Contents list available at CBIORE journal website
Journal of Emerging Science and Engineering
Journal homepage: https://journal.cbiore.id/index.php/jese/index
Research Article

Global research trends and hotspots in solar power tower technology: A bibliometric review

Zeshan Aslam*, Syed Ihtsham Ul Haq Gilani, Taib Iskandar Mohamad, Kehinde Temitope Alao

Mechanical Engineering Department, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Radzuan, Malaysia

Abstract Solar Power Towers (SPTs), as a forefront division of Concentrated Solar Power (CSP), have become a promising option for green electricity generation. This paper presents a bibliometric study of global research output in SPTs using data retrieved from the Scopus and Web of Science databases for the period between 2015 and 2024. The 860 documents dataset was mapped using bibliometric tools like VOSviewer and Bibliometrix to examine publication trends, prominent authors, leading institutions, high-output countries, and hot topics of research. The findings illustrate a picture of tremendous growth in publications since 2008 with China, the United States, and Spain as the leading contributors. Heliostat field design, thermal energy storage, receiver efficiency, and system-level optimization are some of the leading research themes. Keyword co-occurrence and co-authorship analysis reveal thematic clustering and changing collaboration patterns, with increasing yet still modest international collaboration. This review presents the current shape and intellectual structure of SPT research, giving a glimpse of its evolutionary trajectory. The findings can help researchers, practitioners, and policymakers identify knowledge gaps and plan future research agendas in the field of solar thermal technologies.

Keywords: Bibliometric analysis; Concentrated solar power (CSP); Renewable energy; Solar power tower (SPT)

Received: 5th July 2025; Revised: 7th Sept 2025; Accepted: 6th Nov 2025; Available online: 18th Nov 2025

1. Introduction

The growing global demand for clean and sustainable energy has placed renewable energy technologies at the forefront of energy research and development. Among these, solar energy has emerged as one of the most promising alternatives due to its abundance, environmental benefits, and scalability. Solar power can be harnessed through various technologies, including photovoltaic (PV) systems and Concentrated Solar Power (CSP). While PV systems dominate in deployment, CSP technologies offer distinct advantages in large-scale applications, particularly due to their capacity for thermal energy storage and dispatchable power generation. Within the CSP domain, Solar Power Towers (SPTs) stand out as a central-receiver technology that uses a field of heliostats to focus sunlight onto a receiver atop a tower. This high-temperature heat can then be used to generate steam for electricity production or stored for later use, making SPTs a vital component in ensuring grid stability and meeting peak energy demands (Aslam et al., 2025a; García-Ferrero et al., 2022). Over the past two decades, advances in materials, optical tracking systems, thermal storage, and cost optimization have significantly boosted the commercial viability of SPT systems.

The major components comprising the CSP tower systems are heliostats, central receivers, and working fluids. Heliostats track the sun and reflect sunlight onto the receiver, which absorbs concentrated energy and transfers it to the working fluid. Molten salts have been used to a great extent as heat transfer fluid (HTF), which helps in thermal energy storage (TES) and permits electricity generation when sunlight is not available (Achkari & El Fadar, 2020; Aslam et al., 2025a).

CSP tower systems are noted for their high efficiency because they can obtain higher operating temperatures than other CSP technologies, which results in better thermal efficiency (Aslam et al., 2025a). This, in addition, enhances the reliability of TES systems with a steady and dispatchable supply of electricity production, thereby acting against the intermittency of solar energy (Achkari & El Fadar, 2020; Aslam et al., 2025b; Gul et al., 2025). Besides, the CSP tower could be hybridized with conventional energy sources such as natural gas to ensure steady power output (M. Alfailakawi et al., 2023; García-Ferrero et al., 2022). From an economic point of view, even though the initial investment in CSP towers is very high, advances in TES and hybrid systems have made their LCOE increasingly competitive (Achkari & El Fadar, 2020; García-Ferrero et al., 2022; Gul et al., 2025). Environmentally, these systems contribute to reducing greenhouse gas emissions, replacing fossil fuel-based power generation with renewable solar energy (Achkari & El Fadar, 2020; Scott et al., 2021; Webby, 2013).

Despite the advantages offered by CSP tower systems, there are a few challenges, including material durability and scalability, that have to be overcome prior to these systems finding wide application. The advances depend on the improvement in receiver materials and TES technologies (Boretti, 2025a; Khatti et al., 2021). In general, CSP tower systems have experienced phenomenal growth due to

* Corresponding author
Email: zeshan_22009757@utp.edu.my (Z. Aslam)

https://doi.org/10.61435/jese.2025.e47
ISSN: 2252-4940/© 2025.The Author(s). Published by CBIORE

Table 1. Summary of key research contributions in CSP tower systems

Study (Year)	Research Focus	Key Advancements	Efficiency/Performance Improvement	Challenges/Limitations
Jiang et al. (2024)	Dynamic performance prediction	Developed an integrated transient model with a dual-time-scale hybrid method	Reduced calculation time by 32% with low relative error	Highly sensitive to DNI and mass flow variations
Wei et al. (2015)	Cavity receiver performance	Summarized operational principles and recent developments in water/steam cavity receivers	Improved receiver efficiency and heat transfer mechanisms	Future development challenges due to material constraints
Fang et al. (2020)	SPT with S-CO_2 Brayton cycle	Numerical simulation of key operating parameters for thermodynamic optimization	Higher thermal efficiency than conventional SPT plants	Corrosion and material degradation at high temperatures
Xiao et al. (2022)	Large-scale SPT plants	Coupling trough collectors with SPT plants to improve energy conversion	Increased optical efficiency and electricity generation	Decreased heliostat field efficiency with larger plant size
Collado & Guallar (2013)	Heliostat field optimization	Developed an advanced code for fast and accurate calculations of shadowing and blocking factors	Optimized heliostat layouts for maximum annual energy yield	Complexity in integrating variable solar tracking angles
Boretti (2025)	Dual-tower CSP plants	Proposed improved optical efficiency and reduced spillage losses in a dual-tower configuration	Enhanced thermal management and overall system efficiency	Higher capital investment required
Alfailakawi et al. (2024)	Aerosols' impact on CSP efficiency	Hybridization with wind turbines to optimize performance in arid environments	Improved LCOE and water consumption efficiency	Reduced capacity factor without TES integration
Yang et al. (2022)	Integrated SPT-S-CO_2 Brayton cycle	Reviewed integrated design and off-design operation methods	Improved understanding of off-design performance for better control	Variability in operational results across different plant configurations
Gul et al. (2025)	AI-enhanced operational efficiency	AI-based forecasting and optimization for SPT power prediction	Highly accurate predictions and improved dispatch capabilities	Sensitivity to weather and economic factors

technology improvements, supportive policies, and increasing demand for renewable energy in the world. In fact, from a mere 1.3 GW at the end of 2008, the CSP market grew up to 5 GW by 2016 (Heller, 2017; Ondrey, 2009). Technological improvements have positioned CSP tower systems as leaders in areas with high values of direct normal irradiance, such as the United States, the Middle East, North Africa, Australia, and parts of China, on the basis of efficiency and their competitive levelized cost of electricity (Xu et al., 2016). International Energy Agency anticipates that in 2030, the capacity of CSP would rise to 73 GW and hundreds of GW by 2050 on the condition of sustaining an average annual growth of approximately 30% (Lilliestam et al., 2023). However, challenges persist on large capital investment, infrastructure development, and market dynamics influenced by the likes of capacity allocation and local content requirements. Overall, reviewed research work has addressed recent progress on these fields: proposing novel receiver designs, better coatings, heliostat field optimization, and many other ideas.

The main type of CSP-SPT technology plays a very important role in the implementation of renewable energy targets due to their high efficiency, capability for energy storage, economic viability, and environmental benefits. They operate at higher temperatures, enabling superior thermodynamic efficiency, integrated thermal energy storage, and hence electricity production during non-solar hours, solving intermittency problems with solar energy production (Buck & Schwarzbözl, 2018; Guédez et al., 2015; Soltani et al., 2014). Hybrid systems, like Integrated Solar Combined Cycle (ISCC), improve efficiency and further reduce the cost, enhancing their economic viability (M. Alfailakawi et al., 2023; AlKassem, 2021). The use of these systems cuts down greenhouse gas emissions and causes less environmental degradation compared to fossil fuels; therefore, these plants comply with the objectives on climate change at a worldwide level (Soltani et al., 2014). Technological development, both in new materials and design, continuously improves the performance of such systems while reducing costs, thus making them quite promising for large-scale deployment (Achkari & El Fadar, 2020; Telsnig et al., 2017). Especially valuable in regions of high DNI, such as the Middle East and North Africa, solar power towers contribute to energy security and are an economic driver, with successful projects like the PS10 plant in Spain leading the way (Ait Lahoussine Ouali et al., 2022; Buck & Schwarzbözl, 2018; Xu et al., 2016). Moreover, SPT technologies are critical in industrial applications as they deliver the corresponding high-temperature process heat for the synthesis of chemicals, material treatment, and other temperature-requiring processes (Bader & Lipiński, 2017; Blanco & Miller, 2017; D'Auria et al., 2024; Rafique et al., 2024). They allow the decarbonization of industries dependent on high-temperature heat, especially those above 400°C, through renewable thermal energy (Blanco & Miller, 2017; D'Auria et al., 2024; Rafique et al., 2024). Besides, their integration with thermal energy storage ensures continuity with a reliable heat supply even during non-solar periods, hence very useful in industrial processes that demand steady thermal energy (Andreozzi et al., 2019; Crespo et al., 2019; Rodat et al., 2020). The targeted development and deployment of SPT technology are crucial in achieving sustainable energy transitions globally.

This article provides a comprehensive overview of the technological advancements, challenges, and emerging trends in SPT systems. It evaluates the current state of research, identifies key innovations, and examines scalability and economic feasibility within the sector. Through bibliometric analysis, this review highlights research patterns, leading contributors, and evolving thematic trends in CSP research. By integrating bibliometric insights with technological evaluation, this study aims to outline key advancements in SPT systems and provide actionable recommendations for future development, aligned with global renewable energy goals. A summary of key research contributions in SPT systems is presented in Table 1, highlighting notable advancements, efficiency improvements, and existing challenges across various technological domains.

From these findings, the following review discusses some of the most important knowledge gaps in the literature on CSP tower systems. While past research has investigated certain technological advancements such as thermal energy storage, receiver design, and heliostat optimization, none have provided a broad, bibliometric-driven review of overall trends and innovations in the field. This review fills these gaps by contributing to the following areas:

- This paper provides a long-term and systematic review of worldwide research trends in Solar Power Tower technology during almost four decades, indicating the development trend of the field and the changing scientific emphasis.
- The research recognizes the most prolific authors, institutions, and countries, such as China, the United States, and Spain, pointing out main research centers and collaboration networks driving technological advancements in SPTs.
- By keyword co-occurrence and theme clustering, this review maps dominant themes of attention, such as heliostat field design, thermal energy storage, and receiver efficiency, while exposing emerging topics and under-explored research fronts.
- Through the analysis of citation patterns and highly cited articles, the study uncovers the underlying literature that has influenced the field, making a guide for entrants and a benchmark for future research.
- The findings offer strategic intelligence to policymakers and researchers through the identification of knowledge gaps, limited international collaboration, and opportunities for cross-disciplinary integration, which guide the strategic development of SPT technology.

These lessons form the foundation for the further development of CSP tower systems, guiding researchers and practitioners alike to innovate in accordance with sustainability goals and the transition to renewable energy. With the incorporation of bibliometric analysis and technological evaluation, the review provides a strong pillar for future breakthroughs in the field.

2. Methodology

2.1 Description of the bibliometric analysis approach

Bibliometric analysis is the systematic approach of quantification and visualization of the patterns, trends, and impacts of certain areas of research. It provides two important kinds of insights: performance analysis, focusing on productivity and impact as expressed by publications and citations; science mapping displays the structure and dynamics of a body of knowledge (Lim & Kumar, 2024; Mukherjee et al., 2022). The current research has been conducted to investigate the development of SPT research with respect to publication trends, collaboration networks, and influential publications by using bibliometric analysis. It would be a comprehensive insight into the scientific landscape, key players, hot topics, and gaps that need further investigation. This is done by gathering, processing, and analyzing data about bibliometrics based on established frameworks and tools.

2.2 Data sources

The bibliometric analysis is based on bibliometric data covering the broader spectrum of a publication, including the title of the article, source title, list of authors, affiliations, countries, abstracts, keywords, and received citations together with cited references. Leading sources are relied on, among which the sources include Scopus and the Web of Science which offer comprehensive scholarly information across a wide range of fields (Birkle et al., 2020; Pranckutė, 2021).
Scopus gives wider coverage to publications, including non-English language and conference proceedings; hence, it is more complete as a source of thematic diversity. On the other hand, WoS is more reliable, more accurate, and better represents high-impact, peer-reviewed literature (Chirici, 2012; Zyoud et al., 2017). However, these databases differ significantly in document formats, keyword classifications, and time spans covered.
While either Web of Science or Scopus alone might be adequate, it is strongly advised to use both to build a far more extensive and thorough collection of scientific literature (Donthu et al., 2021; Kraus et al., 2022; Paul et al., 2021). Although their coverage varies, which could result in discrepancies, their combined use enables the incorporation of a greater range of contributions (Lim et al., 2024).

2.3 Keywords, search strategy, and analysis tools

In this study, data extraction for the bibliometric analysis was done from renowned databases: Scopus and Web of Science databases. These two databases have been selected in the paper due to their wide coverage of peer-reviewed literature from different disciplines. The keywords (KWs) "solar power tower", "CSP tower", "concentrated solar power tower", "central receiver system", and "solar thermal power tower" are some of the most commonly used author keywords within the titles and abstracts of publications in this area of research. Moreover, for the core components, different sets of additional keywords were combined with main KWs using the Boolean operators, such as AND or OR, together with wildcards. Searches were limited to journals and conference proceedings, all in the English language, covering the period from 2015 to the present.

