant and general ones within the retrieved publications as they are highly connected to other topics in the network (in this case "supercritical CO_2", "concentrating solar power", "performance" and "system").
- Keywords located in the peripheral area of the networking map are secondary within the topic of study as they are located far from the core of the network and with fewer connecting lines (as it is the case of "heliostat field", "combined cycle", solid particles", "phase-change materials", "natural draft dry cooling tower" or "exergoeconomic analysis").
- Node's size indicates the keyword relevance in terms of the number of occurrences; in this case, the most common ones have been gathered in Table 12.
- Keywords are grouped in clusters attending to their frequent jointly appearance in publications what indicates they are referring to similar areas of research. In this study, keywords are organized in seven clusters dominated by "supercritical CO_2", "concentrating solar power", "system", "Brayton cycle", "generation", "optimization" and "designs" keywords.

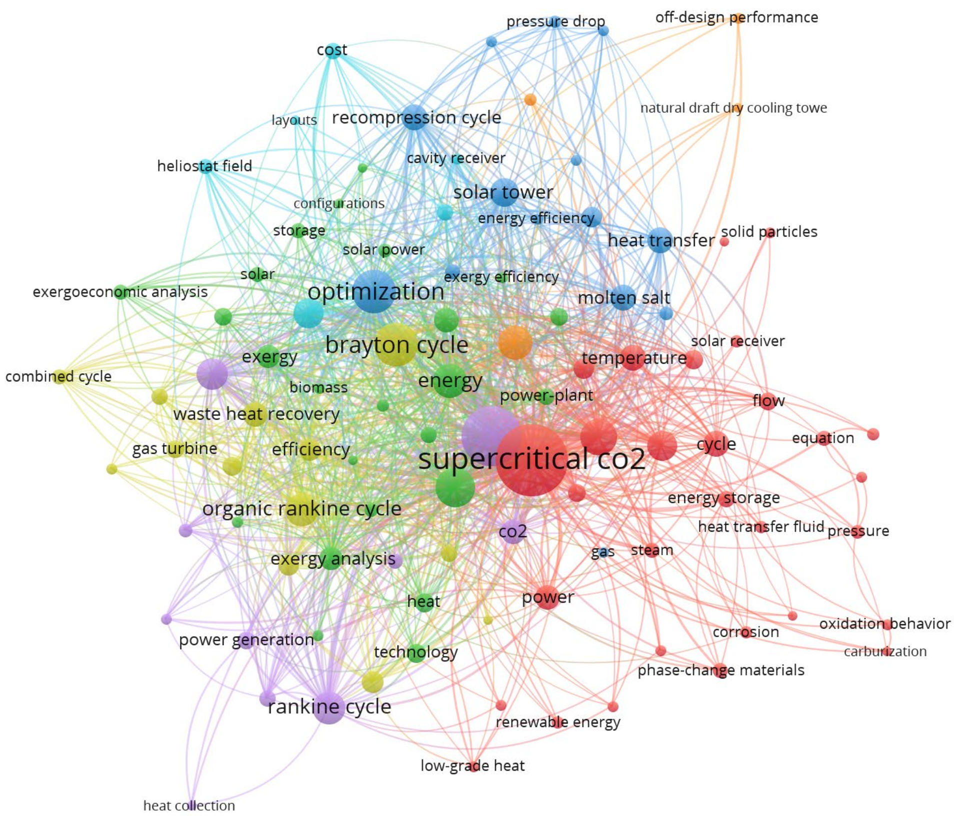

Figure 11. Keywords networking mapping with minimum 5 occurrences.

Table 12 summarizes the most common keywords within the networking map attending to the number of appearances and connections to other keywords in the network. The cluster number and the corresponding colour is indicated for identification purposes within Figure 11.

Table 12. Most common keywords ranking

Ranking	keyword	Number of appearances	Number of connections	Cluster identification
1	Supercritical CO_2	250	101	#1 (red)
2	Concentrating Solar Power	174	101	#5 (purple)
3	Optimization	93	93	#3 (blue)
4	System	75	87	#2 (green)
5	Performance	69	90	#1 (red)
6	Brayton cycle	64	86	#4 (yellow)
7	Generation	59	85	#7 (orange)
8	Energy	58	81	#2 (green)
9	Organic Rankine Cycle	51	75	#4 (yellow)
10	Thermodynamic analysis	49	74	#5 (purple)
11	Thermal Energy Storage	45	74	#1 (red)
12	Designs	44	74	#6 (cyan)
13	Solar Tower	42	76	#3 (blue)
14	Recompression cycle	35	65	#3 (blue)
15	CO_2 Brayton cycle	34	63	#3 (blue)

Figure 12 shows the density visualization map that combines text mining extraction with the number of occurrences for each keyword. As it can be noticed, hot areas in the map are located around terms such as “optimization”, “thermodynamic analysis”, “efficiency”, “exergy analysis” and “system” which reflects the great importance of thermodynamic studies for sCO_2-CSP applications. However, most of those analyses attend to "performance analysis" and "multi objective optimization" according to the central areas of the map while "off-design performance" studies are still in the peripheries what indicates lower relevance in terms of the number of publications. It is also observed the incipient relevance of medium low-temperature applications within sCO_2-CSP as mild coloured areas include keywords such as "Rankine cycle", "transcritical cycle", "organic Rankine cycle", "parabolic trough collector" and "waste heat recovery". And the growing relevance of "energy storage" through common keywords "thermal energy storage" and "phase-change materials". Finally, "heat transfer" analysis and "heat exchanger" designs have been gaining relevance and are approaching the central area of the map.

