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Central Receiver-Based CSP Plants: Trends and Categorization

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Abstract. Central receiver-based concentrated solar power (CSP) systems play a crucial role in solar energy technology, particularly for their ability to operate at higher temperatures than conventional linear concentrators, and for better integration of thermal energy storage in a more direct manner. This paper methodically examines the development and classification of central receiver-based CSP technologies, including power towers, solar furnaces, and beam-down configurations. It aims to emphasize the operational advantages and challenges of these technologies through a literature review. This study identifies recent trends in technology deployment, including hybridization and co-location, highlighting their role in the evolving landscape of CSP, innovation, and possible integration with other renewables.

Keywords: Concentrated Solar Power (CSP), Central Receiver Based Plants, Categorization, Future Trends

1. Introduction

This study focuses on the development and categorization of future trends of central receiver-based concentrated solar power (CSP) plants. The characteristic for a system to fall into this definition is a CSP system that focuses the solar beams into a static focal point, which is the receiver. The configurations that fall into this classification and are considered for this literature review are solar towers (ST), beam-down systems, and solar furnaces. Such systems are relevant to study while, compared to other CSP systems, they can reach higher temperatures [1] at the same time that the receiver is in a fixed position, making it highly compatible with thermal energy storage (TES) systems [2]. The current state of renewable energy seems promising, with an increase in PV installation and novel materials that have increased solar cells' efficiency drastically [3]. However, renewable energies need to combine all strengths to fulfil the Sustainable Development Goals for the middle and long term. Thus, the inclusion of TES in the capability of the RE is one of the major strengths of CSP.

The analysis of future trends can only be supported by incorporating the past and technology development. Central receiver-based technology can be tracked to the mid-20th century [4]with early experimental projects in the order of tens of kWth, from furnace to tower configurations [5], [6]. Early stages utilized direct steam generation and were able to store energy only for self-operational purposes in case of a sunlight fade out such as the Eurelios power plant [7], eventually the transformation of the technology and the advance on the materials used in the heat transfer fluid (HTF) as well as the TES and the receiver itself allowed an increase of storage capacity and a variety of configurations from which there are advantages but also limitations and challenges.

This manuscript has the objective of reviewing experimental and commercial projects to understand the technology trends and categorize the technology. By examining configurations such as direct steam generation, molten salt, and emerging high-temperature technologies, we delve into the future pathways of the technology, highlighting the role of CSP in achieving long-term climate goals. The study also explores strategic opportunities for hybridization, co-location with other renewable technologies, and modular plant designs to reduce costs and increase operational flexibility.

2. Methodology

The methodology integrates a literature review, data collection, and central receiver analysis. The literature search is conducted using the Scopus database, while specific details on CSP plants is sourced from NREL [8], SolarPACES [9], and Guru CSP [10], and CSPfocus [11]. This study categorizes central receivers into four categories, providing a comprehensive overview of operational, under-construction, and demonstration plants. The analysis of the advantages and disadvantages of each technology progresses to the discussion, offering insights into the current status and future directions as highlighted by the reviewed literature. Finally, the paper summarizes key observations and their implications for future research, contributing valuable insights to the broader discourse on central receiver-based CSP plants.

3. Historical transition

The development of central receiver-based CSP technology was initiated in 1950 by the work of V. A. Baum, who first conceptualized the technology, studied the fundamental mathematics of the optical components in the system, and explored the techno-economic aspect of his proposal [12]. Although the first pilot plants were developed using the same general components, the main differences lay in their configurations, as the shape, size, placement of the mirrors, and the height of the receiver were diverse from project to project. The first experimental Solar Furnace was built in the 1950s with the objective of conducting high-temperature experiments in Mont Lius, France [5]. The project had the capacity to generate 50kWth and setting stage for the 1 MW Solar Furnace of Odeillo in France, built in the 1970s [13]. Furthermore, pilot plants such as St. Ilario-Nervi (1965) [6], and Solar plant No.1 (1965) in Genoa, Italy, started to look more to what currently is the solar tower configuration, with a set of mirrors oriented top towards the receiver that was placed in different ways above the mirrors.