Advanced visualization was used throughout, adding VOSviewer and RStudio to process and analyze the bibliometric data. VOSviewer (van Eck & Waltman, 2010) and RStudio (Aria & Cuccurullo, 2017) are powerful tools that have transformed scientific research into many ways. VOSviewer focuses on bibliometric analysis which allows researchers to visualize and interpret networks of co-authorship, co-citation, and keyword co-occurrence. Its capability for mapping trends and collaboration with the help of advanced algorithms, such as the VOS technique, makes it an essential tool for knowledge of the structure of scientific knowledge. VOSviewer is a work of user-friendly, interactive interfaces that simplifies the analysis of large-scale bibliographic data from major databases: Web of

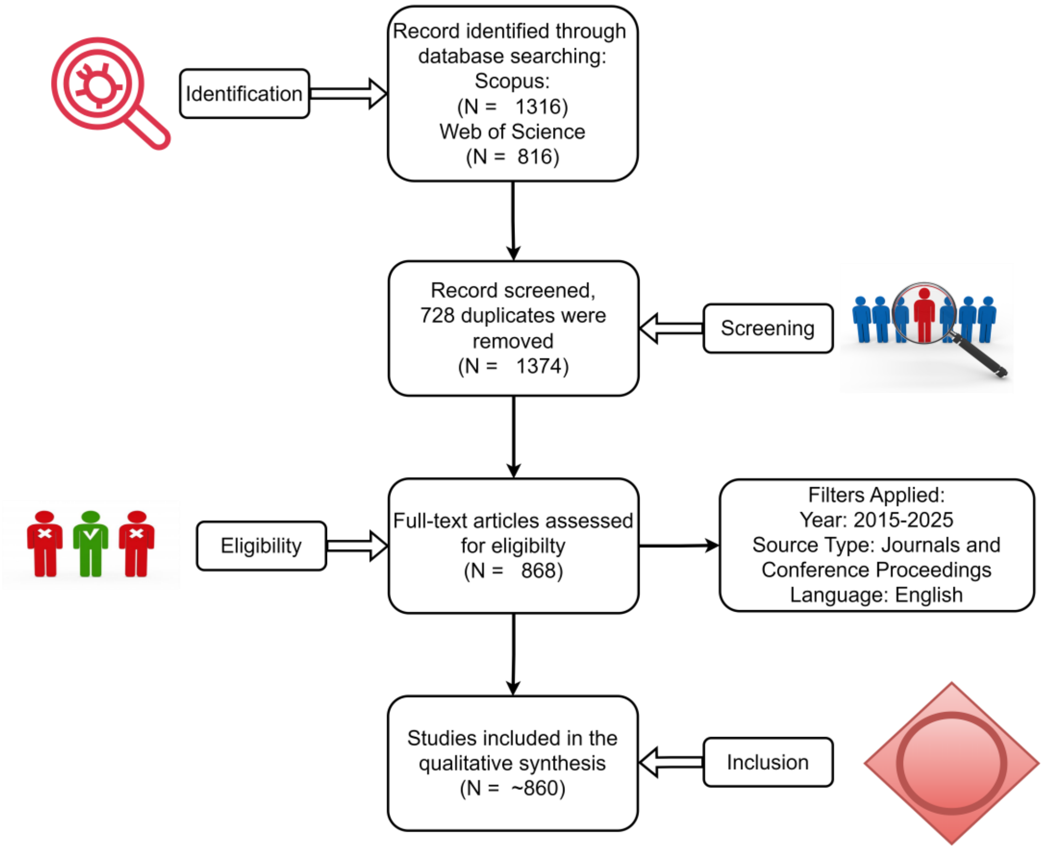


Fig. 1. PRISMA flowchart outlining the methodology for analyzing the research landscape of Solar Power Tower

Science, Scopus, and PubMed (Arruda et al., 2022). Its clustering methods for related items, like authors or keywords, provide insight into the thematic research areas; this thus aids strategic decision-making in policy formulation. The wide applicability underlines its scientific importance for medicine, the social sciences, and technology.

While VOSviewer is a great tool in visualizing bibliometric networks and their structures by understanding the research trend, it primarily acts within the realm of mapping relationships, such as co-authorship, keyword co-occurrence, and citation networks. It does not allow for advanced statistical modeling, data customization, or flexibility with complex datasets beyond what its functionality can handle. That is where RStudio comes into play. RStudio is a comprehensive setting that enables complicated statistical data analysis, data processing, and sophisticated visualization, which goes beyond standard outputs from VOSviewer. It grants researchers the right to clean, manipulate, and merge datasets, apply customized statistical methods, and develop customized visualizations beyond what VOSviewer offers. It allows overcoming some shortcomings in VOSviewer for a deeper and more substantial analysis of bibliometric data.

Contrarily, RStudio is an integrated development environment for the R programming language: a very powerful new way to do data analysis, statistical computing, and data visualization. Advanced statistical methods, machine learning, and even big data processing are possible in RStudio, thus providing a very powerful means for a researcher to perform both exploratory and predictive analytics. RStudio is very good at data visualization because it provides libraries like ggplot2 and shiny for producing high-quality, web-based interactive visualizations and dashboards. Its applications also cover bioinformatics, where other packages, like Bioconductor, perform such analysis on genomic data. As an open-source platform, RStudio is within reach for researchers all over the world, with an active huge community extending the capabilities of R by their various packages and extensions.

Alone in VOSviewer, the data from different data sources cannot be combined. Rstudio provides the prevision to combine and merge the data extracted from different data sources such as Scopus and WOS. VOSviewer and RStudio together meet different needs in scientific research. It is impossible to forgo the understanding of bibliometric networks, and research trends brought by VOSviewer, although in-depth statistical modeling, processing, and visualization are provided within a comprehensive environment in RStudio. These help a researcher dig more, be productive, and thereby contribute to the building of knowledge in different aspects.

2.4 Criteria for study selection and categorization

Selection and categorization for this bibliometric investigation have been done based on predefined inclusion and exclusion criteria to ensure relevance and quality in research, as shown in Fig. 1. The paper selects those articles that focus on concentrated SPT systems, involving the main theme of technological advancement, aspects of system efficiency, and energy storage solutions. The works would include peer-reviewed articles, and high-impact conference papers in English. Such publications over the last decades were targeted to carry the recent developments and trends. Various thematic areas guided the categorization of articles selected for the study, including innovation in heliostat field design, thermal energy storage system development, employing high-temperature materials for efficiency, and comparative analyses of CSP tower systems against other renewable energy technologies. This ensured a wide-based but focused

Table 2. Keyword strings and search results for SPT research across Scopus and Web of Science databases

Primary		Additional KWs	With Filters	
KWs String			Scopus	WoS
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")			809	652
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")	**AND**	("heliostat field" OR "heliostat optimization" OR "heliostat tracking" OR "solar field design")	226	188
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")	**AND**	("solar receiver" OR "high-temperature receiver" OR "volumetric receiver" OR "cavity receiver" OR "molten salt receiver")	170	126
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")	**AND**	("thermal energy storage" OR "molten salt storage" OR "phase change material storage" OR "sensible heat storage")	121	110
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")	**AND**	("optical losses" OR "thermal losses" OR "wind effects on heliostats" OR "mirror degradation" OR "receiver efficiency")	67	45
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")	**AND**	("optimization" OR "numerical simulation" OR "ray tracing" OR "machine learning" OR "artificial intelligence in CSP")	287	315
("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")	**AND**	("hydrogen production from CSP" OR "solar thermochemical hydrogen" OR "solar fuels" OR "hybrid CSP")	9	4

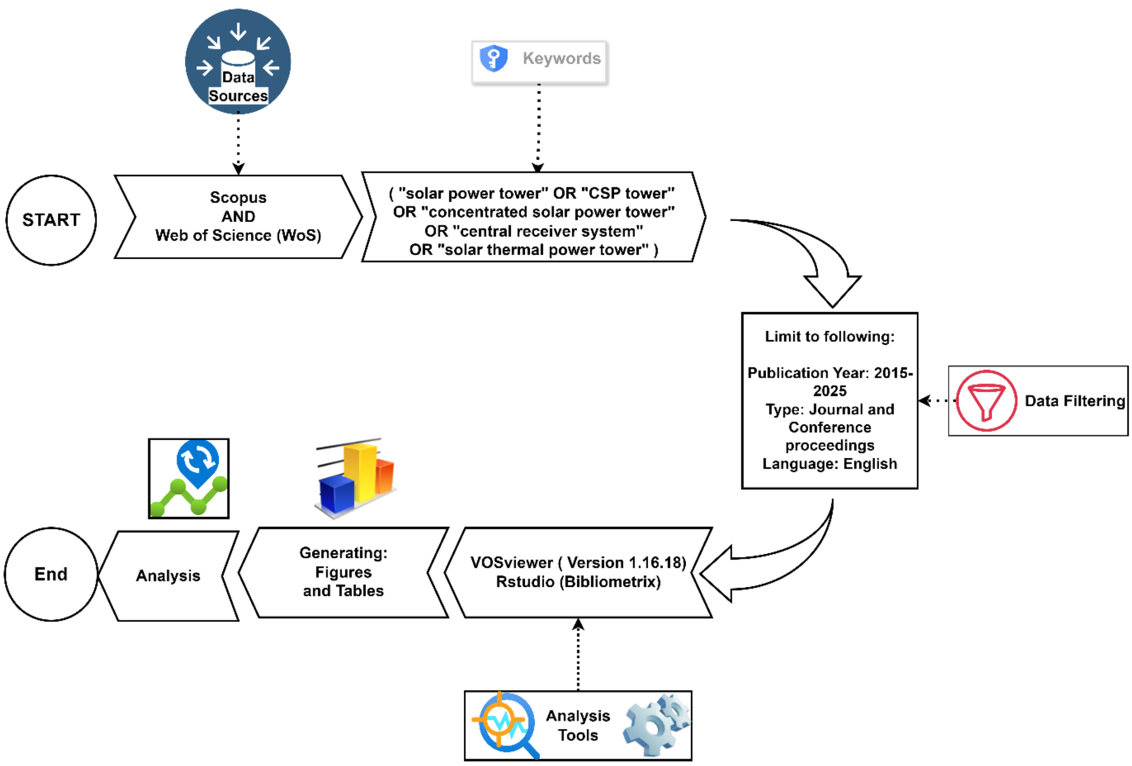


Fig. 2. Methodology for bibliometric analysis

canvassing of technological frontiers in CSP tower systems.

The bibliometric analysis reveals significant insights into the research trends and gaps in the domain of SPTs. When considering the primary keywords alone (such as, ("solar power tower" OR "CSP tower" OR "concentrated solar power tower" OR "central receiver system" OR "solar thermal power tower")), the number of publications is substantial, with 1316 papers in Scopus and 806 in WoS. However, applying the filters "Year = 2015-2025", "Source = Journal & Conference Proceedings", and "Language = English" further decreased the number of publications to 809 papers in Scopus and 652 in WoS.

The number of articles with additional keywords in both Scopus and WoS are shown in Table 2. Heliostat studies, for instance, have yielded 226 and 188 articles in Scopus and WoS, respectively, while studies of solar receivers have yielded 170 (Scopus) and 126 (WoS) articles, illustrating medium interest. The importance of thermal energy storage (TES) is evident from the 121 articles in Scopus and 110 in WoS dedicated to the topic. In contrast, system losses like "optical losses" and "receiver efficiency" receive less attention, with only 67 articles in Scopus and 45 in WoS. Optimization and simulation techniques are most researched with 287 (Scopus) and 315 (WoS) publications that reflect more extensive use of computational tools. However, newer topics such as hydrogen generation and hybrid CSP plants are the least researched, with only 9 (Scopus) and 4 (WoS) publications, reflecting significant gaps and potential areas for future research. Overall, the review emphasizes a strong concentration on conventional components like heliostats, receivers, and TES, and an increasing attention to simulation and optimization approaches. Yet relatively unexplored areas like efficiency losses and hydrogen generation offer possible windows for future innovation and research. Fig. 2 presents the overall methodology for bibliometric analysis.

