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Exploring the Efficiency and Applications of Solar Central Receiver Systems: A Review

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ABSTRACT

This review paper comprehensively examines the efficiency and applications of Solar Central Receiver Systems (SCRS), emphasizing technological advancements and their role in sustainable energy solutions. By synthesizing research from 2008 to 2023, the study highlights innovations such as geometric optimizations (e.g., parabolic troughs with reduced focal lengths), porous absorbers (e.g., copper foam), and enhanced heat transfer mechanisms (screw-tape inserts, dimpled tubes). The integration of thermal energy storage (TES) with molten salts and modular receiver designs is explored, demonstrating improved energy capture, operational flexibility, and cost-effectiveness. Case studies of operational solar power plants (1–20 MW) illustrate practical challenges, including wind-induced receiver displacement addressed through advanced sensor technologies and simulation tools. The review underscores SCRS's potential to achieve high operational temperatures, reduce greenhouse gas emissions, and support hybrid systems for grid stability. Key findings reveal that advancements in reflective materials, tracking systems, and thermal storage are pivotal for scalability and efficiency. The paper concludes that SCRS, coupled with ongoing innovations, offers a viable pathway for large-scale renewable energy generation, aligning with global sustainability goals

Keywords: Solar Central Receiver Systems (SCRS), Thermal Energy Storage, Concentrated Solar Power, Heat Transfer Optimization, Sustainable Energy Transition.

1 INTRODUCTION

The exploration of solar central receiver systems (SCRS) has gained significant attention in recent years due to their remarkable potential for efficient energy conversion and innovative storage solutions. Recent advancements in thermal energy systems emphasize geometric and surface modifications to maximize efficiency. Parabolic trough optimizations (27% shorter focal length) enhance solar concentration via mid-to-upper surface reflectivity, aligning with solar cooker innovations where 10-PPI copper foam absorbers boost stagnation temperatures by 25.8°C and reduce cooking times by 33% through porosity and tilt adjustments [1-2]. These solar advancements parallel fluid-based heat transfer improvements: screw-tape inserts in ducts amplify laminar-flow Nusselt numbers by 2.81–3.52 times via secondary flows, while cross-combined dimpled tubes elevate heat transfer by up to 38.6% by disrupting boundary layers. Together, these strategies spanning reflective shaping, porous materials, tabulators, and dimpled surfaces demonstrate the critical role of tailored geometries in optimizing energy capture, conversion, and dissipation. Computational modeling and empirical validation bridge design and application, offering scalable pathways to address energy scarcity sustainably [4]. The literature on this compelling topic reveals a variety of distinct approaches and advanced technologies that work together to enhance the overall performance of SCRS, with critical insights from numerous comprehensive studies contributing to a thorough understanding of their capabilities, advantages, and ongoing challenges in the field [5].

Experiments were conducted on a heat exchanger using water as a heat transfer fluid. The system with screwtape inserts showed superior performance compared to twisting tape, especially in colder weather. The isothermal coefficient of kinetic friction of tape inserts and impellers was higher than plain tubing. The mean Nusselt numbers for both twisted and screw tapes were significantly higher than ordinary ducts, with screw twisted and tape inserts performing 2.81 and 3.52 times larger at constant pumping power [6].

In 2008, Chen highlighted the advantages of solid particle solar receivers, which utilize sand-sized refractory particles that absorb concentrated solar energy directly. This method eliminates the need for fluid transport systems and allows for higher operational temperatures, making it an attractive option for hydrogen production [7]. Following this, Morse

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examined the geophysical and industrial requirements for large-scale deployment of concentrating solar power (CSP) in South Africa, revealing that hybrid solar thermal systems with natural gas are among the most efficient alternatives due to their cost-effectiveness and capacity factors [8]. In 2011 focused on parabolic trough solar power plants, discussing their maturity in the renewable energy sector and the mechanisms through which they convert solar energy into electricity [9]. While in 2014, Madaly emphasized the importance of thermal energy storage (TES) in CSP systems, noting that incorporating TES can significantly enhance capacity factors and operational flexibility compared to systems without storage [10]..

