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State-Of-The-Art Review On Solar Parabolic Trough Collectors: Academic Contributions And Future Prospects

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In recent years, solar parabolic trough collectors (PTCs) have gained significant attention as a promising solution in the field of renewable energy. They continue to be a subject of active research and development due to their potential for efficient solar energy utilization. Given the growing importance of this technology, the present study reviews various academic contributions related to PTCs. It aims to identify key research trends, highlight existing gaps in the literature, and outline the objectives of the proposed research based on these findings.

Keywords: Parabolic trough collects (PTCs), solar, energy, academic contributions, research.

1. Introduction

Parabolic Trough Collectors (PTCs) are among the most widely adopted and reliable technologies in the field of concentrated solar power (CSP), accounting for over 80% of CSP installations worldwide. (Hamada et al., 2022; Wang et al., 2021). One of the major advantages of PTCs is their ability to achieve high operating temperatures—reaching up to 400°C with thermal oils and up to 600°C when using molten salts. These high temperatures significantly improve the efficiency of converting solar energy into usable power (Bellos & Tzivanidis, 2018; Bellos et al., 2018). To maintain consistent energy capture throughout the day, PTC systems typically track the sun along a single axis, allowing for efficient performance across various geographic locations (Wang et al., 2016; Ghazzani et al., 2017).

Beyond electricity generation, Parabolic Trough Collectors (PTCs) are increasingly being explored for a variety of industrial applications. These include water desalination, process heating in factories, and other thermal energy needs (Ghazzani et al., 2017; Tagle-Salazar et al., 2020). Their adaptability, combined with ongoing technological advancements, makes PTCs especially promising for deployment in sun-rich regions. As the systems become more efficient and cost-effective to manufacture and install, industries are finding it more feasible to integrate them into their operations (Bravo et al., 2018; Tagle-Salazar et al., 2020). Overall, PTCs are emerging as a key player in addressing global energy challenges while contributing to a more sustainable and environmentally friendly future.

Research has shown that several factors—such as the reflectivity of the mirrors, the precision of their alignment, and the choice of heat transfer fluid—play a critical role in determining system efficiency (Natraj et al., 2022; Lotake & Wagh, 2019). To address these challenges, researchers are exploring advanced materials like nanofluids, which offer improved thermal conductivity and heat absorption properties (Kasaeian et al., 2019; Amin et al., 2022). Additionally, innovative design improvements—such as incorporating spiral-shaped receiver tubes (helical pipes)—have been introduced to enhance heat distribution and reduce mechanical stress on components (Arun et al., 2023; Allam et al., 2022). These technological advancements are making PTC systems more efficient, durable, and dependable, reinforcing their role in the global transition to clean and sustainable energy sources.

Considering these facts, the present research work focuses on different academic aspects solar parabolic trough collectors, and concludes with gaps in the research, and objectives of a novel research.

2. Overview of PTCs and Alternate Technologies

A solar parabolic trough collector is basically a curved mirror that follows the sun and focuses its light onto a pipe. The concentrated sunlight heats up fluid flowing through the pipe to around 400°C. This hot fluid can then be used to make electricity or provide heat for industrial uses. The system has three main parts: the curved mirror, the heated pipe, and a motor that turns everything to track the sun throughout the day. It's a simple but effective way to capture solar energy and turn it into useful heat. (Hamada et al., 2022; Bellos et al., 2018; Bellos & Tzivanidis, 2017). PTC technology plays a dominant role in the concentrated solar power (CSP) sector, accounting for more than 80% of global CSP installations, highlighting its critical role in advancing renewable energy solutions (Wang et al., 2021; Kumar, 2013). A schematic diagram of a PTC system is presented in Figure 2.1.

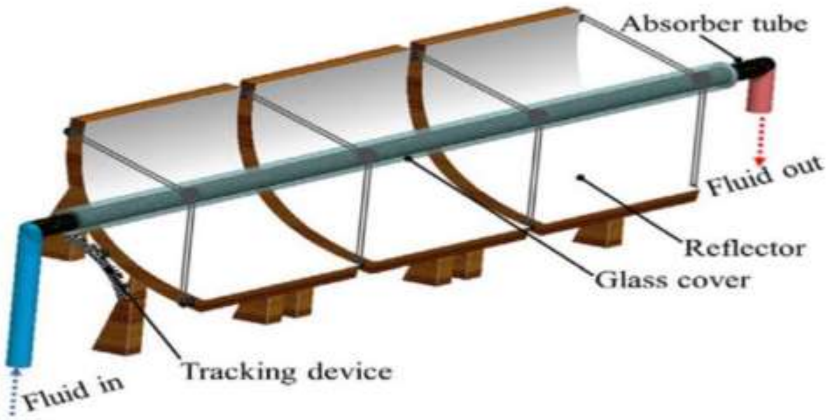

Figure 2.1: Schematic Arrangement of PTC (Singh and Chandra, 2023)

Table 2.1 shows the timeline of PTC.