From 1981 to 1985, the inaugural commercial ST plants were established, including Solar One (USA), Eurelios (Italy), NI COUTUR Nio (Japan), and THEMIS (France), with THEMIS possessing the highest capacity of 2.5 MWe. During this timeframe, other testing facilities were created, including the National Solar Thermal Test Facility (NSTTF) in the United States and Sunshine in Japan. Between 1985 and 1987, the Soviet Union significantly contributed to solar energy development by initiating the SES 5 and SPP-5 experimental plants, culminating in the establishment of the 1 MWth Parkent Solar Furnace in Uzbekistan in 1987.

Initial central receiver systems employed steel tube bundles for solar heat absorption; however, the THEMIS plant was the inaugural facility to utilize molten salt for both heat transmission and thermal storage for nocturnal operation. Initially, air was favored in Europe; however, the GAST experiment in the 1980s exposed the constraints of tube receivers caused by localized overheating. The volumetric receiver concept was first tested in the 1990s, and gave outstanding results with temperatures reaching 800°C. Solar Two (1996-1999) in the U.S. was a pioneering project that utilized Solar Salt and a two-tank storage system, achieving 154 consecutive hours of electricity generation. During the 2000s, 14 SPT projects commenced globally, and innovations such as ceramic volumetric absorbers started to develop. More over, the configuration of Beam Down was first piloted at Masdar Institute Solar Platform. The Beam

Down configuration stands out for its dual reflection, placing the receiver closer to the ground and incorporating a single tank TES, allowing easier maintenance and lower capital cost [14].

Currently, the field is noticing an increase in deployments that are under construction, with the majority of the new developments being ST in regions of the Middle East and China. Figure 1 shows the historical development of central receiver-based power plants, showing the distribution of experimental (below) and commercial (above) projects and clarifying their status by the filling color.