3. Trends in SPT research

3.1 Analysis of publication and citation trends over time

The bibliometric analysis of the research publications, shown in Fig. 3, indicates growth that is gradual but constant, with 53 starting in 2015 and a peak in the years 2018 and 2019 with 97 each. In the year 2020, this fell slightly to 82, then again increased to 87 in the

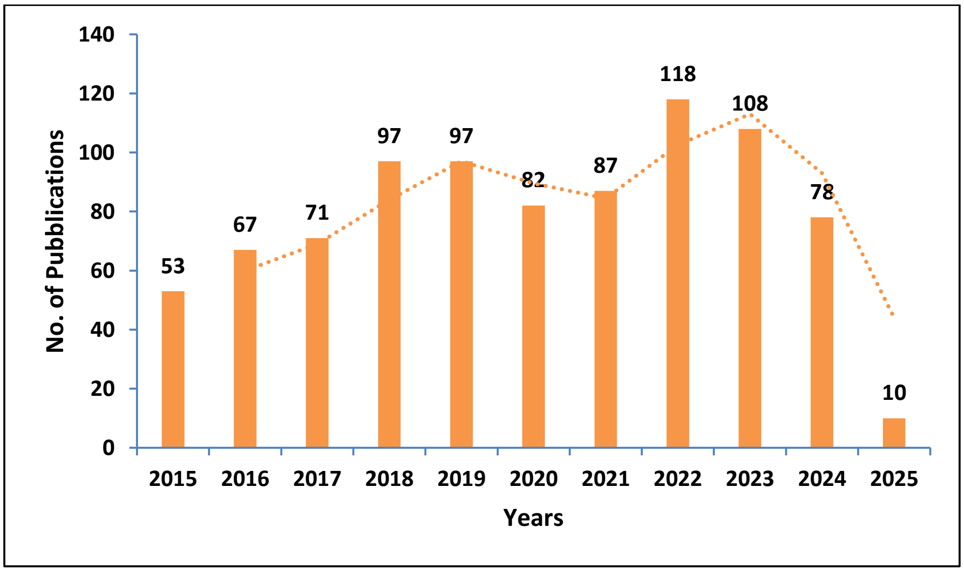


Fig. 3. Publication trends from 2015 to 2025

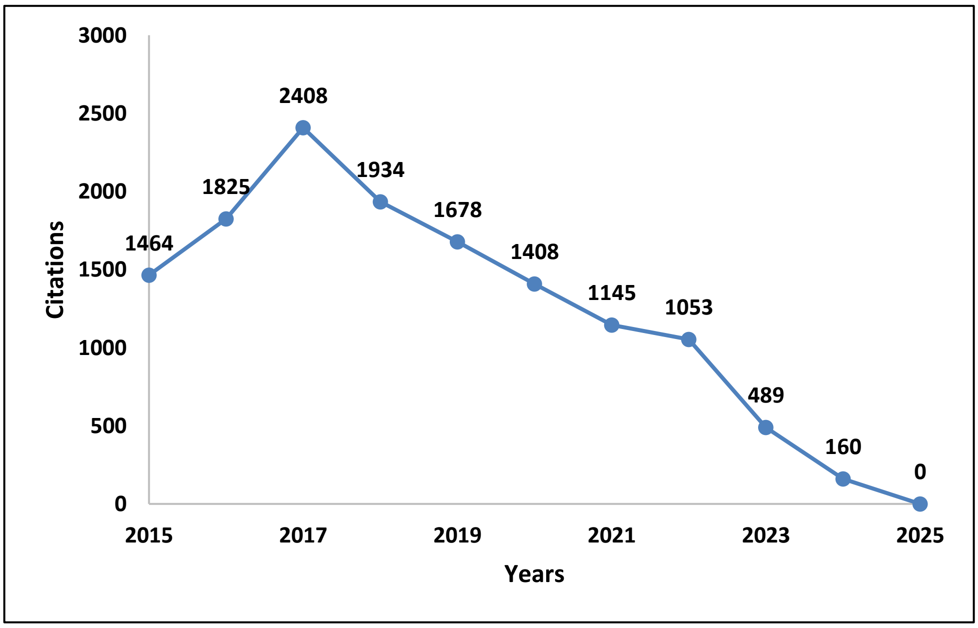


Fig. 4. No. of citations trends from 2015 to 2025

year 2021. The growth was so huge that, in 2022, the research interest reached its climax, with 118 publications. This was followed by a decline in 2023, with 108 publications, and further in 2024, with 78 publications. This may mean a shift of research focus, saturation, or some other factor that affects publication trends. The sharp drop in 2025, with just 10 publications, is presumably due to the incompleteness of the data, since this year is running and more works are expected. Overall, there is a trend of research interest growth until recent years, when fluctuations have become evident.

Fig. 4 presents the number of citations of articles from 2015 to 2025. The citations were highest in 2017 (2,408 citations), suggesting a high impact of research from publications between 2015-2017. Citations decreased steadily after 2017 to 1,934 (2018), 1,678 (2019), and 1,408 (2020), followed by a decline to 1,145 (2021) and 1,053 (2022). The downward trend was steeper in 2023 (489 citations) and 2024 (160 citations), with zero citations in 2025, likely due to the reality that recent publications have not yet had time to receive citations. This is characteristic of the citation life cycle, with earlier papers accumulating citations initially before later decreasing as new research is published. The peak in 2017 indicates that work produced between 2015-2017 was highly influential, and the decrease thereafter indicates changing research priorities and normal citation aging.

3.2 Prolific authors, institutions, and countries

Fig. 5 shows the most prolific authors in SPT research in terms of the number of publications. Santana D is the most prolific author with 47 publications, which is almost twice the next most prolific authors, Rodríguez-Sánchez M and He Y (23 each). This indicates Santana D has made a large contribution to developing research in this area. Other authors like Wang Z (20), Sánchez-González A (18), González-Gómez P (18), and Ballestrín J (18) also make major contributions, comprising a varied panel of experts. Khan Y (17), Alonso-Montesinos J (17), and Du X (16) form the rest of the list, indicating the presence of researchers worldwide. In this review, leading researchers whose work is driving SPT technology forward are identified, and it helps to determine possible collaboration and productive research. Table 3 presents the top institutions for research on solar power towers. Xi'an Jiaotong University ranks first in productivity (45) and impact (1716 citations) with the highest mean citation per paper (38.13). University Carlos III Madrid, though second in output (40), is less productive (16.30 citations per paper). Organizations such as NREL (USA) and DLR (Germany), although publishing fewer articles (21 and 19, respectively), achieve high impact with 21.00 and 22.21 citations per article, indicating an emphasis on high-impact research. Chinese organizations are predominant, with five of the top ten, indicating China's leadership in this area. Spain's institutes

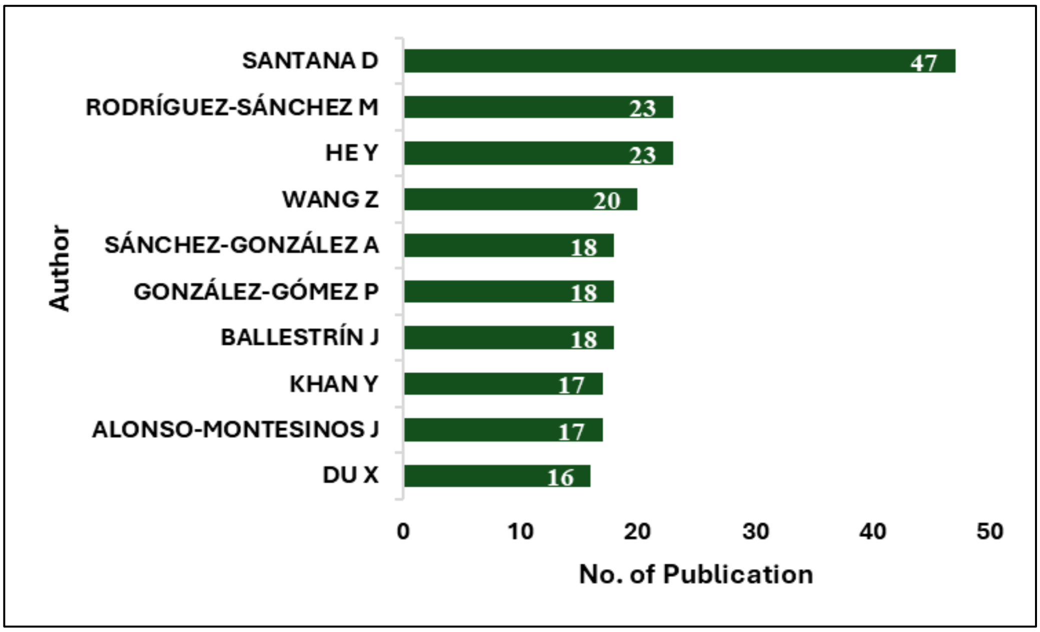


Fig. 5. Most relevant authors from 2015-2025

Table 3. Top 10 Research Institutions in SPT Studies: Publications, Citations, and Impact Metrics

Rank	Organization	Publications	Citations	Average Citation per Article
1	Xi An Jiao Tong Univ	45	1716	38.13
2	Univ Carlos Iii Madrid	40	652	16.30
3	North China Elect Power Univ	31	542	17.48
4	Chinese Acad Sci	27	410	15.19
5	Univ Almeria	27	282	10.44
6	Zhejiang Univ	24	149	6.21
7	Ciemat	23	236	10.26
8	Natl Renewable Energy Lab	21	441	21.00
9	Univ Chinese Acad Sci	20	359	17.95
10	German Aerosp Ctr Dlr	19	422	22.21

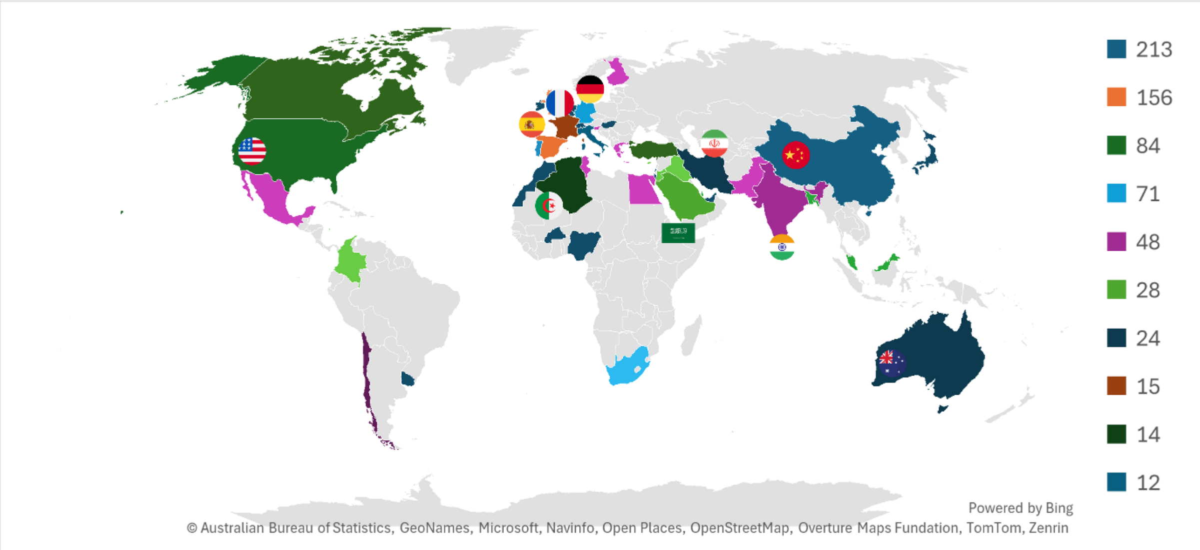


Fig. 6. Number of publications for different countries from 2015-2025

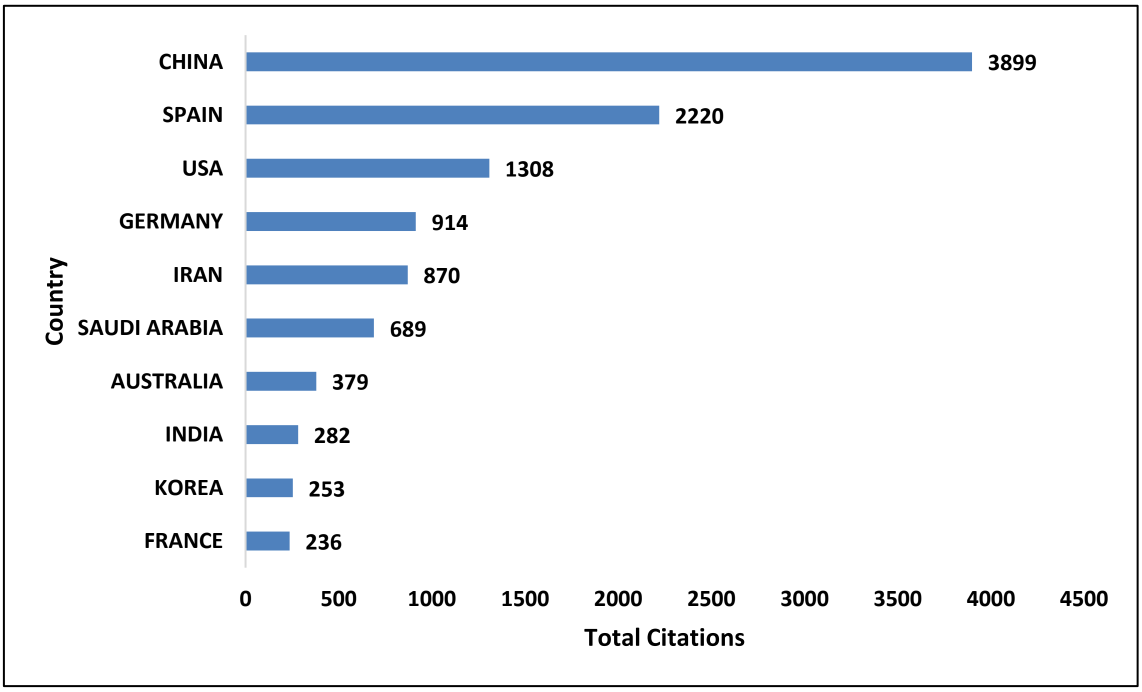


Fig. 7. Most cited countries in terms of TCs

including University Carlos III Madrid and CIEMAT also contribute, but they have less citation impact. Overall, however, while publication count indicates research activity, citation impact signifies influence.