Table 2.1: Timeline of PTC

Year/Period	Milestone/Development	Key Details
1870s-1880s	**Early Concepts & First PTC**	Auguste Mouchout and John Ericsson experimented with solar concentrators for steam generation.
1912-1913	**First Large-Scale PTC Plant**	Frank Shuman built a 55 HP solar-powered steam engine in Egypt using parabolic troughs.
1950s-1960s	**Renewed Interest in Solar Energy**	Research on concentrated solar power (CSP) resurged due to the energy crisis and advancements in materials.
1970s	**First Modern PTC System**	U.S. Department of Energy (DOE) initiated studies on CSP technology, leading to prototype PTC designs.
1980s	**SEGS (Solar Energy Generating Systems) in California**	The world's first commercial PTC-based power plant (SEGS-I) was installed in the Mojave Desert. Subsequent SEGS plants (II-IX) were built, reaching a total capacity of 354 MW.
1990s	**Technological Refinements**	Improved receiver coatings, better tracking systems, and more efficient heat transfer fluids enhanced PTC efficiency.
2000s	**Global Expansion & New Materials**	Countries like Spain, India, and China adopted PTC technology for large-scale solar thermal power projects. Innovations in selective

		coatings and vacuum-insulated receivers improved performance.
2010s	**Integration of Advanced Fluids & Storage**	Development of molten salt-based PTC for improved thermal storage and nanofluids for better heat absorption. Hybrid CSP-PV plants were also introduced.
2020s-Present	**AI-Optimized Tracking & Hybrid Systems**	Artificial intelligence and IoT-enabled tracking systems enhance efficiency. Hybrid solar-biomass and solar-thermal storage systems improve reliability. Research continues on improving nanofluids, coatings, and mirror reflectivity.

The efficiency of a Parabolic Trough Collector (PTC) is significantly influenced by the precision of the reflector's design and alignment. Even minor deviations in the curvature or orientation of the reflector can lead to substantial optical and thermal losses, emphasizing the need for highly accurate manufacturing and assembly techniques (Natraj et al., 2022; Arun et al., 2023). The choice of materials used in constructing the collector is also critical to its overall performance. Recent studies have demonstrated that the use of hybrid nanofluids as heat transfer fluids (HTFs) can offer improved thermal efficiency compared to traditional fluids (Khalil et al., 2020; García-Valladares & Velázquez, 2009). Furthermore, advancements in receiver technology—such as the integration of composite materials and innovative features like cylindrical inserts within the receiver tube—have been developed to enhance heat absorption and reduce thermal losses (Bellos & Tzivanidis, 2017; Bellos et al., 2018).

Ongoing research efforts continue to focus on optimizing Parabolic Trough Collector (PTC) systems to enhance their overall performance and efficiency. Geometric parameters of the trough—such as the aspect ratio and the diameter of the receiver tube—have been shown to significantly influence thermal efficiency (Wang et al., 2016; Pathak & Mohan, 2019). In addition, advancements in tracking mechanisms contribute to more accurate solar alignment, ensuring consistent energy capture throughout the day. Emerging technologies, including self-regulating spectral coatings and next-generation heat exchangers integrated into the receiver, are showing considerable promise in improving energy absorption and conversion efficiency (Wang et al., 2021; Bader et al., 2015). With ongoing design enhancements and material innovations, PTCs are poised to become even more efficient and cost-effective, reinforcing their role in the global shift toward sustainable energy. Table 2.2 provides a comparative overview of advancements across various components of PTC systems.

