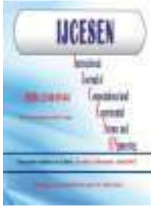
International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 11-No.4 (2025) pp. 4414-4431
http://www.ijcesen.com

Research Article



ISSN: 2149-9144

A Comprehensive Review of Design, Components and Application of Parabolic Trough Solar Collector

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Article Info:

DOI: 10.22399/ijcesen.5128
Received : 04 November 2025
Revised : 25 December 2025
Accepted : 27 December 2025

Keywords

Solar Energy,
Parabolic Trough Collector,
Receiver,
Absorber,
Heat Transfer Fluid.

Abstract:

Solar energy is a potential clean alternative source which can fulfill the world electrical and thermal energy requirements. One of the leading technologies in the solar industry is the parabolic trough collector (PTC) which is critical in enhancing the effectiveness and efficiency of solar energy production. These systems incorporate linear concentrating designs that direct the solar beam toward a receiver that typically carries a heat-transfer fluid, then converts collected energy into usable thermal power or electricity. The review covers various aspects of the parabolic trough collector, including design, effects of the reflecting material used, performance of various heat transfer fluids, novel receiver and sun-tracking systems. Moreover, it goes into research on the use of PTC on residential systems and on industrial-scale applications, mentioning the parabolic trough collector as the most important technology of concentrated solar power of the present time.

1. Introduction

Over the past few decades, rising CO_2 emissions have severely impacted ecosystems and human health due to heavy reliance on fossil fuels, leading to climate change, pollution, habitat destruction, and water contamination during extraction and transport [1-3]. Renewable energy is a viable solution to address global warming, environmental degradation, fossil-fuel depletion, rising sea levels, and reduced agricultural productivity [4–6]. India targets to have 500 GW of renewable installed capacity and a 45% cut in emissions intensity by 2030 [7]. Among renewable sources, solar energy has exceptional potential for meeting global electrical and thermal demands [8], as the Earth receives an immense amount of solar radiation suitable for energy conversion [9–11]. India benefits from high solar irradiance (4–7 kWh/m²/day), nearly 300 sunny days annually, and vast land availability, enabling an estimated annual solar energy potential of about 5×10^{23} kWh [12–15], with the highest radiation recorded in Jodhpur and the lowest in Kolkata [16]. Solar energy can be harnessed via photovoltaic or concentrated solar thermal technologies without greenhouse gas emissions [17]. Solar collectors, classified as non-concentrating and concentrating types, are essential for harnessing this energy [18]. They have been divided into two major groups, namely, non-concentrating collectors and concentrating collectors. Collectors without concentration have more productivity and economical at low temperatures but with higher thermal losses at higher temperatures [19]. Concentrating collectors are better suited for high-temperature applications due to focused solar radiation [20–22]. Technologies such as flat plate collectors, evacuated tubes, parabolic dishes, parabolic troughs, and solar towers are widely used [8,23–25]. Among the array of solar technologies available, solar trough collectors have emerged as a prominent approach for efficiently capturing solar thermal energy [26,27]. Parabolic trough collectors (PTC) serve as a standard device for medium solar thermal operations that can be appropriate in the temperature range up to 500°C [28–30]. A potential alternative to burning crude oil and fossil fuels is presented by generating steam through PTSC, either directly or indirectly. This alternative is essential for decreasing industries carbon footprint and the economic cost of energy generation. Therefore, in different sectors, hybridization with PTSC systems is becoming popular as a reliable backup system that supplies process heat [31].

2. Fundamental elements of parabolic trough collector.

The solar trough is a parabolic form of collector which employes reflecting material, aimed to reflect the rays of the sun onto a receiver tube, where the heat of solar radiation is absorbed by the heat transfer fluid flowing in the tube and this can be utilized in heating different industrial processes or can be used to generate power through steam turbines [8,32]. A sun-tracking mechanism is provided for a steady and reliable output, regulating the system performance [25]. As shown in Figure 1, the parabolic trough solar collectors are composed of multiple components such as structure, parabolic reflectors, absorber tubes, heat transfer fluid, and a tracking mechanism [33]. The various components of PTC systems are described below.