The world map of the distribution of authors, shown in Fig. 6, identifies the foremost countries that have made the largest contributions to research in SPTs. The United States is the leading country with the most papers (213) followed by China (156), demonstrating their wide research interest and investment in the technology of solar energy. The European countries, led by Germany, Spain, France, and Italy, also make strong contributions, in line with their achievements in concentrated solar power (CSP) along with renewable energy policy. India (71) and Australia (24) are the biggest contributors from the Asia-Pacific region, given their greater emphasis on solar power solutions on account of favorable climatic conditions as well as government programs. Whereas developed countries set the pace with regard to publications, emerging economies like Iran, Saudi Arabia, and South Africa show growing activity, which is essential for CSP installation in countries with high solar potential. Cooperation between these countries, especially the research-driven countries and countries/regions rich in high solar resources, may help speed up the development and installation of SPT systems around the world. The distribution trend also indicates the contribution of regional policies, finance prospects, and business partnerships in influencing the research direction of solar energy technologies. The Fig. 7 indicates the total citations (TCs) of papers on SPT studies by nation. China has the highest, with 3,899 citations, reflecting its leading research capacity. Spain has the second-highest number, with

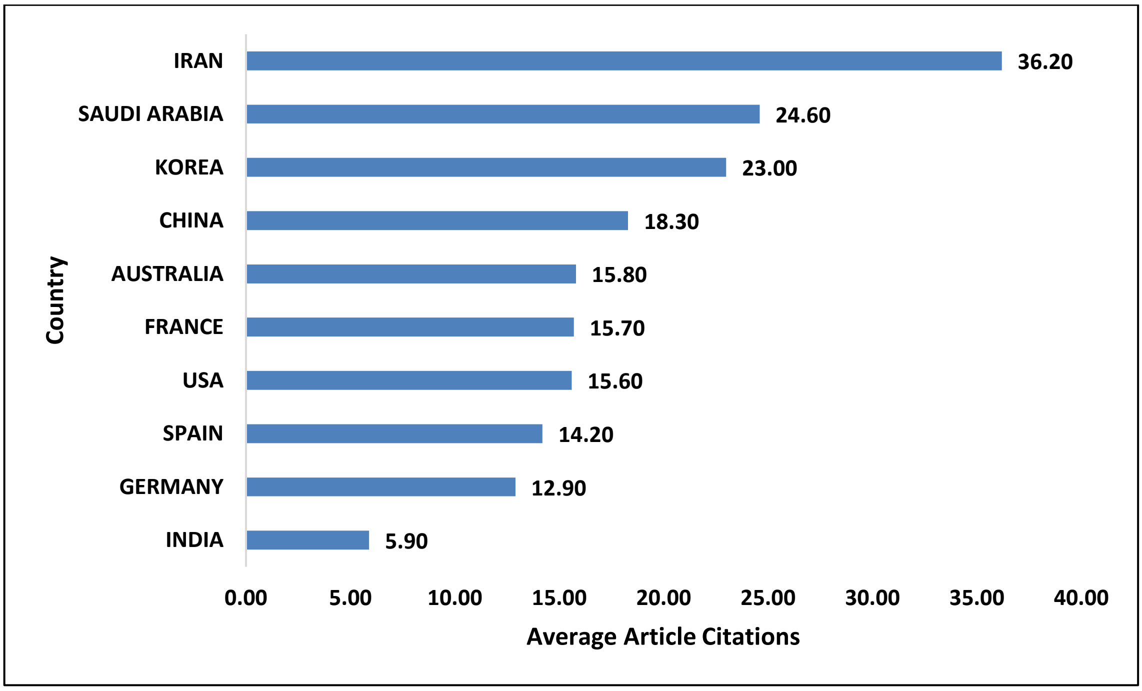


Fig. 8. Top 10 countries in terms of average citations per article

2,220 citations, reflecting its high contributions, which may be due to its advanced solar power plants like PS10 and Gemasolar. The USA has the third position (1,308 citations), reflecting its ongoing research despite lower citations than those of Spain. European nations (France, Germany) and Middle Eastern nations (Saudi Arabia, Iran) also make substantial contributions, indicating worldwide research interest. Australia, India, Korea, and France have comparatively fewer citations but still make contributions to the field. The spread indicates that China and Spain are the main research centers, with other nations making contributions to different extents.

Fig. 8 shows the average number of citations per article for various countries, reflecting research impact and quality rather than total output. Iran leads with 36.2 citations per article, indicating high-impact publications despite a lower total citation count. Saudi Arabia comes next with 24.6, followed by Korea with 23.0; each demonstrates a very strong research impact and thus recognition of the respective works. China (18.3), with the most total citations, has a lower average per article, reflecting high publication numbers but relatively low individual impact. Australia, France, and the USA (~15-16 citations each) are similar in research impact, whereas Spain (14.2) and Germany (12.9), although with high overall contributions, have low citation averages. India (5.9) is the lowest, a sign of lower research impact or newer contributions. This review identifies those certain nations (such as, Iran, Saudi Arabia, Korea) are specialized in high-impact research, whereas others (such as, China, Spain, Germany) are active based on quantity. These patterns inform us regarding the major players along with probable research collaborations.

3.3 Key publications, journals, and conferences driving SPT research

Table 4 presents the most cited articles in SPT research. The most cited study, Ho (2017), focuses on central receiver technologies and thus emphasizes their crucial contribution to system efficiency improvement. Several studies have cited the integration of s-CO_2 Brayton cycles, with Wang et al. (2017, 2018) being some of the more popular ones, hence underlining their emergence due to superior thermodynamic performance. This review of the optimization of s-CO_2 cycles is presented by other works, such as those of Al-Sulaiman et al. (2015) and Reyes-Belmonte et al. (2016), hence pointing to a shift towards research in advanced power cycles. Thermal energy storage is still a vital topic, as Myers (2016) investigated chloride salts and eutectics, and Lorenzin et al. (2016) reviewed liquid metals as alternative heat transfer fluids. The role of computational tools for system optimization is also highlighted: Wagner et al. (2018) propose SolarPilot for improvements in solar field layout, while Sánchez-González et al. (2015) proposed a method to analyze the distribution of solar flux. Future studies in this field will most probably involve further efficiencies in the receiver, hybridization of s-CO_2 cycles with novel storage solutions, and the advancement of heat transfer fluids. Besides, AI-driven optimization and modelling tools would feature more prominently in this area for better performance and economic viability.

Table 5 shows the ranking of journals and conferences in terms of the number of publications, citations, and average citations per article on solar power tower research. Energy Conversion and Management with Rank 5 and Applied Energy with Rank 6 are the two most influential journals with an average citation of 40.92 and 41.03, respectively. Solar Energy is ranked 1st with 74 publications, but it has a lower citation rate, 18.38 citations per article, meaning high research output but comparably moderate influence per paper. Conferences like SolarPACES 2020 and SolarPACES 2017 have lower citation counts and averages, reflecting that conference papers generally receive fewer citations than journal publications. More specially, highly cited research would then seem to emanate from major energy journals while conferences hold a second and very relevant role.

3.4 Keywords analysis

The bibliometric analysis shows that numerous research themes interact with each other in the respective research areas for SPT technologies, as graphically illustrated through the network and overlay map in Fig. 9 (a) and (b), respectively. Centrality of the "solar power tower" underlines its very focal role as a connector of several topics of inter-disciplinary character. Major research themes are the

Table 4. Top 10 cited publications in SPT in both Scopus and Web of Science

Rank	Title	First Author	Journal	Year	Citations	Reference	Current IF
1	ADVANCES IN CENTRAL RECEIVERS FOR CONCENTRATING SOLAR APPLICATIONS	Ho C	SOLAR ENERGY	2017	325	[51]	6.0
2	INTEGRATION BETWEEN SUPERCRITICAL CO_2 BRAYTON CYCLES AND MOLTEN SALT SOLAR POWER TOWERS: A REVIEW AND A COMPREHENSIVE COMPARISON OF DIFFERENT CYCLE LAYOUTS	WANG K	APPLIED ENERGY	2017	313	[52]	10.1
3	THERMODYNAMIC ANALYSIS AND OPTIMIZATION OF A MOLTEN SALT SOLAR POWER TOWER INTEGRATED WITH A RECOMPRESSION SUPERCRITICAL CO_2 BRAYTON CYCLE BASED ON INTEGRATED MODELING	WANG K	ENERGY CONVERSION AND MANAGEMENT	2017	286	[53]	9.9
4	PERFORMANCE COMPARISON OF DIFFERENT SUPERCRITICAL CARBON DIOXIDE BRAYTON CYCLES INTEGRATED WITH A SOLAR POWER TOWER	AL-SULAIMAN F	ENERGY	2015	273	[54]	9.0
5	THERMAL ENERGY STORAGE USING CHLORIDE SALTS AND THEIR EUTECTICS	MYERS P	APPLIED THERMAL ENGINEERING	2016	210	[55]	6.1
6	OPTIMIZATION OF A RECOMPRESSION SUPERCRITICAL CARBON DIOXIDE CYCLE FOR AN INNOVATIVE CENTRAL RECEIVER SOLAR POWER PLANT	REYES-BELMONTE M	ENERGY	2016	184	[56]	9.0
7	A SYSTEMATIC COMPARISON OF DIFFERENT S-CO_2 BRAYTON CYCLE LAYOUTS BASED ON MULTI-OBJECTIVE OPTIMIZATION FOR APPLICATIONS IN SOLAR POWER TOWER PLANTS	WANG K	APPLIED ENERGY	2018	163	[57]	10.1
8	SOLARPILOT: A POWER TOWER SOLAR FIELD LAYOUT AND CHARACTERIZATION TOOL	WAGNER M	SOLAR ENERGY	2018	147	[58]	6.0
9	A REVIEW ON THE APPLICATION OF LIQUID METALS AS HEAT TRANSFER FLUID IN CONCENTRATED SOLAR POWER TECHNOLOGIES	LORENZIN N	INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	2016	128	[59]	8.1
10	SOLAR FLUX DISTRIBUTION ON CENTRAL RECEIVERS: A PROJECTION METHOD FROM ANALYTIC FUNCTION	SÁNCHEZ-GONZÁLEZ A	RENEWABLE ENERGY	2015	124	[60]	9.0

various ensembles through which one gains insight into the development and bifurcation of SPT study lines. Following is the description of the different clusters of network map SPT:

Green Cluster: Heliostat field and receiver design

This cluster is about the development and optimization of heliostat fields and central receiver systems, where words such as "heliostat", "cavity receiver", "radiation", and "flux distribution" are commonly used. The strong connections that exist between the words "heliostat" and "flux distribution" imply considerable research into optimally configuring heliostats to gather maximum solar radiation. There is also considerable focus on central receiver systems and "volumetric receivers," considering the need to add complexity in receiving by integrating state-of-the-art optical and thermal designs.

Red Cluster: Energy Systems and Thermodynamic Analysis

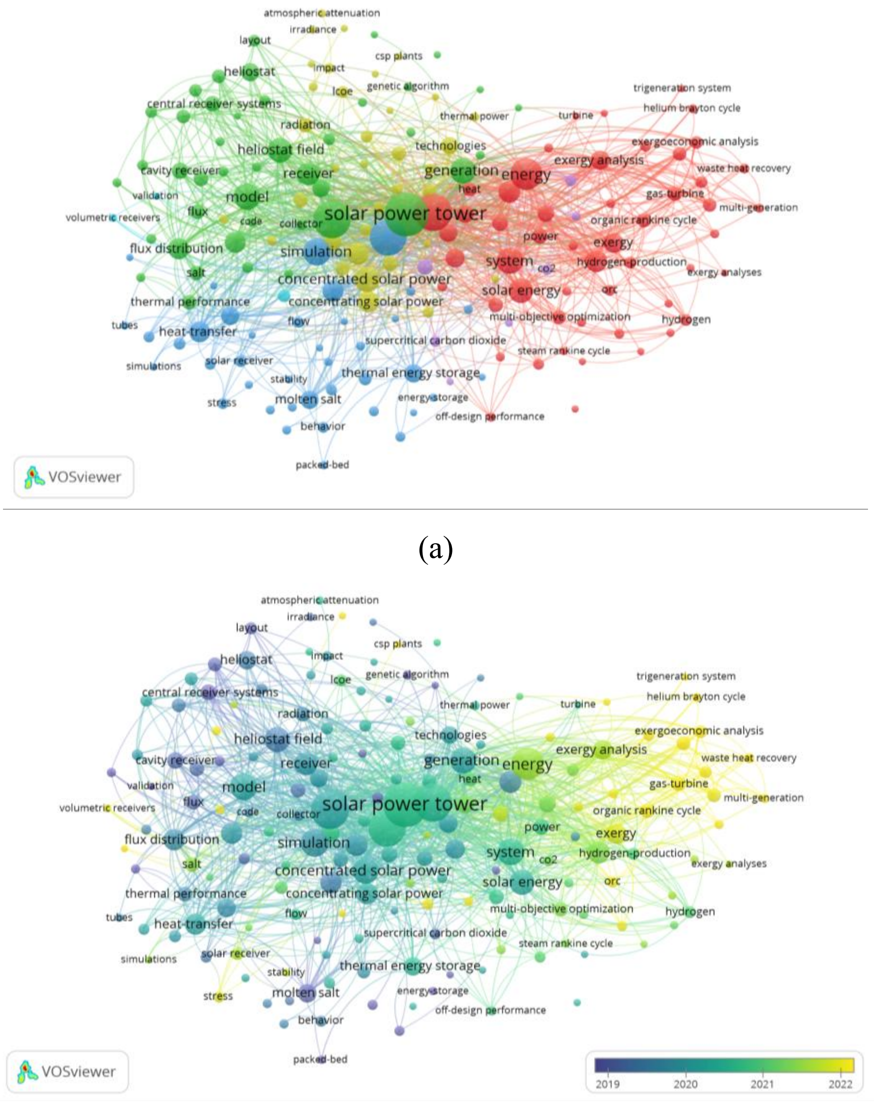
Relevant terms include "generation energy," "exergy analysis," and "organic Rankine cycle," hence the importance that this cluster possesses in terms of system performance. In addition to this, exergy analysis proves meaningful in knowing and analyzing a performance and sustainability concern to energy systems using solar power tower applications. Further, the researched and under-development recent technologies in the area include integrating gas turbines with hydrogen production and multi-generation systems, while all are heading toward hybrid systems for efficiency and versatility.