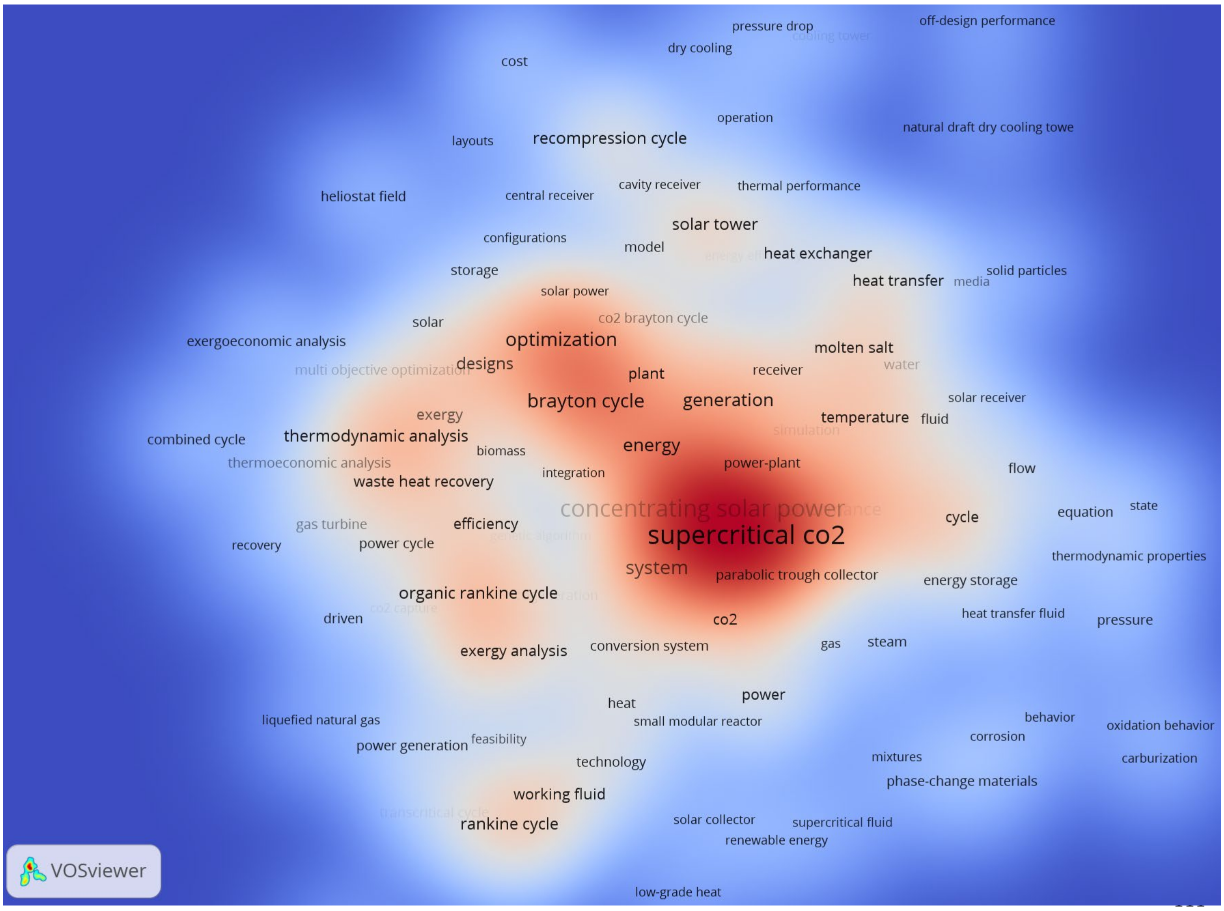

Figure 12. Density visualization of publication text mining analysis

4.2. *Technology prospectives: on-going R&D Projects combining CSP and sCO_2 applications*