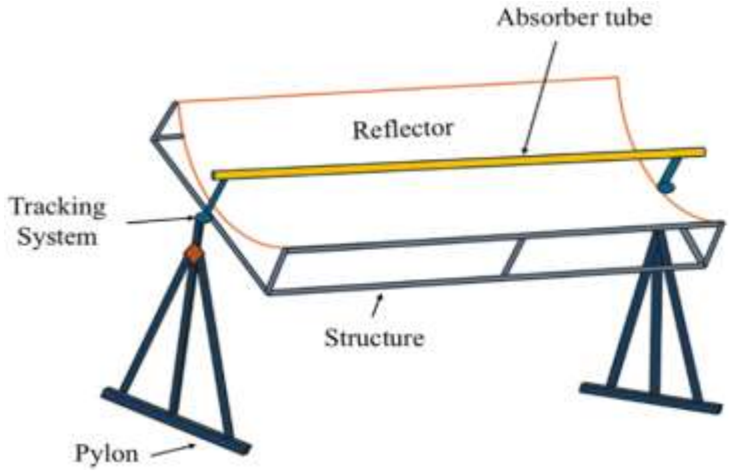


Figure 1 *Parabolic Trough Collector System [33]*

2.1 Structure of Parabolic Trough Collector

Parabolic trough collector can be explained based on multiple variables, which include aperture width, focal distance, trough length, and rim angle, as detailed in **Hata! Başvuru kaynağı bulunamadı.**. These dimensions considerably impact the PTC system efficacy, so researchers continue improving geometric parameters to enhance its functionality and performance [34].Gharat et al. (2023) compared four PTC collector types using CAD, FEA, and structural optimization. The results indicated that the torque box and space tube structures shown in ***Hata! Başvuru kaynağı bulunamadı.*** have better mass, deformation, and ease of manufacturing, making them more efficient collectors [35]. Murtuza et al. (2017) proposed a torque-tube structure as shown in ***Hata! Başvuru kaynağı bulunamadı.***, with an aluminized silver reflective surface and clamping mechanism, demonstrating high strength and effective load management of mild steel ribs [36]. Kapsikar et al. (2023) made up a Novel mini-PTC with dimensions of 1.1 meters in width and 3 meters in length, with a concentration ratio of 8 for Industrial Process heat applications which produces 150 L of hot water, reaching up to 95°C with 61.9% optical efficiency as compared to existing solar collectors [37]. Forman et al. (2015) designed a parabolic trough using cement Nanodur-based high-strength concrete to create a thin, lightweight shell that combines structural support and a reflecting surface into a single component. This advancement substitutes for traditional steel frameworks [38]. Upadhyay et al. (2021) presented a new PTC design that simplifies assembly, transport, and maintenance. It was tested under three conditions: manual without a glass cover, manual with a glass cover, and automatic with a glass cover. The average efficiencies were 11.83 %, 13.50 %, and 14.94 % respectively, demonstrating that automatic tracking and glass covers improve overall efficiency [39]. A novel design methodology combining optical ray tracing and conjugate heat transfer analysis in COMSOL Multiphysics was developed to optimize key parameters of a parabolic trough collector. Results

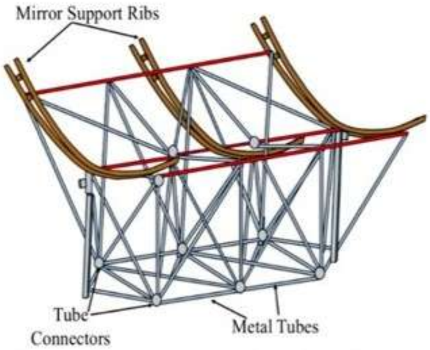


Figure 2 Space Tube Structure [35]