Blue Cluster: Heat Transfer and Thermal Energy Storage

This cluster includes studies on heat transfer fluids and thermal energy storage, including such key terms as "molten salt," "heat transfer,"

Table 5. Top 10 sources in SPT research in both Scopus and Web of Science

Rank	Journal	Publications	Citations	Average Citation per Article
1	Solar Energy	74	1360	18.38
2	Energy	55	1426	25.93
3	Renewable Energy	48	1049	21.85
4	Applied Thermal Engineering	39	1070	27.44
5	Energy Conversion and Management	36	1473	40.92
6	Applied Energy	32	1313	41.03
7	Solarpaces 2020 - 26Th International Conference On Concentrating Solar Power And Chemical Energy Systems	19	40	2.11
8	Energies	16	109	6.81
9	International Conference on Concentrating Solar Power and Chemical Energy Systems (Solarpaces 2017)	16	40	2.50
10	International Conference on Concentrating Solar Power and Chemical Energy Systems, Solarpaces 2014	12	212	17.67

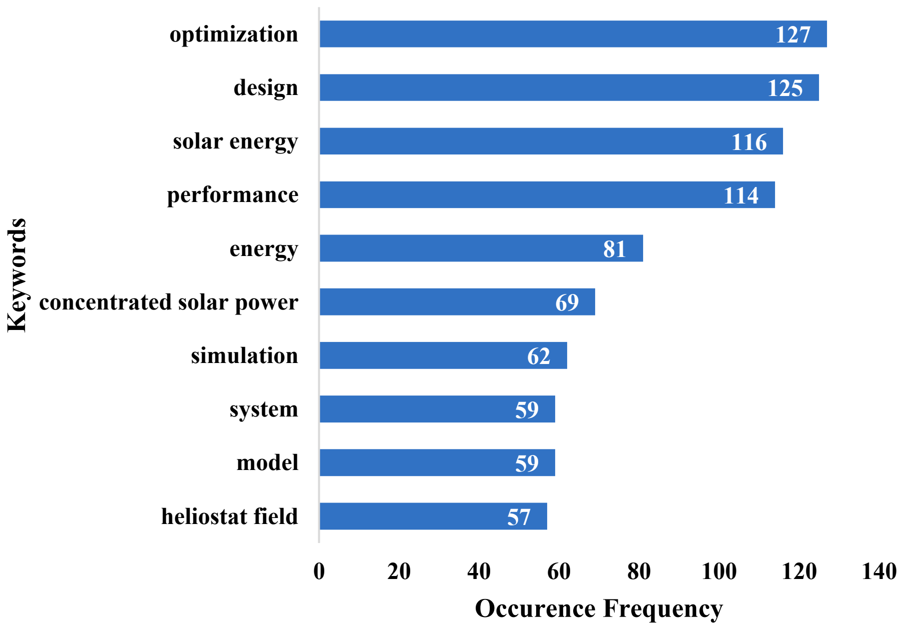


(a)

(b)

Fig. 9. Visualization of author keywords on SPT (a) Networks visualization (b) Overlay visualization

(a)



(b)

Fig. 10. (a) Word cloud of frequently used keywords (a) Top 10 most frequently used keywords

and "thermal energy storage". The strength of linkage between "molten salt" and "thermal energy storage" then figures how molten salt is still primarily the medium of choice applied in the contemporary SPT systems for the transport of heat at high temperatures, as well as for storage. Other topics, like "stress" and "stability," reflect challenges in ensuring the reliability of thermal systems operating under fluctuating conditions.

Yellow Cluster: Optimization Strategies and New Techniques

The broad applicability of optimization methods for SPT is highlighted in this cluster. Keywords such as "genetic algorithm", "optimization", and "layout" indicate the use of advanced computational techniques in system design and performance improvement. Multi-objective optimization frameworks combine improvements in efficiency, cost-effectiveness, and operational stability into one framework for realization.

Cross-Cluster Connections and Emerging Research Trends

The network map depicts high interconnectivity among the clusters, further showing that research on SPT is an interdisciplinary area of work. "Thermal energy storage" and "hydrogen production" linked with SPTs deal with the production of hydrogen for sustainable energy. More important among them are "Simulation," "optimization," and "energy storage" as indicators of using model-based methods to improve system performance. Innovations, specifically AI-driven methods, illustrate the increasing relevance of AI for enhancing heliostat efficiency, heat transfer simulation, and real-time control of systems, with "genetic algorithms" among others being employed to optimize such processes. This bibliometric analysis shows the width and depth of research in the field of SPT systems, including established areas, standing challenges, and emerging trends.

The word cloud, as shown in Fig. 10 (a) identifies the prominent research directions in SPT technology, with a focus on design, optimization, performance, and simulation. The prominent technological aspects are heliostat fields, central receiver systems, molten-salt storage, and heat transfer mechanisms, indicating attempts at improving efficiency and energy conversion. Computational techniques such as multi-objective optimization, thermodynamic analysis, and exergy analysis are commonly used to improve system performance. The emphasis on solar power generation, power towers, and concentrated solar power indicates the relevance of these studies in the development of renewable energy solutions. Fig. 10 (b) presents the top 10 most common keyword searches, indicating the primary research priorities in SPT. Optimization (127) and design (125) take top priority with an emphasis on efficiency improvement, while solar energy (116) and performance (114) emphasize energy conversion and system performance. Energy (81) and concentrated solar power (69) reveal the general research context of CSP. Simulation (62), system (59), and model (59) reflect extensive computational assessment. Heliostat field (57) underlines its important contribution to system efficiency. In general, research focuses on design, performance, and model optimization to improve concentrated solar power technology.

3.5 Thematic Mapping

Fig. 11 shows the thematic map of SPT research that includes development areas that are most significant, future trends, and fundamental themes. Solar power, concentrated solar power, and central receiver systems under the motor themes quadrant are most crucial for CSP technology advancement. While optimization, heliostat fields, and solar power towers are recognized as basic themes, they still need further development. A significant gap exists in the limited focus on cyber-physical integration and system resilience,

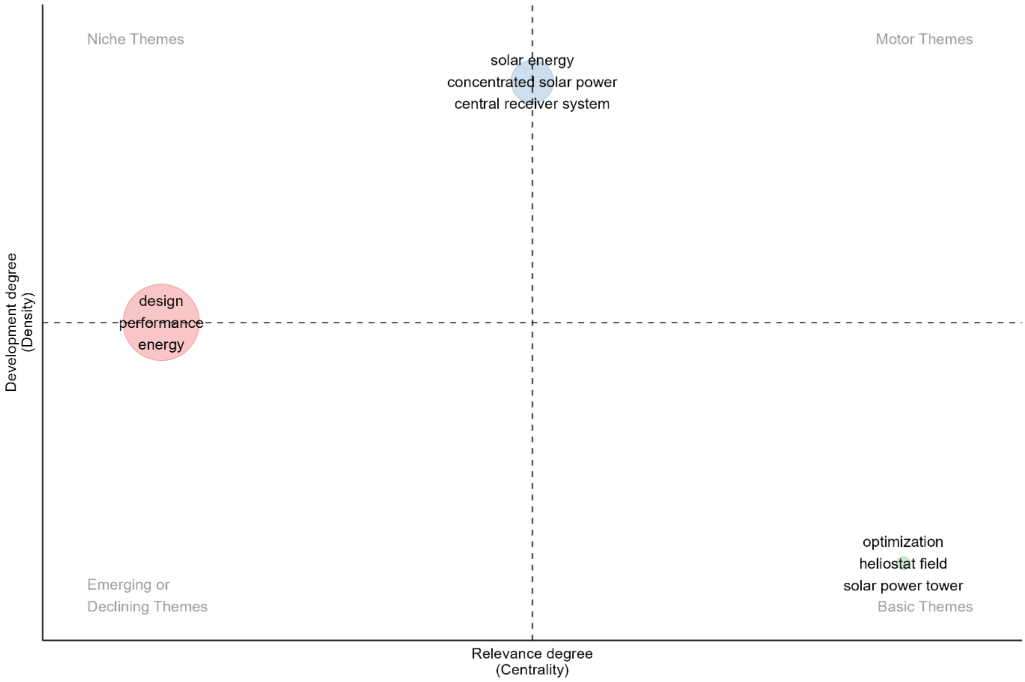


Fig. 11. Thematic map of SPT research

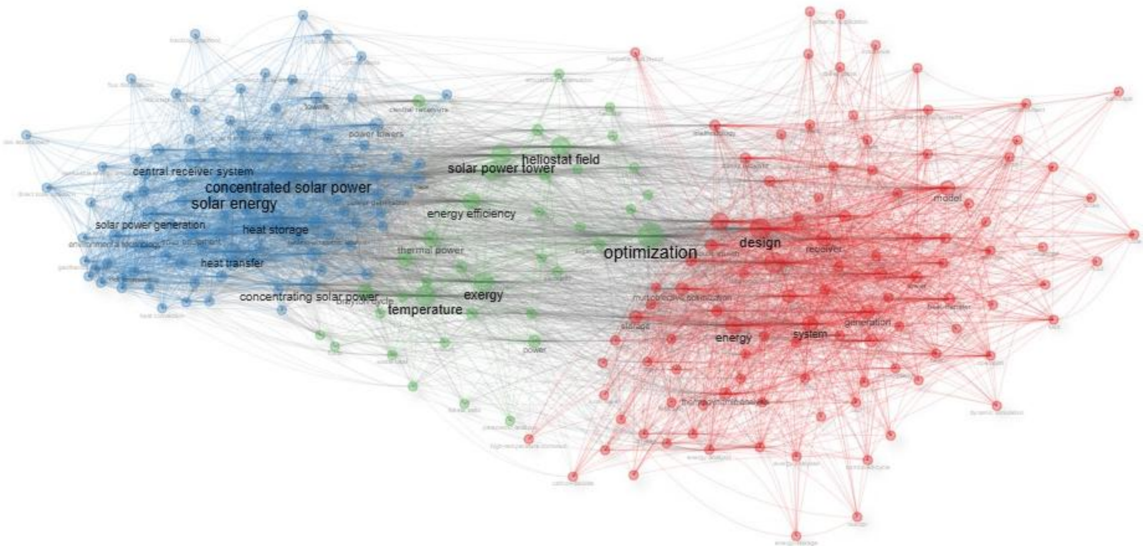


Fig. 12. Thematic Network Map of SPT Research

Table 6. Thematic Network Analysis of Concentrated Solar Power (CSP) Research

Cluster	Key Concepts	Role in CSP Research	Connections & Observations	Justification for Further Research
BLUE: Core CSP Technologies	Concentrated Solar Power, Solar Energy, Central Receiver System, Solar Power Generation, Heat Storage, Heat Transfer	Fundamental research themes form the backbone of CSP advancements.	Highly dense interconnections indicate a well-established research focus.	Essential to refine storage solutions, energy conversion methods, and scalability.
GREEN: Performance Optimization & Energy Efficiency	Optimization, Heliostat Field, Solar Power Tower, Energy Efficiency, Exergy, Temperature, Thermal Power	Focuses on increasing energy efficiency and optimizing CSP performance.	Bridges between efficiency improvements and system integration strategies.	Directly supports economic and environmental optimization of CSP towers.
RED: System Design & Cyber-Physical Aspects	Design, System, Energy, Generation, Receiver, Model	Emphasizes system modeling, simulation, and cyber-physical resilience in CSP.	Strong linkage to optimization, highlighting system resilience and smart control needs.	Strengthens cyber-physical integration, enabling predictive maintenance and system reliability.

which have the potential to enhance CSP systems through real-time data analytics, predictive maintenance, and adaptive control. Cyber-physical systems (CPS) integration can make SPTs more reliable and resilient. Besides, though optimization is a dominant theme, economic and environmental CSP tower optimization is not prioritized. This is an area that must be tackled to ensure cost-effectiveness improvement, energy loss minimization, and sustainability promotion. In this regard, incorporating CPS and economic-environmental optimization into CSP studies is crucial in filling research gaps, optimizing system performance, and facilitating long-term sustainability.

The Fig. 12 presents the thematic network map of SPT Research. Design and Cyber-Physical Aspects (Red). The blue cluster indicates core CSP technologies, such as solar energy, power generation, and heat storage, and emphasizes their firmly established position in research. Green cluster is centered on optimization approaches, i.e., heliostat field operation, exergy analysis, and temperature control, that act as a bridge between underlying CSP principles and system enhancement. The red cluster is dedicated to system design, modeling, and cyber-physical integration, with stress on why CSP systems need to be smartly monitored, proactively maintained, and automatically controlled.

Thematic network analysis of SPT research identifies three core clusters: Core CSP Technologies (Blue), Performance Optimization and Energy Efficiency (Green), and System Design & Cyber-Physical Aspects as shown in Table 6. The main findings of the analysis are that CSP core technologies are mature and fundamental, in need of advancements in scalability and integration of energy storage. Optimization approaches are essential in order to enhance system efficiency and sustainability, facilitating economic and environmental optimization of CSP towers. System modeling and cyber-physical integration are also emerging priorities, required for facilitating system resilience, reliability, and intelligent control. Cross-links between the clusters also indicate the necessity of interdisciplinary research between renewable energy technologies, AI-driven automation, and thermodynamics in unlocking CSP potential in the most optimal way. The dominant presence of optimization as a bridging factor also says a lot about the cost-saving and high-performance CSP solutions being required.