Tables 13 and 14, below, summarize all main ongoing R&D projects which explicitly refer to CSP and sCO_2 systems in their objectives, in the EU and the USA respectively. The tables present the name of the project, its general objective, the project coordinator, and participants, as well as the duration, funding received and funding agency. As of 2021, ongoing projects combining CSP and sCO_2 can be divided into two groups: one focused on system integration of sCO_2 cycles with state-of-the-art CSP technologies; and another focused on new systems, components, and materials at higher temperatures with lower maturity. Among the demonstration group of projects, worth highlighting the SOLARSCO2OL and the TESTBED, in EU and USA respectively, which both aim at a MW-scale pilot to show the technical and economic viability of integrating a conventional CSP molten salt system with a novel sCO_2 cycle, therefore limited to a turbine inlet temperature of 565 °C approximately. This is also the case of the pilot plant being developed by EDF in China [57]. Other demonstration projects not included in the tables below, but of high relevance for CSP and sCO_2 are the STEP project and Phase 2 of the US DOE Gen3 CSP program. The STEP project aims at demonstrating the technical viability of a 10 MW sCO_2 cycle operating at 700 °C, at different configurations, with heat provided by natural gas. Phase 2 of the US DOE Gen3 CSP program on the other hand focuses on demonstrating a new particle-based CSP system able to collect useful heat up to 900 °C, which can potentially enable high-temperature CSP-sCO_2 systems in the future. Indeed, particle-based systems seem to be the preferred path forward for future high-temperature CSP applications, at 700 °C or above, being considered both in the EU and in the USA. Considering that the maturity and commercial viability of such particle-based systems is yet to be proven, it can be estimated that should sCO_2 systems enter the CSP sector then projects in the near term (i.e. up to 2030) will focus on using proven molten salt technology, and so allocating most of the risk on the sCO_2 system itself.

Table 13. Selected ongoing projects in the EU specifically referring to CSP and sCO2 in their objectives (as of July 2021) [58–63]

Project	General Objectives	Project Coordinator and Partners	Project Duration and Received Grant
ACES2030-CM Concentrated solar thermal energy in the transport sector and the production of heat and electricity	The collaborative structure in ACES2030 promotes synergy between facilities and laboratories around solar thermal technology in support of the industry's R&D activities, with the ambition of being the seeds of a future Network of unique infrastructures in the Community of Madrid including. In particular relation to sCO_2, the project aims to develop technologies for next-generation concentrated solar thermal power plants that are efficient, operational and competitive in a scenario of increasing electrification of society. This objective is aligned with the recent priorities set out in the US Department of Energy's Gen3 CSP program, and primarily with pressurised gas technology (sCO_2).	IMDEA Energia, CIEMAT, Universidad Carlos III, CSIC, UNED, Universidad Rey Juan Carlos, Universidad Politécnica Madrid, Abengoa Energia, Empresarios Agrupados, Grupo Cobra, Protermosolar, Repsol, Rioglass Solar	2019 – 2023 1.0 M€ Comunidad de Madrid, Spain (S2018/EMT-4319) co-funded with structural funds of the European Union
SCARABEUS Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plants	The project aims to demonstrate that the application of supercritical CO_2 blends to CSP plants. There are two main areas of research in this project: the first is the identification of the optimal additives, which would reduce the size and increase the efficiency of the power block. The second is the development of tailored heat exchanger designs, particularly for the air-cooled condenser, to operate with the innovative fluid as these are key enabling components for the proposed technology. The project will demonstrate the innovative fluid and newly developed heat exchangers at a relevant scale (300 kWth) for 300 h in a CSP-like operating environment (700 °C).	Politecnino di Milano, TU Wien, Universidad de Sevilla, City University of London, Universita' degli Studi di Brescia, Kelvion Thermal Solution, Baker Hughes, Abengoa, Quantis	01 April 2019 - 31 March 2023 5.0 M€ European Commission (GA 814985)
CARBOSOLA supercritical carbon dioxide	The CARBOSOLA project is intended to be the entry into the development of sCO_2 technology in Germany. The main goal of the	Technische Universität Dresden, Helmholtz-Zentrum	1 October 2019 –