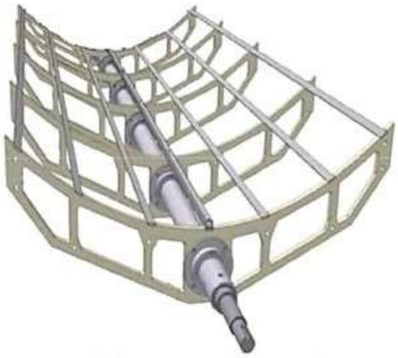


Figure 3 Torque tube structure [36]

show that Syltherm 800 is the optimal HTF, with a mass flow rate of 1.1 kg/s and a 70° rim angle, achieving best performance for 4 hours around solar noon in winter. [40,41]. Natraj et al. (2021) used CFD analysis to study wind effects on PTC stability, finding that drag forces and slope deviations increase as wind speed rises from 5 to 25 m/s, with aluminum troughs showing greater deviations than glass, particularly at higher speeds [42]. Combining the torque box and cantilever beam cross-section sizes improved rigidity while reducing weight, thereby enhancing the structural efficiency of the PTC support structure [43].

Table 1 *Different Geometrical parameters used in previous investigations*

S. No	**Authors**	**Length**	**Width**	**Aperture Area**	**Focal length**	**Rim Angle**	**Absorber Diameter**		**Concentration ratio**
							D Outer	**D inner**	
		(m)	**(m)**	**(m²)**	**(m)**	**(°)**	**(m)**	**(m)**	
1	Alhamayani (2024) [44]	7.8	5	-	-	-	0.07	0.066	22.74
2	AbdEl-Rady Abu-Zeid et al. (2024) [45]	1.50	1.0	1.5	-	-	0.008	0.008	-
3	A.Ahmad et al. (2024) [3]	99	-	-	-	-	0.07	0.066	-
4	Arun et al. (2024) [46]	1.8	1.2	0.96	-	-	-	-	-
5	Simeu et al. (2024) [31]	7.8	5	-	1.84	68.38	0.07	0.066	22.42
6	Oketola et al. (2024) [47]	5	9.7	-	-	80	0.080	0.0735	121
7	Al-Rabeeah et al. (2023) [48]	1.7	0.07	1.19	0.0205	82	0.012	0.010	18.568
8	Natraj et.al (2023) [49]	4	5.77	6	-	-	0.070	0.066	-
9	Kapsikar et al. (2023) [37]	3	1.1	-	-	-	-	-	8
10	Dou et al. (2023) [50]	4	5.77		1.71		0.070	0.065	-
11	Darbari et al. (2023) [51]	7.8	5.0	39	-	70	0.070	0.066	22.7
12	Al-Rabeeah et al. (2023) [52]	1.7	0.07	1.19	0.0205	82	0.080	0.075	18.56
13	Ram et al. (2023) [53]	2.1	1.2	2.45	-	90	0.03058	0.0286	12.17
14	Nagamani Prabu et al. (2023) [54]	0.40	0.52	0.22	1.3	90	0.028	-	6.26
15	Omidi et al. (2023) [55]	1.8	1.25	1.25	0.355	70	0.047	-	-
16	M. Ghodbane et al. (2022) [2]	12.27	1.2	-	0.6	53.13	0.016	0.0142	40.65
17	Praveen et al. (2022) [56]	100	5.75	545	2.11	-	0.07	0.066	-
18	Shaker et al. (2022) [57]	7.8	5	39	1.84	-	0.07	0.066	22.74
19	Natraj et al. (2022) [58]	4	5.77	23.08	1.71	80.3	0.07	0.066	-
20	Stanek et al. (2022) [59]	1.5	1	-	0.25	-	0.0337	0.0297	-
21	Othman et al. (2022) [60]	5.8	2.26	13.1	-	-	0.042	0.035	20.9

Marcotte et al. (2014) showed that the space tube design reduced costs and improved optical performance by using a steel helical space frame. It saved material, allowed a larger aperture, and enabled simplified, jig-free assembly, all confirmed through successful mechanical and optical testing [61]. Wind loads on parabolic trough collectors are highest at 0° yaw and pitch angles above 15°, and decrease as yaw angle increases. Deeper troughs face stronger aerodynamic forces than shallower ones, but they deliver better thermal performance, indicated by lower Nusselt numbers at the receiver across most angles [62]. Farr et al. (2009) introduced a lightweight aluminum space frame that reduces part count and weight, removes the need for support pylons and foundations, and significantly shortens collector installation time [63].