Table 2.2: Advancements in different parts of a PTC

Category	Variant	Key Features	Advantages	Disadvantages	Applications

Based on Collector Geometry	**Conventional Parabolic Trough**	Standard continuous parabolic reflector	Proven design, widely used	Higher manufacturing and transport costs	Large-scale CSP plants, industrial heating
	Compact/Segmented PTC	Uses modular mirror segments	Easier to manufacture and transport	Slightly lower optical efficiency	Medium-scale solar thermal applications
	V-Shaped Parabolic Trough	Split reflector with two angled mirrors	Improved optical efficiency, simpler tracking	Complex assembly	High-efficiency solar heating systems
Based on Receiver Design	**Vacuum Tube Receiver**	Glass envelope with vacuum insulation	Minimal heat loss, high temperature capability	Expensive fabrication	Power generation, high-temp CSP
	Non-Vacuum Insulated Receiver	Uses ceramic or air insulation	Lower cost, simpler manufacturing	Higher heat loss	Medium-temp industrial heating
	Direct Absorption Receiver	Absorbs sunlight directly into working fluid	Enhanced heat transfer, higher efficiency	Fluid selection challenges	Nanofluid-based solar thermal systems
Based on Tracking Mechanism	**Single-Axis Tracking PTC**	Tracks the sun in one direction	Simple, cost-effective	Limited sun exposure at certain angles	Most CSP power plants, industrial heat
	Dual-Axis Tracking PTC	Tracks both horizontal & vertical angles	Maximizes solar absorption	High mechanical complexity, expensive	High-precision solar applications
	Fixed Focus PTC	Static receiver, moving mirrors	Reduces wear on tracking system	Less efficient than full tracking systems	Industrial heating, small-scale CSP

Based on Working Fluid	**Water-Based PTC**	Uses water as heat transfer fluid	Simple and cost-effective	Limited to low-medium temperatures	Solar water heating, process heat
	Oil-Based PTC	Uses thermal oil for heat transfer	High thermal stability, better storage	Requires secondary heat exchanger for power gen	CSP plants, industrial heating
	Molten Salt PTC	Uses molten salt for heat storage	Enables long-duration energy storage	High initial cost, salt freezing risk	CSP with thermal storage, hybrid plants
	Nanofluid-Based PTC	Uses nanoparticles to enhance heat absorption	Improves thermal conductivity, increases efficiency	Complex fluid preparation and stability issues	Advanced solar thermal applications

Table 2.3 shows the technologies alternate to PTCs.

Table 2.3: Alternatives to PTCs

Technology	Working Principle	Efficiency	Advantages	Disadvantages	Applications
Solar Power Tower	Heliostats focus sunlight onto a central tower	High (up to 50%)	Higher temperature, better thermal storage	High land usage, expensive	Large-scale power generation
Linear Fresnel Reflector (LFR)	Flat mirrors focus light onto a linear receiver	Medium (30-40%)	Lower cost than PTC, simple design	Lower efficiency, optical losses	Industrial heat, steam generation
Parabolic Dish Collector	Dish mirror focuses light on a single point	Very High (50-60%)	High concentration, efficient	Complex tracking, high cost	Small-scale power, hybrid solar systems

Photovoltaic (PV) Panels	Converts sunlight directly into electricity	Variable (15-25%)	No moving parts, easy installation	Energy storage required, weather-dependent	Residential & commercial power supply
Compound Parabolic Collector (CPC)	Uses non-imaging optics for light concentration	Low-Medium (10-30%)	Works without tracking, cost-effective	Lower efficiency compared to PTC	Water heating, desalination, low-temp heat
Solar Chimney Power Plant	Uses solar-heated air to drive turbines	Low (5-15%)	Simple design, low maintenance	Requires large structures, low efficiency	Power generation in hot climates
Solar Pond	Utilizes salt-gradient to trap heat in water	Low (5-15%)	Cost-effective, passive heat storage	Large area required, slow heat transfer	Industrial heating, desalination
Thermophotovoltaic (TPV) Systems	Converts infrared radiation into electricity	Medium (20-40%)	High energy density, direct conversion	Expensive materials, emerging technology	High-temperature heat-to-electricity conversion
Molten Salt Solar System	Uses molten salt for heat storage and transfer	High (40-50%)	Efficient energy storage, long-duration power supply	High installation cost	Large-scale CSP plants, grid power supply

3. Scenario of Research in the Field of PTCs

Figure 3.1 illustrates research contributions over the past five years (2019-2023) on Solar Parabolic Trough Collectors, comparing global publications with those from Indian researchers. The dark color represents worldwide contributions, while the light color highlights contributions from India.