(sCO_2) as an alternative working fluid for downstream processes and solar-thermal applications - Design methods for sCO_2 power plant technology	industrial partner Siemens is the conceptual design of a demonstrator with which the validation of the sCO_2 technology is performed. The core of the project is the component and system design of a technology demonstrator for the use of secondary heat and the development of the theoretical and experimental methods needed for further technology development to commercial maturity. The sCO_2 technology will first be compared with conventional technologies in the areas of recuperation of waste heat (downstream processes for gas turbine plants) and solar thermal power plant technology (CSP) and subjected to a technical-economic evaluation	Dresden-Rossendorf, DLR, SIEMENS AG	30 September 2022 0.4 M€ Ministry for Economic Affairs and Energy (BMWi), Germany (GA 03EE5001B)
SOLARSCO2OL SOLAR based supercritical Carbon Oxide Operating Low-cost plants	SOLARSCO2OL aims at developing an innovative, economically viable and replicable supercritical CO_2 (sCO_2) power block for demonstrating the use of sCO_2 cycles as a potential key technology to increase the flexibility of concentrated solar power (CSP) plants. This will reduce their Levelised Cost of Electricity (LCOE) to values below 10 c€/kWh in Europe and promote an innovative power plant cycle layout not requiring water. The innovative SOLARSCO2OL plant layout, coupled with fast-reactive electric heaters and efficient heat exchangers (HEXs), will enable the operation and design of novel integrated CSP plant layouts.	RINA Consulting, Kungliga Tekniska Högskolan (KTH), Masen, Ikerlan, Universita Degli Studi Di Genova, CERTH, Magtel, Franco Tosi Meccanica, ESTELA, MAS, Lointek, Baker Hughes, Seico, Abengoa, OCMI OTG	1 October 2020 - 30 September 2024 10.0 M€ European Commission (GA 952953)
COMPASsCO2 Components' And Materials' Performance For Advanced Solar Supercritical CO_2 Power plants	The COMPASsCO2 project aims at integrating solar energy into sCO_2 Brayton cycles for electricity production. The project will design, test and model tailored particle-alloy combinations able to face the extreme operating conditions regarding temperature, pressure, abrasion, oxidation, and corrosion during the plant lifetime. Testing of the particle-sCO_2 heat exchanger will validate the innovative materials developed.	DLR, CIEMAT, John Cockerill, Research Center REZ, Dechema Research Institute, Julich Research Center, OCAS, Observatoire Mediterraneen De L'energie, Saint-Gobain, Sugimat, University of Birmingham, Teknologian Tutkimuskeskus (VTT)	1 November 2020 – 31 October 2024 6.0 M€ European Commission (GA 958418)
DESOLINATION DEmonstration of concentrated SOLar power coupled wIth	The DESOLINATION project aims to couple efficiently the low grade wasted heat of two different CSP cycles to an innovative desalination system based on forwarding osmosis. Indeed, the demonstration in Saudi Arabia already hosts a 100kWe air Bryton cycle that will be coupled with the innovative forward	Polytechnic University of Milan, Lund University, Protarget, Baker Hughes, ACS Cobra, Fraunhofer ISE, Aalborg CSP, Cranfield	1 June 2021 – 31 May 2025 10.0 M€ European Commission

advaNced desAlinaTion system in the gulf regION	osmosis desalination system developed in DESOLINATION. Moreover, to consider the future and most efficient cycles, a 1MWe CO_2 blends power cycle will be installed on-site and demonstrated alongside the existing power plant. DESOLINATION will thus provide solutions to be integrated into existing CSP plants across the region as well as an innovative more efficient coupling with a tailored made power cycle for more efficient and cost-effective new CSP plants based on CO_2 blends. Through the developments of the CSP+D system and its demonstration in a real environment, DESOLINATION will foster the use of solar energy for desalination in the EU, in the GCC countries, and the rest of the world.	University, Fundacion Tekniker, Lappeenranta University of Technology (LUT), University of Brescia, Eindhoven University of Technology, Temisth, University of Maribor, Luleå University of Technology, Euroquality, King Saud University, University of Bahrain, German University of Technology in Oman	(GA 101022686)

Table 14. Selected ongoing R&D projects in the USA specifically referring to CSP and sCO_2 in their objectives (as of July 2021) [64,65,74–80,66–73]

Project	General Objectives	**Project Coordinator** and Partners	Project Duration and Received Grant
SETO 2018 - Mechanically, Thermally, and Chemically Robust High-Temperature Ceramic Composites	To evaluate the corrosion and heat resistance of new ceramic-metal composite materials for use in components in concentrating solar-thermal power (CSP) plants. Objectives: • Develop composites stiffer and stronger than nickel-based superalloys at 550-750 °C. • Test the heat- and corrosion resistance of these composite working with air, sCO_2 and chloride salts • Evaluate less expensive methods of manufacturing components from these materials.	**Purdue University**	2019 - 2021 0.4 M$ US DOE
SETO 2018 740H Diffusion Bonded Compact Heat Exchanger for High Temperature and Pressure Applications	This project team is developing new manufacturing techniques for an advanced alloy, Inconel 740H, which has extremely high strength at the temperatures required for next-generation CSP plants. Specific Objectives: • Develop manufacturing processes using iterative testing of different approaches to address challenges involved in using 740H • Improve etching a diffusion bonding techniques for 740H	**CompRex LLC** Special Metals University of Wisconsin-Madison Advanced Vacuum Systems	2019 - 2021 1.2 M$ US DOE