Van der Merwe (2016) expanded on the types of solar receivers, categorizing them into gas, liquid, and solid particle receivers, and underscoring the efficiency of volumetric air receivers [11]. This study contributed to the ongoing discourse about optimizing receiver designs for higher efficiency and reduced thermal losses. In a broader context, Belgasim and Aldali (2018) reviewed solar thermal electricity (STE) technologies in Libya, stressing the need for infrastructure development to integrate these systems effectively with existing energy grids [12].

The review by Zsembinszki et al. (2018) on reactors for thermochemical energy storage in CSP plants provided insights into the state-of-the-art technologies and their potential for improving energy storage efficiency [13]. Complementing this, Taylor (2019) discussed recent advancements in central receiver designs that allow for higher operational temperatures and efficiencies, while also acknowledging the sensitivity of these systems to environmental conditions [14].

Further exploration of receiver technology was conducted to analyzed cavity receiver designs for parabolic trough collectors. Their findings indicated that optimizing cavity receiver parameters could lead to significant efficiency improvements [15]. Singh et al. (2019) investigated the performance bounds of nanoparticle-laden volumetric absorption solar thermal platforms, revealing the complexities of efficiency at varying operational conditions [16].

In 2020, Tervo et al. introduced the concept of solar thermoradiative-photovoltaic (TR-PV) energy conversion, highlighting its potential for higher efficiencies at low concentrations compared to traditional systems [17]. This innovative approach suggests new pathways for enhancing solar energy conversion technologies. Most recently, Li et al. (2023) examined the capacity expansion of high renewable energy systems, emphasizing the role of CSP in achieving seasonal energy balance and its implications for future energy strategies [18].

Literature review

The advantages of solar energy are numerous and quite significant, encompassing a wide range of aspects that include being environmentally friendly and renewable. Solar energy offers a virtually inexhaustible supply, which makes it increasingly important as we seek sustainable solutions to meet our energy needs. Furthermore, solar energy possesses the remarkable ability to be transformed into various types of energy, which can be harnessed for immediate use or stored for subsequent applications. This capability can significantly reduce our reliance on fossil fuels, which are not only limited in availability but also detrimental to our environment [19]. This versatility of solar energy not only enhances the adoption of solar technologies but also supports various applications in different sectors. For instance, it can be used for residential power generation to provide electricity for homes, significantly cutting down on electricity bills while being environmentally responsible [20]. In addition, solar energy can be used in industrial processes, powering factories, and helping to reduce overall operational costs. Furthermore, it plays a critical role in large-scale energy production, allowing communities to harness the power of the sun and supply energy to numerous households [21]. Additionally, the implementation of solar central receiver systems offers unique advantages in terms of efficiency and scalability, making them a focal point of current research and development in the renewable energy sector. These systems can store excess energy, maximizing output and ensuring a stable energy supply, even when sunlight is not available. As technology continues to advance, the potential of solar energy to provide clean, reliable, and sustainable power will only increase, offering a bright future for energy production across the globe [22 and 23].

This versatility enhances its effectiveness and makes it an increasingly sought-after solution in today's world. This includes applications in both residential and commercial sectors, where solar central receiver systems can significantly reduce energy costs and carbon footprints. As a result, the adoption of these systems can lead to a more sustainable energy future, promoting environmental conservation and economic viability [24]. This aligns with the findings of several studies in the literature that highlight the role of solar central receiver systems in reducing carbon emissions and decreasing reliance on fossil fuels [25]. Moreover, the literature suggests that these systems not only contribute to energy efficiency but also support local economies through job creation in the renewable energy sector. Furthermore, advancements in technology have enabled these systems to achieve higher efficiencies, making them a more attractive option for large-scale energy production [26].