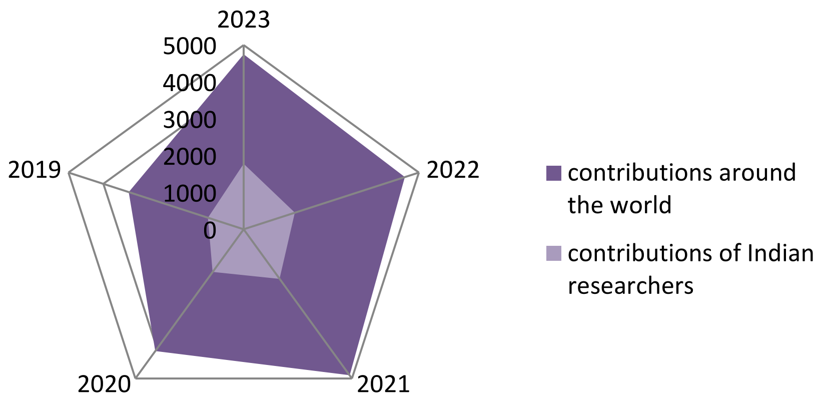

Figure 3.1: Research Publications showing contributions of researchers in last five years for the keywords Solar Parabolic Trough Collectors

The radar graph shows a steady increase in research activity, with global contributions peaking around 5000 publications in 2023, whereas Indian contributions remain significantly lower in comparison. Despite this disparity, Indian research output has shown gradual growth over the years.

The five-year trend indicates that while Indian researchers are making progress in this domain, their contributions are still a small fraction of global research. This suggests a need for more focused efforts in India to enhance research output on Solar Parabolic Trough Collectors**,** possibly through increased funding, collaborations, and policy support. The figure effectively highlights the gap between global and Indian research contributions, emphasizing the scope for further development in this field.

4. Contributions of Researchers in the field of PTCs

As these technological developments continue, PTCs are becoming an increasingly vital component in the global transition toward sustainable and renewable energy production. The design of parabolic trough collectors (PTCs) leverages parabolic-shaped reflectors to concentrate solar radiation onto an absorptive receiver, thereby enhancing thermal efficiency and overall cost-effectiveness. Recent studies by Hamada et al. (2022) demonstrate that the use of mono and hybrid nanofluids as heat transfer fluids can significantly improve the thermal performance of PTC systems, suggesting valuable directions for future collector designs. Additionally, research by Natraj et al. (2022) underscores the critical role of maintaining high shape accuracy in reflectors; even slight deviations can lead to notable reductions in efficiency, highlighting the need for precision in PTC fabrication and alignment. Continuous efforts to optimize the optical properties and geometrical configurations of PTCs are essential for maximizing energy output, and remain a central focus of ongoing research (Bellos & Tzivanidis, 2018).

Recent studies, such as those by Arun et al., have explored various receiver designs—including configurations using stainless steel and glass-coated copper tubes—with the goal of enhancing thermal absorption and overall system efficiency (Singh & Chandra, 2023). In parallel, Bellos and Tzivanidis have evaluated a range of thermal enhancement strategies, emphasizing the importance of advanced working fluids and innovative receiver designs in achieving optimal thermal performance at temperatures reaching up to 400 °C (Arun et al., 2023). Furthermore, research by Abdel-Hady et al. underscores the ongoing search for sustainable and cost-effective materials, reinforcing the dynamic evolution of PTC technology within the broader context of solar energy innovation (Bellos & Tzivanidis, 2017).

Furthermore, the integration of advanced technologies—such as dynamic modeling and simulation—has significantly enhanced the understanding of Parabolic Trough Collector (PTC) system performance, operational efficiency, and scalability. For example, Luo et al. highlighted the importance of dynamic modeling techniques to evaluate thermal behavior and optimize PTC performance across varying operating conditions (Abdel-Hady et al., 2016). This approach reflects a broader trend of employing computational methods for detailed performance analysis, ensuring that future solar energy systems are both efficient and cost-effective (Luo et al., 2015). The economic aspect of PTC technology is equally critical. Tian et al. examined the thermo-economic optimization of hybrid solar district heating plants incorporating PTCs, underscoring the necessity of integrating economic considerations alongside technical design to promote sustainable development (Tagle-Salazar et al., 2020).

5. Gaps in the Research and Objectives of Proposed Research

During the survey of available research, the following research gaps were found:

a) There were very less papers found which focused on the analysis of PTCs for long durations; and
b) There were very few research papers which focused on changes receiver pipe materials, reflector sheet materials, and heat transfer fluids, simultaneously.

Based on the investigated gaps, following are the objectives of proposed research:

a) Determination of performance parameters for long runs; and
b) Investigations on performance parameters with different combinations of receive pipe materials, reflector sheet materials and heat transfer fluids.

6. Concluding Remarks

The present research work was devoted to the academic contributions in the field of solar PTCs, which highlighted different unique characteristics as well as research aspects about PTCs, which are necessary for researchers and practicing engineers for making baseline assessment of upcoming research in the field. Considering the dire need of the time, the research may be considered as one of the smaller steps in the field of green energy.

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