	• Test a prototype heat exchanger made of 740H and produced using industry-standard manufacturing techniques, at a 100 kW scale		
SETO 2018 Additively Manufacturing Recuperators via Direct Metal Laser Melting and Binder Jet Technology	Develop additive manufacturing processes for the heat exchangers in sCO_2 cycles. • Use binder jet printing to enable new heat exchanger geometries (3D channels, curved features) • Evaluate the new process and determine if it's capable of producing CSP compatible power cycles that cost $900/kW and produce energy at $0.05/kWh • Perform mechanical tests to ensure that the resulting heat exchangers can withstand the high operating temperatures and pressures • Create a risk reduction plan for scaling the heat exchanger design from lab-scale to a full-scale, including, a modular design	**General Electric**	2019 - 2021 1.4 M$ US DOE
SETO 2018 Reduced Levelized Cost of Energy in CSP Through Utilizing Process Gas Lubricated Bearings in Oil-Free Drivetrains	De-risk a novel bearing design for the turbines used in concentrating solar-thermal power (CSP) plants with sCO_2 power cycles. Replace existing oil lubrication with gas-bearing lubrication technology, to increase plant efficiency, reduce maintenance costs, and reduce the manufacturing costs of power blocks. Objectives: • Perform mechanical tests and simulate rotor tests • Perform techno-economic analysis to determine if the design can achieve a 50% efficient power cycle to lower costs to $0.05/kWh	**General Electric**	2019 - 2021 2.4 M$ US DOE
SETO 2018 Development of a High-Efficiency Hybrid Dry Cooler System for sCO_2 Power Cycles in CSP Applications	Develop a compact dry cooling heat exchanger for supercritical carbon dioxide (sCO_2) power cycles in CSP plants. Objectives: • Create and optimize a dry cooling heat exchanger with microchannels on the sCO_2 side and a geometry that uses plates and finned chambers on the airside. • Test the dry cooling system at the megawatt scale with a sCO_2 test loop, to determine the reliability of the fabrication method, and validate performance. • The improvements could increase the cooling efficiency to 90%, reduce the cooler cost from $168/kW to $95/kW and reduce cooling power consumption by 14%.	**Southwest Research Institute**	2019 - 2021 1.9 M$ US DOE
SETO 2018 High-Temperature	This project will develop a high-temperature dry gas seal (DGS) by replacing the temperature-sensitive elements with more durable components, enabling the	**Southwest Research Institute**	2019 - 2021 2.0 M$

Dry-Gas Seal Development and Testing for sCO_2 Power Cycle Turbomachinery	DGS to reach operating temperatures over 500 °C and enable higher efficiency levels. Because the DGS design would also be significantly smaller in size, the DGS would reduce the complexity of the sCO_2 turbine design, helping to increase operational reliability and improve turbine efficiency. Specific objectives • Replace the polymers in the dry gas seal with materials that carry the same properties but can withstand higher temperatures • Test and validate materials in a dry gas seal package at a temperature of 500 °C • By simplifying the turbine's heat-shielding requirements, the new technology should improve the efficiency of sCO_2 power turbines by up to 4%.		US DOE
SETO 2018 Additively-Manufactured Molten Salt-to-Supercritical Carbon Dioxide Heat Exchanger	Develop an additively manufactured, nickel superalloy primary heat exchanger (PHX) for advanced molten salt concentrated solar-thermal power (CSP) systems. The PHX will be made using nickel superalloys and laser powder bed 3-D printing, resulting in a compact design that is durable under cyclic operation at high temperatures and pressures in a corrosive salt environment. Objectives: • Characterize and test different alloy powders both in conditions representative of Gen 3 CSP systems—720 °C and supercritical carbon dioxide pressures of 200 bar—and at conditions relevant to current commercial systems—molten nitrate salt at temperatures up to 550 °C. • Validate a thermal model that can predict performance in a chloride salt environment • Develop a 20-kilowatt design to test the mechanical integrity of the fabricated PHX.	**University of California, Davis**	2019 - 2021 2.2 M$ US DOE
SETO 2018 Narrow-Channel, Fluidized Beds for Effective Particle Thermal Energy Transport and Storage	Develop and test narrow-channel, counterflow fluidized bed receiver and heat exchanger designs. These will be used to analyze flow conditions and improve heat transfer rates in the receiver and heat exchanger. The team will then use these insights to test a modular panel for an indirect particle receiver and/or particle to a supercritical carbon dioxide power cycle heat exchanger. Objectives: • Achieve heat exchange efficiency higher than 90% at 700 °C inlet temperature	**Colorado School of Mines** Sandia National Laboratories Carbo Ceramics	2019 - 2021 1.9 M$ US DOE