4. Research Gaps and Future Directions

The bibliometric study in the preceding section offers a holistic view of the evolution and intellectual landscape of SPT research. Yet, there are some key research gaps and emerging fields that deserve special attention to take the field forward. This section identifies these gaps and suggests strategic research directions for future study for technological advancement.

4.1 Receiver Design and TES Technological Gaps

Solar Power Tower (SPT) systems rely heavily on the efficiency of their thermal energy storage (TES) and receiver technologies for system efficiency, reliability, and economic viability. In spite of considerable progress, ongoing challenges continue to exist in both receiver design and TES media, particularly under the severe thermal and mechanical conditions necessitated by next-generation CSP applications. Molten salts, most typically Solar Salt (a eutectic mixture of $NaNO_3$ and KNO_3), are prevalent in commercial SPT systems because they have comparatively high energy density, thermal stability, and commercial readiness. Nevertheless, they also have some serious limitations. From a thermal perspective, Solar Salt is stable only to a temperature of around 565°C, which limits system efficiency and restrain integration with advanced high-temperature power cycles like supercritical CO_2 Brayton systems (Arévalo & Abánades, 2023; Majó et al., 2025; Niedermeier et al., 2018). Additionally, their freezing point is high (generally >240°C) such that it must be continuously heated to avert solidification, which raises parasitic energy use (Bonanos et al., 2019; Bonk et al., 2022). From a chemical standpoint, molten salts can also degrade with time, indicated through nitrite formation, and are corrosive to structural materials, which demand costly corrosion-resistant alloys (Bonanos et al., 2019; Ma et al., 2021). These issues lead to inefficiencies during operation and higher costs, particularly in startup and shutdown processes (Bonanos et al., 2019; Niedermeier et al., 2018).

Addressing the inadequacies of molten salt, several alternative TES materials have been suggested and investigated. Liquid metals, such as sodium, possess better thermophysical properties and can be used at temperatures above 1000°C but are very unsafe from a safety point of view due to their chemical activity (Arévalo & Abánades, 2023; Niedermeier et al., 2018; Yakufu et al., 2023). Chloride salts provide an extension of temperature up to 800°C and provide better thermal conductivity but are still too corrosive to contend with (Caraballo et al., 2021; Chung et al., 2023; Ding et al., 2018). Solid substances like quartzite and BOF slag are promising because of their high thermal capacity, stability at high temperature, and low price, especially for thermocline systems (Calderón et al., 2018; Elfeky et al., 2021; Majó et al., 2025). Salt doped with nanoparticles has higher specific heat and lower corrosiveness but is limited by issues of cost, nanoparticle agglomeration, and stability over the long term (Devaradjane & Shin, 2012; Muñoz-Sánchez et al., 2017). Fluoride salts, which function between 700-850°C, have the potential to raise thermal-to-electric conversion efficiency to as high as 50%, but are still in the early stages of development (Forsberg et al., 2007).

Thermochemical storage materials, i.e., metal hydrides and solid-gas reaction-based systems (for instance, Ca-looping), have very high energy density and reversibility, and thus are very well suited to be used at high temperatures. Yet, these systems still have substantial technical as well as economic hurdles with respect to the selection of material, integration, and thermal cycling stability (André et al., 2016; Tesio et al., 2019; Ward et al., 2016).

SPT receivers must function reliably under temperatures above 600°C, and as a consequence, there is a strong need for material selection and design optimization. Typical metallic materials such as stainless steel and nickel-based alloys have inadequate creep resistance and oxidation at high temperature (Colas et al., 2020). New materials like alumina-forming alloys (such as, FeCrAl) and ceramic parts have demonstrated better mechanical strength and oxidation resistance (D. Chen et al., 2019; Colas et al., 2020; Gobereit et al., 2016). However, the tradeoff between performance and manufacturability and cost is still a significant challenge (Conroy et al., 2018; Silva-Pérez, 2017).

Thermal cycling during operation causes fatigue and microstructural degradation, resulting in ultimate failure. Coatings like aluminum nitride (AlN) enhance thermal fatigue resistance but can crack during high-rate cyclic oxidation (D. Chen et al., 2019; Laporte-Azcué et al., 2021). Wind loading causes convective heat losses and mechanical loading, which can compromise structural efficiency and integrity. Emerging receiver developments and structural optimizations need to be carried out to counter these influences (Paetzold et al., 2014; Senthil et al., 2017). High solar flux densities cause high temperature gradients, which generate thermal stress that damages or deforms receiver materials. Non-uniform solar irradiance can cause local overheating, and heat flux distribution has to be carefully controlled while thermally stable absorber materials have to be developed (Y. Chen et al., 2022; J. Fang et al., 2021; Maytorena & Hinojosa, 2023).

In comparing TES materials, newer candidates have a tendency to improve over the standard molten salts in both thermophysical and financial terms. Examples include thermochemical and nanoscale salt-enhanced systems having higher energy densities and specific heat capacities than nitrate salts (Caraballo et al., 2021; Ma et al., 2021; Yakufu et al., 2023). Chloride salts provide higher operating temperatures than Solar Salt and have superior thermal conductivity at the cost of higher corrosion properties (Ding et al., 2018; Myers et al., 2015; D. Wei et al., 2024). Solid particles, such as quartzite and industrial slag, provide high-temperature stability and reduced costs, especially for single-tank thermocline systems (Elfeky et al., 2021; López Sanz et al., 2019; Majó et al., 2025). Economic analyses indicate that newer TES systems such as encapsulated PCMs and thermocline tanks with inexpensive filler materials can take advantage of a 25-50% cost savings compared to traditional two-tank molten salt systems (Jacob et al., 2016). Furthermore, the application of alternative materials such as slag and concrete shows reduced environmental impacts in terms of lower embodied energy compared to nitrate-based salts (Jacob et al., 2016; Miró et al., 2015).

In order to develop TES and receiver technology further, work should be targeted towards the development of inexpensive, corrosion-resistant, high-temperature storage media. Hybrid molten salt-solid particle or liquid metal systems have the potential to enhance thermal performance and system durability. Pilot-scale demonstration and long-term cyclic durability tests need to be conducted to ascertain the performance of these materials at operating conditions.

For receiver design, future research should focus on materials for high-temperature absorbers, thermal fatigue-resistant coatings, and receiver configurations that minimize thermal gradients and resist deformation. Integration of computational models and experimental results will still be required to optimize materials and system-level performance for the next generation of CSP tower applications.

4.2 Underexplored Themes: Hydrogen, AI, CPS Integration

New technologies like solar thermochemical hydrogen production, artificial intelligence (AI), and cyber-physical systems (CPS) provide transformational potential to improve the performance, reliability, and sustainability of SPT systems. However, in spite of recent developments, these topics are significantly under-investigated in current SPT research.

Recent developments in solar thermochemical hydrogen production have been in the direction of reactor efficiency, cost, and scale-up of the system. Advances in reactor design and materials science have increased the solar-to-fuel conversion efficiency in hybrid thermochemical cycles like the sulfuric acid cycle (Hojiev et al., 2024; Kumar, 2024). Hybrid systems coupling solar power towers with novel thermochemical cycles can potentially reduce the cost of hydrogen production relative to conventional photovoltaic-electrolyzer systems (Kolb et al., 2007). Novel processes, for instance, photothermal-assisted hydrogen evolution, also utilize solar thermal energy in improving process efficiency by pyroelectric enhancement and recombination suppression (Zhang et al., 2024). However, challenges persist, particularly regarding the thermal and chemical stability of materials used in high-temperature reactors, which drive up system costs and complexity (Kumar, 2024; Z. Liu et al., 2025). Moreover, the integration of high-efficiency thermochemical reactors into tower infrastructure presents considerable engineering and control difficulties. While the long-term potential for clean hydrogen production is promising, further research is needed to improve system reliability and economic feasibility (Hojiev et al., 2024; Pregger et al., 2009).

Artificial intelligence has also started playing a significant part in SPT operation optimization, such as heliostat control, thermal energy storage, and predictive maintenance. AI-driven algorithms, i.e., neural networks and other machine learning algorithms, have greatly enhanced heliostat tracking accuracy and control over the traditional calibration procedures (Q. Liu et al., 2025; Sievers et al., 2025). These methods provide real-time mirror position optimization with improved solar field performance overall. AI also enables predictive maintenance through historical and real-time data analysis to foresee equipment failure, minimize unplanned downtime, and prolong asset life (Pramanik, 2024). In TES system control, AI-based models like Random Forest Regressors and cross-validation frameworks have been employed to optimize important parameters like flow rates and mirror angles and thereby maximize storage capacity and minimize operating costs (Gul et al., 2025).

In addition, AI algorithms provide accurate predictions of solar irradiance and system output to improve energy management and operation planning for different environmental conditions (Gul et al., 2025; Pramanik, 2024). Despite their availability, large-scale applications of AI systems in CSP plants remain low because of data availability, model generality, and demands on computational resources. Cyber-physical systems (CPS), like digital twins integrated with Internet of Things (IoT) technologies, offer enabling capabilities for real-time system monitoring, system optimization, and predictive diagnostics in solar energy systems. Digital twins offer a virtual replica of physical assets, which allows operators to monitor, simulate, and control processes remotely (Aghazadeh Ardebili et al., 2025; Awouda et al., 2024; Stary et al., 2022). These models can enhance system reliability and sustainability through fault prediction and proactive maintenance intervention.

IoT sensor-based CPS systems and digital models also enable operational resilience through real-time information during outages and system recovery strategies (Aghazadeh Ardebili et al., 2025; Lampropoulos et al., 2024). Integration of CPS in solar towers enables data-driven decision-making, making it possible to forecast energy, balance loads, and schedule maintenance more effectively (Altan et al., 2025; Awouda et al., 2024).

In conclusion, the incorporation of hydrogen production, AI, and CPS into SPT systems is a viable direction for advancement. Their complete potential shall need to surmount technical, economic, and infrastructural challenges through multiscale research, pilot-scale demonstration, and standards development for safe and scalable deployment.

5. Conclusion

This bibliometric review provides a comprehensive analysis of global research trends, technological advancements, and emerging themes in SPT systems. Over the past decade, the field has experienced substantial growth in research output, driven by the need for sustainable, dispatchable energy solutions. The analysis reveals China, the United States, and Spain as dominant contributors to the field, with Xi'an Jiaotong University and the University Carlos III Madrid among the most prolific institutions. Influential authors, journals, and collaborations have shaped the intellectual structure of SPT research, particularly in areas such as heliostat field optimization, high-temperature receiver design, and thermal energy storage (TES) development.

The thematic mapping and keyword analyses highlight a strong research emphasis on system design, performance optimization, and the integration of advanced power cycles such as supercritical CO_2 Brayton cycles. While molten salts remain the prevalent TES medium, limitations in thermal stability, freezing point, and corrosivity have prompted significant exploration into alternative materials, including liquid metals, chloride salts, solid particles, and thermochemical systems. These novel materials offer higher operational temperatures and economic advantages, yet their widespread deployment is constrained by challenges in material compatibility, long-term stability, and cost.

Furthermore, this study identifies several underexplored but promising avenues of research. Solar thermochemical hydrogen production is gaining traction due to its potential for zero-carbon fuel generation, although material durability and complex integration remain concerns. The application of artificial intelligence (AI) in heliostat tracking, predictive maintenance, and TES control is beginning to transform SPT operations, improving efficiency and reliability. Similarly, cyber-physical systems (CPS), including digital twins and IoT-enabled platforms, offer real-time system optimization and resilience, although barriers such as data security, interoperability, and implementation costs must be addressed. In synthesizing bibliometric trends with technical evaluation, this study uncovers critical research gaps-particularly in materials development, CPS integration, and techno-economic optimization. As nations intensify their transition to renewable energy, SPT systems stand poised to play a pivotal role in achieving global sustainability and energy security goals.

Declaration of Competing Interest

The authors declared that no known competing interest is associated with this study from any organization or collaboration that could affect this process.

Acknowledgment

The authors of this work profoundly acknowledged the financial assistance received from the Higher Education Commission (HEC) - Pakistan and PETRONAS - Malaysia via grant YUTP - FRG, Cost Center No: 015LC0-544 for the supplementary funding of this research.

References

Achkari, O., & El Fadar, A. (2020). Latest developments on TES and CSP technologies – Energy and environmental issues, applications and research trends. Applied Thermal Engineering, 167. https://doi.org/10.1016/j.applthermaleng.2019.114806

Aghazadeh Ardebili, A., Martella, C., Longo, A., Rucco, C., Izzi, F., & Ficarella, A. (2025). IoT-Driven Resilience Monitoring: Case Study of a Cyber-Physical System. Applied Sciences 2025, Vol. 15, Page 2092, 15(4), 2092. https://doi.org/10.3390/APP15042092

Ait Lahoussine Ouali, H., Khouya, A., & Alami Merrouni, A. (2022). Numerical investigation of high concentrated photovoltaic (HCPV) plants in MENA region: Techno-Economic assessment, parametric study and sensitivity analysis. Sustainable Energy Technologies and Assessments, 53, 102510. https://doi.org/10.1016/j.seta.2022.102510

Alfailakawi, M., Alzahrani, K., Ingham, D., Hughes, K., Ma, L., & Pourkashanian, M. (2023). Multi-Objective Optimization of Solar Power Tower Hybridization with Gas Turbine and Thermal Energy Storage Back Up. Proceedings - International Conference on Energy Research and Development, ICERD, 2023(November).