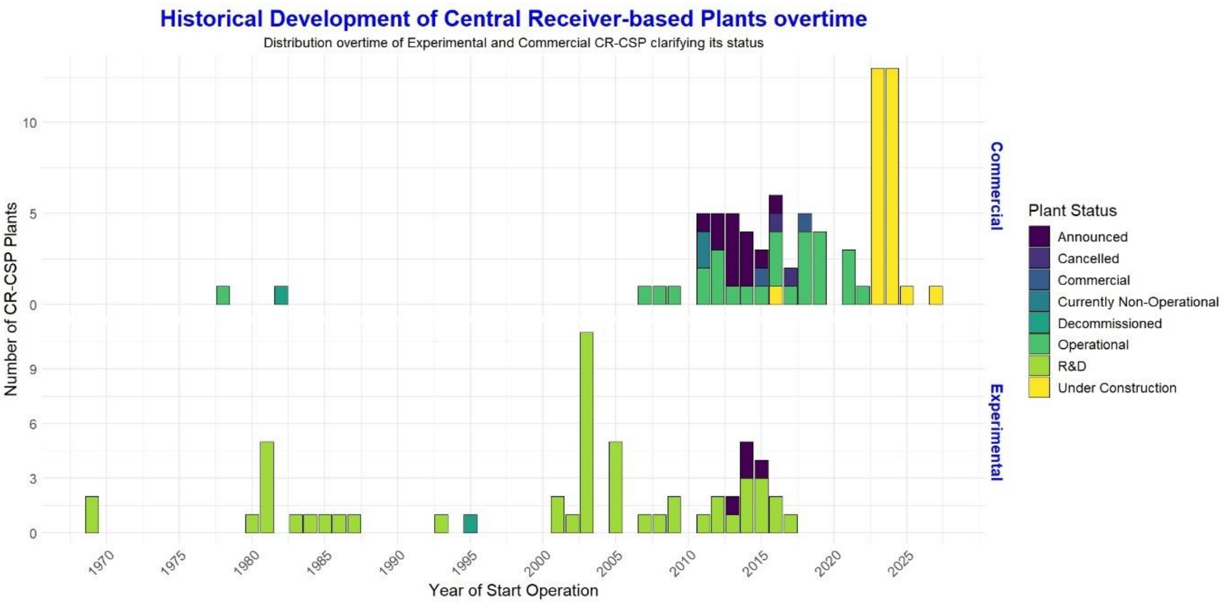

Figure 1. *Historical Development of Central Receiver-based Plants Over Time, clustered by commercial and experimental plants and current plant status (Own elaboration based on public data from [8], [9], [10]).*

4. Categorization

Figure 2 presents the categorization of the central receiver-based CSP plants based on the literature review into direct steam generation, molten salt, Liquid Sodium, and high-temperature technologies, including particle receiver, air ceramic, and sCO2.

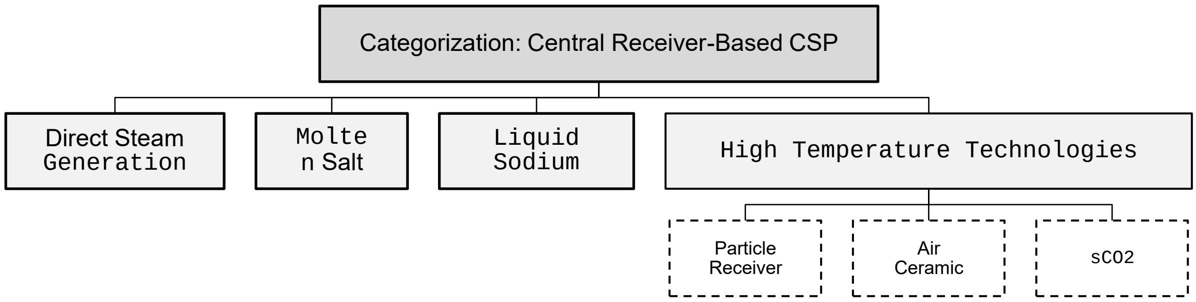

Figure 2. *Categories for central receiver-based CSP plants based on the literature review. Continuous lines denote commercial plants; dotted lines highlight R&D technologies.*

As demonstrated in projects like PS10 in Spain [10], direct steam generation simplifies the system by directly producing steam. While this technology boasts lower operating and maintenance costs, its limitations include a reliance on sunlight for operational hours and the requirement for pressure and tank materials, increasing capital expenses. In addition, the temperatures will not be higher, but lower than molten salts. The 2-tank molten salt technology stands out as the standard technology among central receiver-based CSP options. Exemplified by projects such as Gemasolar in Spain [15], molten salt technology offers high energy storage capacity, allowing continuous power generation during periods without sunlight. Gemasolar was the first commercial project of its kind having 19.9 MWe capacity with a 140 m tower and uses molten salt (290 - 565°C) to power a 20 MWe steam turbine (Rankine Cycle) [16], and 15 hours of thermal energy storage capacity. Compared to its predecessor, the newest built project of that kind, Mohamed bin Rashid Al Maktoum (MBRM) Solar Park in its phase 4 has a ST of 262.44m and a capacity of 100 Mwe. Built in Dubai, it is part of a bigger energy project that combines solar PV with CSP in Dubai, UAE [17].

On the other hand, developed by companies such as Vast, liquid sodium technology offers high efficiency and thermal conductivity, operating at elevated temperatures for enhanced overall system efficiency [18]The project is a 1.1 MW demonstration project in Australia. It utilizes a modular array system with a point-focusing mechanism and innovates by using liquid sodium as HTF, a two-tank molten salt TES technology in a multiple-tower configuration. The modular polar solar array yields a remarkable 17% improvement in the Coefficient of Performance, resulting in lower capital and operating costs, reduced environmental impact, and enhanced safety [18]. However, challenges arise from sodium's flammability and reactivity, necessitating manageable solutions for potential leakage and containment issues.