	• Deliver detailed multiphase flow modelling tools to assess how receiver and heat exchanger designs can meet receiver cost targets of \$150/kWh,th and thermal-energy system targets of \$15/kWh,th		
SETO 2018 Narrow-Channel, Fluidized Beds for Effective Particle Thermal Energy Transport and Storage	Develop and test narrow-channel, counterflow fluidized bed receiver and heat exchanger designs. These will be used to analyze flow conditions and improve heat transfer rates in the receiver and heat exchanger. The team will then use these insights to test a modular panel for an indirect particle receiver and/or particle to a supercritical carbon dioxide power cycle heat exchanger. Objectives: • Achieve heat exchange efficiency higher than 90% at 700 °C inlet temperature • Deliver detailed multiphase flow modelling tools to assess how receiver and heat exchanger designs can meet receiver cost targets of \$150/kWh,th and thermal-energy system targets of \$15/kWh,th	**Colorado School of Mines** Sandia National Laboratories Carbo Ceramics	2019 - 2021 1.9 M\$ US DOE
SETO 2019 Economic Weekly and Seasonal Thermochemical and Chemical Energy Storage for Advanced Power Cycles	Integrate multiple thermochemical energy storage components into a concentrating solar-thermal power (CSP) design so that a plant can have multiple storage durations, including daily and long-term. Objectives: • Design TES for sCO_2 power loop integration • Conduct techno-economic analyses to improve CSP system design and operation for guaranteed year-round energy dispatchability.	**Arizona State University** Oregon State University, Sandia National Laboratories, Siemens, Southwest Research Institute	2020 - 2022 3.3 M\$ US DOE
SETO 2019 Creep and Fatigue Characterization of High-Strength Nickel Alloys Thin Sections in Advanced CO2 Heat Exchangers	Examine creep behaviour in thin-sheet nickel alloys 740H and 282, to see whether they can improve the lifetime of supercritical carbon dioxide (CO_2) heat exchangers in high-temperature concentrating solar-thermal power plants. Objectives: • Provide information about structural characteristics in metals used to build heat exchangers • Determine the optimal thickness of these components • Heat exchanger performance modelling • Basic materials research and fabrication of test specimens for characterization	**Brayton Energy** Oak Ridge National Laboratory	2020 - 2022 0.7 M\$ US DOE

	• Experimental design and bench-scale laboratory experiments		
SETO 2019 Advanced Compressors for CO2-Based Power Cycles and Energy Storage Systems	Develop a large-scale, low-cost, single-shaft compressor for supercritical carbon dioxide (sCO_2) power cycles and energy storage systems to improve the performance of concentrating solar-thermal power systems.	**Echogen Power System** University of Notre Dame	2020 - 2022 4.4 M$ US DOE
SETO 2019 Near-Net-Shape Hot Isostatic Press Manufacturing Modality for sCO_2 CSP Capital Cost Reduction	Fabricate advanced supercritical carbon dioxide (sCO_2) power cycle structures for CSP plants from metal powders by using powder metallurgy, near-net-shape (NNS) hot isostatic pressed (HIP) technology. Objectives: • A turbine nozzle ring, turbine case, cylindrical structure, and dual alloy pipe would be fabricated as a demonstration of the technology's viability • Activities to be performed would include material characterization (e.g.alloy powder assessment), data collection, component design, component fabrication (e.g. prototype nozzle ring, casing, and dual-alloy pipe), validation testing (e.g. microstructural analysis), and cost modelling.	**General Electric** Synerthec	2020 - 2022 2.5 M$ US DOE
SETO 2019 Vertically Aligned Carbon Nanotube Arrays as Novel, Self-Lubricating, High-Efficiency Brush Seal for CSP Turbomachinery	Develop a new scalable seal brush on a flexible base that will improve the seal's efficiency and durability. The seal will be made of a vertically aligned carbon nanotube array and use a chemical vapour deposition process without a catalyst. The main aim is to improve turbine efficiency and reduce the manufacturing cost by at least half.	**Oak Ridge National Laboratory**	2020 - 2022 1.4 M$ US DOE
SETO 2019 Oxidation-Resistant, Thermomechanically Robust Ceramic-	Develop cost-efficient ceramic-composite primary heat exchangers that are highly resistant to corrosion by supercritical carbon dioxide and molten salt and will not deform or fracture at temperatures as high as 800 °C. Objectives: • Developed HEx to be resistant to corrosion, creep, fracture, and thermal cycling when transferring	**Purdue University,** Massachusetts Institute of Technology, TharEnergy	2020 - 2023 3.5 M$ US DOE

Composite Heat Exchangers	heat from high-temperature molten salt to supercritical carbon dioxide-based fluid • Test the Hex under relevant working conditions		
SETO 2020 Integrated TESTBED	Develop, build, and operate a sCO_2 power cycle integrated with thermal energy storage at temperatures in the range of 550 °C to 630 °C. Objectives: • Develop, build, and operate a supercritical carbon dioxide (sCO_2) power cycle integrated with thermal energy storage, heated by a concentrated solar thermal energy supplied by a newly built heliostat field. • Operate at a TIT of 600 °C	**Heliogen Inc.**	2021 - 2024 39.0 M$ US DOE
SETO 2020 Small Innovative Projects in Solar (SIPS) - Enhancing Particle-to-sCO_2 Heat Exchanger Effectiveness Through Novel High-Porosity Metallic Foams	This project aims to increase the effectiveness of particle-to-supercritical carbon dioxide (sCO_2) heat exchangers by packing the particle-side channels with high-porosity cellular structures. The approach includes metal additive manufacturing of small length-scale fibres with complex three-dimensional interconnections. Objectives: • Increase the interstitial heat-transfer coefficient between moving particles and metallic fibres, and the effective thermal conductivity of particle channel. • Test the Hex design at Sandia test rig • Scaling up of the technology	**Mississippi State University.** Sandia National Laboratories, National Renewable Energy Laboratory	2021 - 2022 0.3 M$ US DOE
SETO 2020 Small Innovative Projects in Solar (SIPS) - Enabling Robust Compressor Operation under Various sCO_2 Conditions at Compressor Inlet	This project team will study how supercritical carbon dioxide (sCO_2) flows in a compressor cascade in a concentrating solar-thermal power system. Objectives: • Develop a new design methodology for the compressor's leading-edge suction surface so that the compressor can work well over a range of ambient conditions, without problems caused by condensation • Identify and quantify condensation at the compressor's leading edge, and characterize detailed sCO_2 flows within the compressor	**University of Central Florida.** CRAFT Tech	2021 - 2022 0.3 M$ US DOE