Alfailakawi, M. S., Michailos, S., Ingham, D. B., Hughes, K. J., Ma, L., & Pourkashanian, M. (2024). Enhancing the performance of an aerosols-affected solar power tower in arid regions: A case study of wind turbines hybridization. Results in Engineering, 24. https://doi.org/10.1016/j.rineng.2024.102968

AlKassem, A. (2021). A performance evaluation of an integrated solar combined cycle power plant with solar tower in Saudi Arabia. Renewable Energy Focus , 39, 123–138. https://doi.org/10.1016/j.ref.2021.08.001

Al-Sulaiman, F. A., & Atif, M. (2015). Performance comparison of different supercritical carbon dioxide Brayton cycles integrated with a solar power tower.

Energy, 82, 61–71. https://doi.org/10.1016/J.ENERGY.2014.12.070
Altan, H., Chaer, I., Ozarisoy, B., Ba, L., Tangour, F., Abbassi, I. El, & Absi, R. (2025). Analysis of Digital Twin Applications in Energy Efficiency: A Systematic Review. Sustainability 2025, Vol. 17, Page 3560, 17(8), 3560. https://doi.org/10.3390/SU17083560
André, L., Abanades, S., & Flamant, G. (2016). Screening of thermochemical systems based on solid-gas reversible reactions for high temperature solar thermal energy storage. Renewable and Sustainable Energy Reviews, 64, 703–715. https://doi.org/10.1016/j.rser.2016.06.043
Andreozzi, A., Buonomo, B., Ercole, D., & Manca, O. (2019). Parallel triangular channel system for sensible heat thermal energy storages with external heat losses. ASME 2019 Heat Transfer Summer Conference, HT 2019, Collocated with the ASME 2019 13th International Conference on Energy Sustainability. https://doi.org/10.1115/HT2019-3607
Arévalo, R., & Abánades, A. (2023). THERMAL EVALUATION OF A SOLAR POWER TOWER EXTERNAL RECEIVER WITH LIQUID METAL AS HEAT TRANSFER FLUID IN NORTHERN CHILE. Heat Transfer Research, 54(2), 57–72. https://doi.org/10.1615/HeatTransRes.2022043516
Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics, 11(4), 959–975. https://doi.org/10.1016/J.JOI.2017.08.007
Arruda, H., Silva, E. R., Lessa, M., Proença, D., & Bartholo, R. (2022). VOSviewer and Bibliometrix. Journal of the Medical Library Association : JMLA, 110(3), 392. https://doi.org/10.5195/JMLA.2022.1434
Aslam, Z., Gilani, S. I. U. H., Mohamad, T. I., Muhammad, M., & Alao, K. T. (2025a). Technological frontiers and optimization in solar power towers: innovations in thermal energy storage, receivers, and heliostat systems. Clean Technologies and Environmental Policy 2025, 1–29. https://doi.org/10.1007/S10098-025-03337-Z
Aslam, Z., Gilani, S. I. U.-H., Mohamad, T. I., Muhammad, M., & Alao, K. T. (2025b). Optical performance analysis of small-scale heliostats field layout of solar power tower system in Malaysia. Energy Nexus, 100489. https://doi.org/10.1016/J.NEXUS.2025.100489
Awouda, A., Traini, E., Bruno, G., & Chiabert, P. (2024). IoT-Based Framework for Digital Twins in the Industry 5.0 Era. Sensors 2024, Vol. 24, Page 594, 24(2), 594. https://doi.org/10.3390/S24020594
Bader, R., & Lipiński, W. (2017). Solar thermal processing. In Advances in Concentrating Solar Thermal Research and Technology. https://doi.org/10.1016/B978-0-08-100516-3.00018-6
Birkle, C., Pendlebury, D. A., Schnell, J., & Adams, J. (2020). Web of science as a data source for research on scientific and scholarly activity. Quantitative Science Studies, 1(1), 363–376. https://doi.org/10.1162/QSS_A_00018
Blanco, M. J., & Miller, S. (2017). Introduction to concentrating solar thermal (CST) technologies. In Advances in Concentrating Solar Thermal Research and Technology. https://doi.org/10.1016/B978-0-08-100516-3.00001-0
Bonanos, A. M., Georgiou, M. C., Stokos, K. G., & Papanicolas, C. N. (2019). Engineering aspects and thermal performance of molten salt transfer lines in solar power applications. Applied Thermal Engineering, 154, 294–301. https://doi.org/10.1016/j.applthermaleng.2019.03.091
Bonk, A., Braun, M., & Bauer, T. (2022). Phase diagram, thermodynamic properties and long-term isothermal stability of quaternary molten nitrate salts for thermal energy storage. Solar Energy, 231, 1061–1071. https://doi.org/10.1016/j.solener.2021.12.020
Boretti, A. (2025). Perspective on Dual-Tower Concentrated Solar Power Plants. Applied Research, 4(1). https://doi.org/10.1002/appl.202400207
Buck, R., & Schwarzbözl, P. (2018). Solar Tower Systems. In Comprehensive Energy Systems (Vol. 4, pp. 692–732). Elsevier. https://doi.org/10.1016/B978-0-12-809597-3.00428-4
Calderón, A., Palacios, A., Barreneche, C., Segarra, M., Prieto, C., Rodriguez-Sanchez, A., & Fernández, A. I. (2018). High temperature systems using solid particles as TES and HTF material: A review. Applied Energy, 213, 100–111. https://doi.org/10.1016/j.apenergy.2017.12.107
Caraballo, A., Galán-Casado, S., Caballero, Á., & Serena, S. (2021). Molten salts for sensible thermal energy storage: A review and an energy performance analysis. Energies, 14(4). https://doi.org/10.3390/en14041197
Chen, D., Colas, J., Mercier, F., Boichot, R., Charpentier, L., Escape, C., Balat-Pichelin, M., & Pons, M. (2019). High temperature properties of AlN coatings deposited by chemical vapor deposition for solar central receivers. Surface and Coatings Technology, 377. https://doi.org/10.1016/j.surfcoat.2019.07.083
Chen, Y., Wang, D., Zou, C., Gao, W., & Zhang, Y. (2022). Thermal performance and thermal stress analysis of a supercritical CO_2 solar conical receiver under different flow directions. Energy, 246. https://doi.org/10.1016/j.energy.2022.123344
Chirici, G. (2012). Assessing the scientific productivity of Italian forest researchers using the Web of Science, SCOPUS and SCIMAGO databases. IForest - Biogeosciences and Forestry, 5(3), 101. https://doi.org/10.3832/IFOR0613-005
Chung, K. M., Zhang, Y., Zeng, J., Haddad, F., Adapa, S., Feng, T., Li, P., & Chen, R. (2023). In-situ thermophysical measurement of flowing molten chloride salt using modulated photothermal radiometry. Solar Energy, 265. https://doi.org/10.1016/j.solener.2023.112124
Colas, J., Charpentier, L., & Balat-Pichelin, M. (2020). Oxidation in Air at 1400 K and Optical Properties of Inconel 625, FeCrAlloy and Kanthal Super ER. Oxidation of Metals, 93(3–4), 355–370. https://doi.org/10.1007/s11085-020-09959-6
Collado, F. J., & Guallar, J. (2013). A review of optimized design layouts for solar power tower plants with campo code. Renewable and Sustainable Energy Reviews, 20, 142–154. https://doi.org/10.1016/j.rser.2012.11.076
Conroy, T., Collins, M. N., Fisher, J., & Grimes, R. (2018). Levelized cost of electricity evaluation of liquid sodium receiver designs through a thermal performance, mechanical reliability, and pressure drop analysis. Solar Energy, 166, 472–485. https://doi.org/10.1016/J.SOLENER.2018.03.003
Crespo, A., Barreneche, C., Ibarra, M., & Platzer, W. (2019). Latent thermal energy storage for solar process heat applications at medium-high temperatures – A review. Solar Energy, 192, 3–34. https://doi.org/10.1016/j.solener.2018.06.101
D'Auria, M., Grena, R., Lanchi, M., & Liberatore, R. (2024). Heat Supply to Industrial Processes via Molten Salt Solar Concentrators. Energies, 17(18). https://doi.org/10.3390/en17184541
Devaradjane, R., & Shin, D. (2012). Enhanced heat capacity of molten salt nano - Materials for concentrated solar power application. ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 8, 269–273. https://doi.org/10.1115/IMECE2012-87737
Ding, W., Bonk, A., & Bauer, T. (2018). Corrosion behavior of metallic alloys in molten chloride salts for thermal energy storage in concentrated solar power plants: A review. Frontiers of Chemical Science and Engineering, 12(3), 564–576. https://doi.org/10.1007/s11705-018-1720-0
Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research, 133, 285–296. https://doi.org/10.1016/J.JBUSRES.2021.04.070
Elfeky, K. E., Mohammed, A. G., & Wang, Q. (2021). Thermo-Economic Evaluation of Thermocline Thermal Energy Storage Tank for CSP Plants. Chemical Engineering Transactions, 88, 241–246. https://doi.org/10.3303/CET2188040
Fang, J., Zhang, C., Tu, N., Wei, J., & Wan, Z. (2021). Thermal characteristics and thermal stress analysis of a superheated water/steam solar cavity receiver under non-uniform concentrated solar irradiation. Applied Thermal Engineering, 183. https://doi.org/10.1016/j.applthermaleng.2020.116234
Fang, L., Li, Y., Yang, X., & Yang, Z. (2020). Analyses of thermal performance of solar power tower station based on a supercritical CO<inf>2</inf> brayton cycle. Journal of Energy Resources Technology, Transactions of the ASME, 142(3). https://doi.org/10.1115/1.4045083
Forsberg, C. W., Peterson, P. F., & Zhao, H. (2007). High-temperature liquid-fluoride-salt closed-brayton-cycle solar power towers. Journal of Solar Energy Engineering, Transactions of the ASME, 129(2), 141–146. https://doi.org/10.1115/1.2710245
García-Ferrero, J., Merchán, R. P., Santos, M. J., Medina, A., & Calvo-Hernández, A. (2022). Techno-economic analysis of Brayton concentrated solar power systems in the context of other power generation technologies. Proceedings of ECOS 2022 - 35th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 353–363.
Gobereit, B., Hofmann, D., Schwarzbözl, P., & Uhlig, R. (2016). High Temperature Solar Receiver with Ceramic Materials. In Ceramic for Energy

Conversion, Storage, and Distribution Systems (Vol. 255). https://doi.org/10.1002/9781119234531.ch19

Guédez, R., Topel, M., Spelling, J., & Laumert, B. (2015). Enhancing the Profitability of Solar Tower Power Plants through Thermoeconomic Analysis Based on Multi-objective Optimization. Energy Procedia, 69, 1277–1286. https://doi.org/10.1016/j.egypro.2015.03.155

Gul, E., Baldinelli, G., Wang, J., Bartocci, P., & Shamim, T. (2025). Artificial intelligence based forecasting and optimization model for concentrated solar power system with thermal energy storage. Applied Energy, 382. https://doi.org/10.1016/j.apenergy.2024.125210

Heller, P. (2017). Introduction to CSP Systems and Performance. In The Performance of Concentrated Solar Power (CSP) Systems: Analysis, Measurement and Assessment (pp. 1–29). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100447-0.00001-8

Ho, C. K. (2017). Advances in central receivers for concentrating solar applications. Solar Energy, 152, 38–56. https://doi.org/10.1016/J.SOLENER.2017.03.048

Hojiev, T., Akhmadov, K., Halimov, A., & Akhatov, J. (2024). Advancements in Solar Thermochemical Reactors for Sustainable Hydrogen Production. https://doi.org/10.1051/e3sconf/2024508

Jacob, R., Belusko, M., Inés Fernández, A., Cabeza, L. F., Saman, W., & Bruno, F. (2016). Embodied energy and cost of high temperature thermal energy storage systems for use with concentrated solar power plants. Applied Energy, 180, 586–597. https://doi.org/10.1016/j.apenergy.2016.08.027

Jiang, R., Li, M.-J., Wang, W.-Q., Li, M.-J., & Ma, T. (2024). A novel numerical methodology of solar power tower system for dynamic characteristics analysis and performance prediction. Energy, 292. https://doi.org/10.1016/j.energy.2024.130469

Khatti, S. S., Jeter, S., & Al-Ansary, H. (2021). Preliminary techno-economic optimization of 1.3 MW_e particle heating receiver based CSP power tower plant for the mena region. Proceedings of the ASME 2021 15th International Conference on Energy Sustainability, ES 2021. https://doi.org/10.1115/ES2021-63926

Kolb, G. J., Diver, R. B., & Siegel, N. (2007). Central-Station Solar Hydrogen Power Plant. Journal of Solar Energy Engineering, 129(2), 179–183. https://doi.org/10.1115/1.2710246

Kraus, S., Breier, M., Lim, W. M., Dabić, M., Kumar, S., Kanbach, D., Mukherjee, D., Corvello, V., Piñeiro-Chousa, J., Liguori, E., Palacios-Marqués, D., Schiavone, F., Ferraris, A., Fernandes, C., & Ferreira, J. J. (2022). Literature reviews as independent studies: guidelines for academic practice. Review of Managerial Science, 16(8), 2577–2595. https://doi.org/10.1007/S11846-022-00588-8/FIGURES/3

Kumar, A. (2024). Solar-integrated hydrogen production and utilization in India. Clean Energy: Technology, Advances, and Applications, 243–258. https://doi.org/10.1201/9781003521341-15

Lampropoulos, G., Larrucea, X., & Colomo-Palacios, R. (2024). Digital Twins in Critical Infrastructure. Information 2024, Vol. 15, Page 454, 15(8), 454. https://doi.org/10.3390/INFO15080454

Laporte-Azcué, M., González-Gómez, P. Á., de los Reyes Rodríguez-Sánchez, M., & Santana, D. (2021). Creep and fatigue damage assessment for molten-salt central receivers. Proceedings - ISES Solar World Congress 2021, 211–218. https://doi.org/10.18086/swc.2021.13.02