Research is also progressing in high-temperature technologies, such as particle receivers [19], [20], air ceramics [20], and supercritical CO_2 [21], which are still in the pilot or research stage. Particle receiver technology, for instance, achieves high temperatures with efficient heat transfer and storage capabilities but faces issues like abrasion and erosion of particles, which can affect system durability and challenges in particle containment and handling. Air ceramic technology, demonstrated by the Jülich DLR power tower in Germany [22], offers high-temperature tolerance and stability, using air as a heat transfer medium to minimize environmental impact. Nevertheless, limitations include a comparatively lower energy storage capacity than molten salt and challenges in achieving and maintaining high temperatures. These emerging technologies suggest promising future pathways for CSP.

5. Future Pathway

The literature review analysis identifies strategic pathways for future deployments in central receiver-based CSP technologies.

- Stand-alone: This strategy involves operating central receivers as stand-alone units, leveraging solar thermal energy independently, a practice commonly observed in early CSP deployments.
- Co-location: This strategy combines central receivers with other energy sources to enhance efficiency, flexibility, and cost reduction.
- Hybridization: emerges as a pivotal strategy involving integrating system components with other technologies or energy sources. This approach aims to improve overall system efficiency and reduce operational costs, reflecting a trend towards more sophisticated, integrated renewable energy solutions.
- Modularity: Implementing modularity in design and construction could be a way to optimize construction and scale-up of plants [23]. When several separate parts or modules function independently and then are integrated into a broader system, some costs in price and time can be decreased. Modular designs provide flexibility for greater adaptability to various terrains and local circumstances, bringing the concept of multi-tower architecture. An example is the Yumen Xinneng Beam Down project [24].

6. Conclusion

By 2023, the global installed capacity for CSP reached 6 GW. The technology's evolution is underscored by the development of projects like MBRM in Dubai, UAE, and numerous initiatives in China, which indicate a strong shift towards hybrid renewable energy systems. Thus, the study focuses on understanding the development of the technology by first providing a review of the existing projects over time under the category of central receiver-based configuration of CSP. This is provided by the graphical visualization of the experimental and commercial projects over time, mentioning the current status of the plant.

Results show an increase of projects after 2010 and also a peak of projects under construction from 2023. Also, 90% of the projects after 2011 correspond to the category of molten salt, more specifically to the two-tank configuration, which can be understood by the maturity of the technology. This can be backed up by the capacity of the ST that oscillates in the 100-200MW_e. Finally, there is a tendency on projects including MBRM and the projects under construction to share the project land with one or two other RE technologies such as solar photovoltaic or wind. This highlights one of the emerging pathways: co-location. Co-location enables multiple technologies to operate within the same space, sharing solar resources without competing for them. This setup offers spatial efficiency by filling unused corners of the square heliostat field with PV panels, reducing component costs through shared equipment like transformers, and increasing operational flexibility through diversified electricity conversion methods. Other strategies presented after data analysis are stand-alone, hybridization, and modularity.

We aim to set the stage for further work that can be applied to guide policy making and the incentive of research and investment in future projects by referring to the technology's best practices and operational milestones.

Author contributions

Brenda Hernandez Corona: Writing – original draft, Investigation, Visualization

- Dr. Matteo Chiesa: Funding acquisition, Resources, Writing – review & editing
- Dr. Ahmad Mayyas: Resources. Supervision. Writing – review & editing
- Dr. Nicolas Lopez Ferber: Methodology, Writing – review & editing
- Dr. Nicolas Calvet: Conceptualization, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

Data availability statement

This work was done by data found in NREL [8], SolarPACES [9], and Guru.CSP [10], and CSPfocus [11] databases as mentioned in the methodology.

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