5. Conclusions

Research activities on supercritical CO2 (sCO_2) for concentrating solar power (CSP) applications have gained massive attention over the last few years. This recent interest is based on the high conversion efficiency predictions that are exceeding 50% for the moderated temperature range and its suitability for solar energy integration. That interest is reflected also in the vast scientific bibliography (441 WOS indexed publications since 1993) and publicly funded research projects

(24 projects in Europe and United States since 2019). The main conclusions derived from the bibliometrics analysis conducted in this publication are as follows:

- One-third of the existing sCO_2 literature relates to solar energy applications
- Exponential growth on sCO_2 scientific publications has been observed as 70% of the total number of documents were published after 2015 and 80% of citations were received after 2016
- The most productive publishing countries during 2020 were China and Spain that both accounted for almost 50% of the total publications while the top 10 most productive countries contributions sum up 86.5% of the total
- Considering the whole publishing timeframe; institutions from United States, China and Australia still dominate in terms of publishing and citations terms. This is confirmed by the high number of interactions among authors and institutions from these countries
- Despite the wide number of publishing sources (105), most documents were retrieved from 10 general energy-related sources that are also the more connected ones in terms of citations.
- Regarding text-mining techniques applied to the indexed publications; the most common keywords referred to cycle optimization, system analysis and performance studies. Growing interest was observed for medium-low temperature applications through related keywords such as Rankine cycle, organic Rankine cycle and waste heat recovery.
- Areas of research related to heat exchangers design and energy storage solutions were detected through heat map visualization that is in line with ongoing projects objectives from Europe and the United States.

Appendix A

Table A1. Authors distribution by cluster (from Figure 8)

Author	Affiliation	Author	Affiliation
Cluster #1 (red)		*Cluster #2 (green)*	
Bell, S.	Queensland University of Technology	Duniam, S.	University of Queensland
Belusko, M.	University of South Australia	Ehsan, M.	University of Queensland
Bruno, F.	University of South Australia	Guan, Z.	University of Queensland
Liu, J.	Xi'an Jiaotong University	Gurgenci, H.	University of Queensland
Liu, M.	University of South Australia	Hooman, K.	University of Queensland
Ma, Y.	Xi'an Jiaotong University	Klimenko, A.	University of Queensland
Sarvghad, M.	Queensland University of Technology	Sun, Y.	North China Electric Power University
Steinberg, T. A.	Queensland University of Technology	Veeraragavan, A.	University of Queensland
Tay, N. H. S.	University of South Australia	Wang, J.	Xi'an Jiaotong University
Will, G.	Queensland University of Technology		
Yan, J.	Xi'an Jiaotong University		
Zhang, X.	Peking University		
Cluster #3 (red)		*Cluster #4 (red)*	
Guo, J.	Xi’an Jiaotong University	Dai, Y.	Xi’an Jiaotong University
He, Y.	Xi’an Jiaotong University	Li, X.	North China Electric Power University
Li, M.	Xi’an Jiaotong University	Liu, C.	North China Electric Power University
Li, P.	University of Arizona	Sun, Z.	Xi’an Jiaotong University
Liu, Z.	Xi’an Jiaotong University	Wang, JF.	Xi’an Jiaotong University
Qiu, Y.	Xi’an Jiaotong University	Wang, X.	Chinese Academy of Sciences
Wang, K.	Xi’an Jiaotong University	Xu, X.	University of Arizona
Xu, J.	North China Electric Power University		
Zhu, H.	Xi’an Jiaotong University		
Cluster #5 (red)		*Cluster #6 (red)*	
Bayon, A.	CSIRO	Jacobs, P.	The University of Queensland
Benito, R.	CSIRO	Jan, I.	The University of Queensland
De la calle, A.	CSIRO	Kearney, M.	The University of Queensland

Padilla, R. V.	CSIRO	Miller, S.	CSIRO
Stein, W.	CSIRO	Rowlands, A.	The University of Queensland
Too, Y. S.	CSIRO	Singh, R.	The University of Queensland
Cluster #7 (red)		*Cluster #8 (red)*	
Besarati, S.	University of South Florida	Bai, Z.	Chinese Academy of Sciences
Chen, H.	Suzhou Adv Mat Res Inst	Jin, H.	Chinese Academy of Sciences
Goswami, D.	University of South Florida	Lei, J.	North China Electric Power University
Rahman, M.	University of South Florida	Liu, Q.	Chinese Academy of Sciences
Stefanakos, E.	University of South Florida	Wang, X.	Chinese Academy of Sciences
Cluster #9 (red)		*Cluster #10 (red)*	
Abbas, A.	University of Sydney	Li, X.	Chongqing University
Mcnaughton, R.	CSIRO	Xu, C.	North China Electric Power University
Milani, D.	University of Sydney	Yang, Y.	North China Electric Power University
Minh, T.	University of Sydney		