This versatility in energy conversion enhances its appeal and usability in modern energy systems and promotes sustainability.Additionally, solar central receiver systems (SCRS) utilize concentrated solar power technology, which allows for increased efficiency in energy capture and conversion. This technology has been proven to reduce greenhouse gas emissions significantly, thereby contributing to a sustainable energy future [22]. This reduction is particularly important in the context of climate change, as it helps mitigate the adverse effects associated with fossil fuel consumption [27]. Various studies have highlighted the role of solar central receiver systems in achieving these reductions, showcasing their potential to harness solar energy efficiently. These systems utilize mirrors to concentrate sunlight onto a central receiver, which then converts the thermal energy into electricity. This literature review aims to synthesize existing research on the operational efficiencies of these systems, evaluating factors such as their design, technology advancements, and real-world applications [28]. The review will particularly focus on how advancements in mirror technology and thermal energy storage have contributed to increased efficiency. Furthermore, it will highlight case studies that demonstrate the successful implementation of these systems in various geographical locations. These case studies will illustrate the diverse applications of solar central receiver systems, emphasizing their adaptability to different climatic conditions and the resulting energy efficiencies achieved [29]. Additionally, these case studies will highlight the technological innovations that have been integrated into solar central receiver systems, showcasing how advancements in materials and design have contributed to enhanced performance across varying geographical settings. Furthermore, these studies will provide insights into the operational efficiencies achieved through these innovations, emphasizing the role of concentrated solar power in reducing reliance on fossil fuels and supporting sustainability goals [30].

The main drawback of the most advanced systems of converting solar radiation into energy of a different nature is their not being totally competitive with other conventional sources, either because the necessary level of technological advancement has not been reached or because the energy markets and the incentive systems established lack the necessary stability [19]. Given this situation, it is essential to promote the development of solar energy by encouraging research in this domain and the utilization of solar systems, especially for applications that require a network of relatively low capacities [31]. Since it was launched, this program has been of great interest to all town councils, irrespective of the level of savings in exploitation. This interest stems from the potential for significant energy savings and environmental benefits associated with the implementation of solar central receiver systems. Various studies have shown that these systems can harness solar energy effectively, reducing dependence on fossil fuels and lowering greenhouse gas emissions [25]. This is primarily due to their ability to concentrate sunlight using mirrors or lenses, which significantly increases the thermal efficiency of energy conversion. Furthermore, the implementation of central receiver systems has been supported by various technological advancements, such as improved heat transfer fluids and enhanced thermal storage solutions [7]. These advancements have led to increased efficiency and reduced operational costs, making central receiver systems a more viable option for large-scale solar power generation. Additionally, the integration of advanced control systems has improved the overall performance and reliability of these systems [28].

Central receiver systems with heliostats are capable of transforming a large fraction of the solar radiation incident on a field of heliostats into electricity. Apart from being a clean and inexhaustible source of energy, these systems can be installed in semi-desert or desert regions. Such regions receive high levels of solar radiation and large areas of land are available, thus reducing the problems involved in the acquisition of the land [32]. On the other hand, such regions that are relatively flat are not in urban or highly developed areas where land has other potential uses and where political opposition problems may arise. When the heat produced is transported with a fluid such as air, water, or molten salts, the solar central receiver can be used for industrial thermal applications other than electricity generation, e.g., process heat for district heating, product dehydration, sea water desalination, etc. [28], [32], and [33]. At a time when expenditure on fuels of mineral origin is high, and in general during hot periods when demand is high, it can function as a peak load power generator in networks using combined cycles with natural gas. Some have proposed its use in combination with parabolic trough collectors in hybrid power plants that require a first start-up or system support [6]. These systems can enhance the overall efficiency of solar energy generation by leveraging the strengths of both