Lilliestam, J., Du, F., Gilmanova, A., Mehos, M., Wang, Z., & Thonig, R. (2023). Scaling Up CSP: How Long Will it Take? AIP Conference Proceedings, 2815(1). https://doi.org/10.1063/5.0148709

Lim, W. M., & Kumar, S. (2024). Guidelines for interpreting the results of bibliometric analysis: A sensemaking approach. Global Business and Organizational Excellence, 43(2), 17–26. https://doi.org/10.1002/JOE.22229

Lim, W. M., Kumar, S., & Donthu, N. (2024). How to combine and clean bibliometric data and use bibliometric tools synergistically: Guidelines using metaverse research. Journal of Business Research, 182, 114760. https://doi.org/10.1016/J.JBUSRES.2024.114760

Liu, Q., Dai, Z., Wei, Y., Wang, D., & Xie, Y. (2025). Transformative Impacts of AI and Wireless Communication in CSP Heliostat Control Systems. Energies 2025, Vol. 18, Page 1069, 18(5), 1069. https://doi.org/10.3390/EN18051069

Liu, Z., Xie, J., Song, C., Yang, X., & Kalogirou, S. A. (2025). A review of hydrogen production through solar energy with various energy storage devices. International Journal of Hydrogen Energy. https://doi.org/10.1016/J.IJHYDENE.2025.01.274

López Sanz, J., Cabello Nuñez, F., & Zaversky, F. (2019). Benchmarking analysis of a novel thermocline hybrid thermal energy storage system using steelmaking slag pebbles as packed-bed filler material for central receiver applications. Solar Energy, 188, 644–654. https://doi.org/10.1016/j.solener.2019.06.028

Lorenzin, N., & Abánades, A. (2016). A review on the application of liquid metals as heat transfer fluid in Concentrated Solar Power technologies. International Journal of Hydrogen Energy, 41(17), 6990–6995. https://doi.org/10.1016/j.ijhydene.2016.01.030

Ma, B., Shin, D., & Banerjee, D. (2021). One-step synthesis of molten salt nanofluid for thermal energy storage application – a comprehensive analysis on thermophysical property, corrosion behavior, and economic benefit. Journal of Energy Storage, 35. https://doi.org/10.1016/j.est.2021.102278

Majó, M., Svobodova-Sedlackova, A., Barcelona, P., Fernández, A. I., Calderón, A., & Barreneche, C. (2025). Long-Term Compatibility Testing of Solar Salt and Solid Particles at High Temperatures: A Thermal and Chemical Characterization. Energy Storage, 7(2). https://doi.org/10.1002/est2.70153

Maytorena, V. M., & Hinojosa, J. F. (2023). Computational analysis of passive strategies to reduce thermal stresses in vertical tubular solar receivers for safety direct steam generation. Renewable Energy, 204, 605–616. https://doi.org/10.1016/j.renene.2023.01.043

Miró, L., Oró, E., Boer, D., & Cabeza, L. F. (2015). Embodied energy in thermal energy storage (TES) systems for high temperature applications. Applied Energy, 137, 793–799. https://doi.org/10.1016/j.apenergy.2014.06.062

Mukherjee, D., Lim, W. M., Kumar, S., & Donthu, N. (2022). Guidelines for advancing theory and practice through bibliometric research. Journal of Business Research, 148, 101–115. https://doi.org/10.1016/J.JBUSRES.2022.04.042

Muñoz-Sánchez, B., Nieto-Maestre, J., Imbuluzqueta, G., Marañón, I., Iparraguirre-Torres, I., & García-Romero, A. (2017). A precise method to measure the specific heat of solar salt-based nanofluids. Journal of Thermal Analysis and Calorimetry, 129(2), 905–914. https://doi.org/10.1007/s10973-017-6272-x

Myers, P. D., & Goswami, D. Y. (2016). Thermal energy storage using chloride salts and their eutectics. Applied Thermal Engineering, 109, 889–900. https://doi.org/10.1016/J.APPLTHERMALENG.2016.07.046

Myers, P. D., Goswami, D. Y., Bhardwaj, A., & Stefanakos, E. (2015). Chloride salt systems for high temperature thermal energy storage: Properties and applications. ASME 2015 9th International Conference on Energy Sustainability, ES 2015, Collocated with the ASME 2015 Power Conference, the ASME 2015 13th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2015 Nuclear Forum, 1. https://doi.org/10.1115/ES2015-49460

Niedermeier, K., Marocco, L., Flesch, J., Mohan, G., Coventry, J., & Wetzel, T. (2018). Performance of molten sodium vs. molten salts in a packed bed thermal energy storage. Applied Thermal Engineering, 141, 368–377. https://doi.org/10.1016/j.applthermaleng.2018.05.080

Ondrey, G. (2009). Solar's second coming. Chemical Engineering, 116(3), 18–21.

Paetzold, J., Cochard, S., Vassallo, A., & Fletcher, D. F. (2014). Wind engineering analysis of parabolic trough solar collectors: The effects of varying the trough depth. Journal of Wind Engineering and Industrial Aerodynamics, 135, 118–128. https://doi.org/10.1016/j.jweia.2014.10.017

Paul, J., Lim, W. M., O'Cass, A., Hao, A. W., & Bresciani, S. (2021). Scientific procedures and rationales for systematic literature reviews (SPAR-4-SLR). International Journal of Consumer Studies, 45(4), O1–O16. https://doi.org/10.1111/IJCS.12695

Pramanik, S. (2024). AI's function in sustainable development's renewable energy planning. In Next Generation Materials for Sustainable Engineering. https://doi.org/10.4018/979-8-3693-1306-0.ch016

Pranckutė, R. (2021). Web of Science (WoS) and Scopus: the titans of bibliographic information in today's academic world. Publications, 9(1). https://doi.org/10.3390/PUBLICATIONS9010012

Pregger, T., Graf, D., Krewitt, W., Sattler, C., Roeb, M., & Möller, S. (2009). Prospects of solar thermal hydrogen production processes. International

Journal of Hydrogen Energy, 34(10), 4256–4267. https://doi.org/10.1016/J.IJHYDENE.2009.03.025

Rafique, M. M., Saw, W., Lee, L., Ingenhoven, P., & Nathan, G. (2024). Performance assessment of a system to provide steady high temperature air via solar thermal suspension flow technology with storage and combustion back-up. Solar Energy, 268. https://doi.org/10.1016/j.solener.2023.112270

Reyes-Belmonte, M. A., Sebastián, A., Romero, M., & González-Aguilar, J. (2016). Optimization of a recompression supercritical carbon dioxide cycle for an innovative central receiver solar power plant. Energy, 112, 17–27. https://doi.org/10.1016/J.ENERGY.2016.06.013

Rodat, S., Abanades, S., Boujjat, H., & Chuayboon, S. (2020). On the path toward day and night continuous solar high temperature thermochemical processes: A review. Renewable and Sustainable Energy Reviews, 132. https://doi.org/10.1016/j.rser.2020.110061

Sánchez-González, A., & Santana, D. (2015). Solar flux distribution on central receivers: A projection method from analytic function. Renewable Energy, 74, 576–587. https://doi.org/10.1016/j.renene.2014.08.016

Scott, A. W., Adefarati, T., Bansal, R. C., & Naidoo, R. (2021). CONCENTRATED SOLAR POWER COMPARISON FOR POWER TOWER AND PARABOLIC TROUGH SYSTEMS. IET Conference Proceedings, 2021(5), 476–481. https://doi.org/10.1049/icp.2021.2322

Senthil, R., Gupta, M., & Rath, C. (2017). Parametric analysis of a concentrated solar receiver with Scheffler reflector. International Journal of Mechanical and Production Engineering Research and Development, 7(5), 261–268. https://doi.org/10.24247/ijmperdoct201727

Sievers, L. T. E., Pargmann, M., Maldonado Quinto, D., & Hoffschmidt, B. (2025). End-to-end sensitivity analysis of a hybrid heliostat calibration process involving artificial neural networks. Solar Energy, 287. https://doi.org/10.1016/j.solener.2024.113219

Silva-Pérez, M. A. (2017). Solar power towers using supercritical CO<inf>2</inf> and supercritical steam cycles, and decoupled combined cycles. In Advances in Concentrating Solar Thermal Research and Technology. https://doi.org/10.1016/B978-0-08-100516-3.00017-4

Soltani, R., Mohammadzadeh Keleshtery, P., Vahdati, M., Khoshgoftarmanesh, M. H., Rosen, M. A., & Amidpour, M. (2014). Multi-objective optimization of a solar-hybrid cogeneration cycle: Application to CGAM problem. Energy Conversion and Management, 81, 60–71. https://doi.org/10.1016/j.enconman.2014.02.013

Stary, C., Elstermann, M., Fleischmann, A., & Schmidt, W. (2022). Behavior-Centered Digital-Twin Design for Dynamic Cyber-Physical System Development. Complex Systems Informatics and Modeling Quarterly, 2022(30), 31–52. https://doi.org/10.7250/CSIMQ.2022-30.02

Telsnig, T., Weinrebe, G., Finkbeiner, J., & Eltrop, L. (2017). Life cycle assessment of a future central receiver solar power plant and autonomous operated heliostat concepts. Solar Energy, 157, 187–200. https://doi.org/10.1016/j.solener.2017.08.018

Tesio, U., Guelpa, E., Ortiz, C., Chacartegui, R., & Verda, V. (2019). Optimized synthesis/design of the carbonator side for direct integration of thermochemical energy storage in small size Concentrated Solar Power. Energy Conversion and Management: X, 4. https://doi.org/10.1016/j.ecmx.2019.100025

van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523–538. https://doi.org/10.1007/S11192-009-0146-3/FIGURES/7

Wagner, M. J. M. J., & Wendelin, T. (2018). SolarPILOT: A power tower solar field layout and characterization tool. Solar Energy, 171(August 2016), 185–196. https://doi.org/10.1016/j.solener.2018.06.063

Wang, K., & He, Y. L. (2017). 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, 135, 336–350. https://doi.org/10.1016/J.ENCONMAN.2016.12.085

Wang, K., He, Y. L., & Zhu, H. H. (2017). Integration between supercritical CO2 Brayton cycles and molten salt solar power towers: A review and a comprehensive comparison of different cycle layouts. Applied Energy, 195, 819–836. https://doi.org/10.1016/J.APENERGY.2017.03.099

Wang, K., Li, M. J., Guo, J. Q., Li, P., & Liu, Z. Bin. (2018). A systematic comparison of different S-CO2 Brayton cycle layouts based on multi-objective optimization for applications in solar power tower plants. Applied Energy, 212, 109–121. https://doi.org/10.1016/J.APENERGY.2017.12.031

Ward, P. A., Corgnale, C., Teprovich, J. A., Motyka, T., Hardy, B., Sheppard, D., Buckley, C., & Zidan, R. (2016). Technical challenges and future direction for high-efficiency metal hydride thermal energy storage systems. Applied Physics A: Materials Science and Processing, 122(4). https://doi.org/10.1007/s00339-016-9909-x

Webby, B. (2013). Sensitivity analysis for concentrating solar power technologies. Proceedings - 20th International Congress on Modelling and Simulation, MODSIM 2013, 1496–1501.

Wei, D., Zhu, L., Ling, X., & Jiang, F. (2024). Research progress of MgCl<inf>2</inf>-NaCl-KCl molten salt for high-temperature heat storage | 高温储热用 MgCl<inf>2</inf>-NaCl-KCl 熔盐的研究进展. Energy Storage Science and Technology, 13(12), 4421–4435. https://doi.org/10.19799/j.cnki.2095-4239.2024.0855

Wei, J., Wan, Z., & Tu, N. (2015). Progress in water/steam cavity receivers in tower-type solar power plants | 塔式太阳能热发电水工质腔式吸热器研究进展. Kexue Tongbao/Chinese Science Bulletin, 60(7), 603–612. https://doi.org/10.1360/N972014-01050

Xiao, G., Nie, J., Xu, H., Zhang, C., & Zhu, P. (2022). Performance analysis of a solar power tower plant integrated with trough collectors. Applied Thermal Engineering, 214. https://doi.org/10.1016/j.applthermaleng.2022.118853

Xu, X., Vignarooban, K., Xu, B., Hsu, K., & Kannan, A. M. (2016). Prospects and problems of concentrating solar power technologies for power generation in the desert regions. Renewable and Sustainable Energy Reviews, 53, 1106–1131. https://doi.org/10.1016/j.rser.2015.09.015

Yakufu, A., Yang, Z., Xu, Y., & Wang, Q. (2023). Research on Thermal-Hydraulic Characteristics of Liquid Sodium Versus Molten Salt as A Fluid in Heat Exchanger. 2023 7th International Conference on Power and Energy Engineering, ICPEE 2023, 434–438. https://doi.org/10.1109/ICPEE60001.2023.10453870

Yang, J., Yang, Z., & Duan, Y. (2022). A review on integrated design and off-design operation of solar power tower system with S–CO<inf>2</inf> Brayton cycle. Energy, 246. https://doi.org/10.1016/j.energy.2022.123348

Zhang, J., Hu, Z., Zheng, J., Xiao, Y., Song, J., Li, X., Cheng, C., & Zhang, Z. (2024). Photothermal-assisted solar hydrogen production: A review. Energy Conversion and Management, 318, 118901. https://doi.org/10.1016/J.ENCONMAN.2024.118901

Zyoud, S. H., Waring, W. S., Al-Jabi, S. W., & Sweileh, W. M. (2017). Global cocaine intoxication research trends during 1975-2015: A bibliometric analysis of Web of Science publications. Substance Abuse: Treatment, Prevention, and Policy, 12(1), 1–15. https://doi.org/10.1186/S13011-017-0090-9