Table A2. Organization distribution by cluster (from Figure 9)

Organization	Country	Organization	Country
Cluster #1 (red)		*Cluster #2 (green)*	
Georgia Inst Technology	United States	Beijing University	China
Hunan University	China	Chinese Academy of Sciences	China
King Saud University	Saudi Arabia	North China Electric Power University	China
MIT	United States	Technical University Berlin	Germany
Oak Ridge National Lab	United States	Tsinghua University	China
Purdue University	United States	University of Arizona	United States
Saudi Electricity Co	Saudi Arabia	University of Chinese Academy of Sciences	China
University of Wisconsin	United States	Xi'an Jiao Tong University	China
Cluster #3 (blue)		*Cluster #4 (yellow)*	
Cyprus Int Univ	Cyprus	Colorado School of Mines	United States
Mirpur University	Pakistan	Indian Institute of Sciences	India
Must	Pakistan	NREL	United States
Natl Univ Sci & Tech	Pakistan	Sandia Natl Labs	United States
University of California	United States	Universidad Carlos III	Spain
Virginia Tech	United States	University of Western Australia	Australia
Zhejiang University	China		
Cluster #5 (purple)		*Cluster #6 (light blue)*	
GE Global Res	United States	Henan University	China
Hanwha Techwin	South Korea	Shahrood University	Iran
Montana State University	United States	University of Queensland	Australia
Southwest Res Inst	United States	University of Tehran	Iran
SW Res Inst	United States	Wuhan University	China
US DOE	United States		
Cluster #7 (purple)		*Cluster #8 (light blue)*	
Australian National University	Australia	Queensland University	Australia
CSIRO	Australia	University of South Australia	Australia
Southern Cross University	Australia		
University of Sidney	Australia		
Univ Tech Federico Santa Maria	Chile		

Table A3. Publishing sources distribution by cluster (from Figure 10)

Publishing source	Publishing source

Cluster #1 (red)	*Cluster #2 (green)*
8th International Conference on Applied Energy	4th International Seminar on ORC power systems
Applied Thermal Engineering	Applied Energy
Energy Conversion and Management	Applied Sciences
International Journal of Heat and Mass transfer	Energies
Journal of cleaner production	Energy
Journal of energy resources technology – Transactions of the ASME	Journal of Engineering for Gas Turbines and Power – Transactions of the ASME
Proceedings of the SolarPaces	Proceedings of the ASME Turbo Expo
Renewable Energy	
Cluster #3 (blue)	*Cluster #4 (yellow)*
International Journal of Energy Research	International Conference on Concentrating Solar Power and Chemical
Oxidation of Metals	International Journal of Exergy
Renewable & Sustainable Energy Reviews	Journal of Supercritical fluids
Solar Energy	Proceedings of the ASME International Conference on Energy
Solar Energy Materials and Solar Cells	Proceedings of the ASME Power Conference
Cluster #5 (purple)	*Cluster #6 (light blue)*
Journal of Solar Energy Engineering – Transactions of the ASME	International Journal of Hydrogen Energy
Journal of Thermal Science Processes	Journal of Energy Engineering
Cluster #7 (orange)	
Advances in Concentrating Solar Thermal	

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72. US DOE SETO 2018 - Additively Manufacturing Recuperators via Direct Metal Laser Melting and Binder Jet Technology. Project website.
73. US DOE SETO 2018 - Narrow-Channel, Fluidized Beds for Effective Particle Thermal Energy Transport and Storage. Project website.
74. US DOE SETO 2020 - Integrated TESTBED. Project website.
75. US DOE SETO 2019 - Oxidation-Resistant, Thermomechanically Robust Ceramic-Composite Heat Exchangers. Project website.
76. US DOE SETO 2019 - Vertically Aligned Carbon Nanotube Arrays as Novel, Self-Lubricating, High-Efficiency Brush Seal for CSP Turbomachinery. Project website.
77. US DOE SETO 2019 - Near-Net-Shape Hot Isostatic Press Manufacturing Modality for sCO2 CSP Capital Cost Reduction. Project website.
78. US DOE SETO 2019 - Advanced Compressors for CO2-Based Power Cycles and Energy Storage Systems. Project website.
79. US DOE SETO 2019 - Creep and Fatigue Characterization of High-Strength Nickel Alloys Thin Sections in Advanced CO2 Heat Exchangers. Project website.

80. US DOE SETO 2019 - Economic Weekly and Seasonal Thermochemical and Chemical Energy Storage for Advanced Power Cycles. Project website.