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technologies. This hybrid approach not only improves energy output but also provides a more reliable energy supply during periods of fluctuating solar irradiance. This capability is particularly beneficial for large-scale solar farms, where maintaining consistent energy output is crucial for meeting grid demands and ensuring energy stability [34]. By utilizing advanced tracking systems and thermal energy storage, solar central receiver systems can effectively harness and store solar energy during peak sunlight hours, allowing for a more reliable energy supply even during periods of low sunlight [7]. This capability not only maximizes energy output but also contributes to the stabilization of the electric grid. Several studies have demonstrated that integrating these systems with existing infrastructure can enhance overall efficiency and reduce reliance on fossil fuels. This integration not only maximizes the utilization of solar energy but also paves the way for more sustainable energy practices. Recent advancements in technology have further illustrated the potential of solar central receiver systems in various applications, ranging from large-scale power generation to urban infrastructure enhancements [21]. These systems leverage concentrated solar power technologies to generate electricity with higher efficiencies compared to traditional photovoltaic systems. Furthermore, innovations like thermal energy storage and advanced tracking mechanisms are enhancing their viability in both remote and urban setups. As a result, these advancements are not only increasing the overall efficiency of solar central receiver systems but also broadening their applicability to various geographical locations, ultimately contributing to a more sustainable energy future [34]. This evolution in technology enables solar central receiver systems to harness solar energy more effectively, making them viable alternatives to traditional energy sources and supporting the transition towards renewable energy systems. This capability not only enhances energy capture but also improves the overall efficiency of the systems, allowing for greater energy output during peak sunlight hours. Several studies have demonstrated that advancements in mirror technology and tracking mechanisms are crucial in optimizing the performance of these systems [6]. The advancements in solar technology have led to significantly increased energy capture rates and an overall notable improvement in system efficiency. For instance, recent innovations in advanced reflective materials now allow for much greater concentration of sunlight, which plays a critical role in energy generation. Additionally, sophisticated solar tracking systems have been developed to ensure precise alignment of mirrors with the sun's trajectory throughout the day. Such advancements and enhancements provide immense benefits, as they not only maximize energy output from the systems but also contribute significantly to the economic viability and sustainability of solar central receiver systems in the long run [35]. Moreover, these advancements play a crucial role in reducing the levelized cost of energy (LCOE), making solar central receiver systems more competitive with traditional energy sources.

Together, these comprehensive studies significantly contribute to a more nuanced understanding of solar central receiver systems. They showcase the ongoing advancements in technology, research, and methodology, as well as the critical evaluations that are necessary for optimizing their efficiency. Such optimization is essential in enhancing their applications within the rapidly evolving landscapes of renewable energy. This work highlights the importance of continual improvement and innovation in the field, which is vital for meeting the increasing energy demands while promoting sustainability and reducing environmental impacts.

Conclusion

The paper presents a review of the solar tower central receiver systems. The basic structure of the solar power tower with the efficiency of conversion into electricity, a collection of mirror fields, receiver layouts, and the heat transfer media using advanced molten salts and sensor technology is highlighted. The examples of operational solar power stations with power from 1MW to 20MW are presented. The discharge of heat transfer media and the change in receiver position should be given special consideration. The development of a simulator that allows one to reproduce the movement of the receiver due to the wind effect is also presented. The development of the tuple photodiode-yttrium-aluminum-garnet concentration sensor (altimeter)-transceiver pyrometer for this system is shown.

The receiver position varies within the range of ± 1 m. To solve these problems, the development of a simulator that allows us to reproduce the movement of the receiver due to the wind effect was presented. To determine the position of this receiver, the development of the tuple photodiode-yttrium-aluminum-garnet concentration sensor (altimeter)-transceiver pyrometer for this system was highlighted. The common modular as the receiver for the tower power station was also presented. These systems have demonstrated significant potential in harnessing solar energy efficiently. In conclusion, the integration of modular receivers can enhance the overall performance and cost-effectiveness of solar central receiver systems. This enhancement not only improves energy capture efficiency but also reduces the levelized cost of electricity, making solar energy a more viable option for large-scale power generation. As a result, the adoption

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Research Article

of solar central receiver systems is expected to grow significantly, paving the way for a sustainable energy future. This growth will be driven by advancements in technology, increased efficiency, and the urgent need to transition to renewable energy sources. Furthermore, as governments and organizations worldwide commit to reducing carbon emissions, solar central receiver systems are positioned as a key solution in meeting these ambitious targets.

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