2.2 Reflector

Mirrors are mainly used to reflect solar radiation and focus it on the receiver. They consist of materials with a high reflectivity of aluminum or silver and contain substrates and superstrates to protect the reflective material against corrosion and wear, which increase their durability [64]. Other alternative materials such as aluminum foil, anodized alumina sheets and silver-coated PVC sheets, as indicated in **Hata! Yer işareti başvurusu geçersiz.**, are already being studied, and put in place to lower the price of PTC systems [65]. Natraj et al. (2023) showed that PTC performance depends heavily on structural rigidity and precise alignment; wind and temperature-induced bending can reduce optical efficiency from 86% to 67.24% with 10 mm receiver deformation, while combined reflector and receiver deflections cause an overall efficiency loss of about 17.7% [49]. A receiver with a combination of solar and high-reflectivity hot mirrors has been suggested to increase the operational efficiency of the solar trough collector. Optical efficiency of the modified receiver design is 78.02, which is similar to that of the conventional system [8,66].Tonatiuh ray-tracing combined with response surface methodology showed that adding a secondary reflector improved solar flux uniformity, reducing the coefficient of variation from 1.0836 to 0.58 and enhancing overall thermal performance [67]. A solar trough collector was experimentally studied by Yuan et al. (2020) using the ethylene tetrafluoroethylene (ETFE) foil. These findings showed 63%, 55%, and 54% collector efficiencies at average receiver fluid temperatures of 27 °C, 63 °C, and 81 °C, respectively [68,69]. V Prakash et al. (2017) compared the output of PTC using two distinct kinds of reflectors: a stainless-steel sheet and an acrylic mirror sheet. The result indicated that the stainless-steel reflector showed higher efficiency than the acrylic reflector [70]. Jamali (2019) showed that mirror reflectance strongly influences PTC efficiency. Silver and aluminum mirrors, prepared using techniques such as PVD and sol–gel deposition, achieved high thermal efficiencies of about 0.8 and 0.7 due to their high reflectance, with silver offering the best performance [71,72]. The Monte Carlo Method (MCM) was used to analyze the Local Concentration Ratio (LCR) to improve the optical performance of PTCs. The outcome indicates that the intercept factor and optical efficiency increased by 0.98 and 65, respectively, as the rim angle increased [73]. Farr et al. (2009) utilized ReflecTech Mirror Film to create lightweight, affordable, and indestructible non-glass reflectors. These reflectors are like silver glass mirrors but are easy to install and repair. This innovation provides an easy alternative to glass mirrors [63].

Table 2 *Summary of the reflector used in previous investigations*

Sr. No.	Authors	Mirror type	Reflectance	Peak Optical Efficiency %	Major outcomes
1	Natraj et.al (2023) [49]	-	0.96	86	Bending effects reduce optical efficiency from 86% to 67.24%.
2	Al-Rabeeah et al. 2023 [52]	Silver chrome film	0.99	80.4	Silver-chrome–coated aluminum reflectors improve solar radiation reflection.
3	Büker et al. (2022) [74]	Polished aluminium sheets	0.93	-	Peak air temperature of 45.8 °C achieved at 60 m³/h, with optimal dehumidification at 80 m³/h.
4	Zhao et al. 2022 [75]	Silver/ glass	0.93	-	Advanced selective coatings reduce heat loss by 29.3% and improve efficiency by 4.3% at 290–550 °C.
5	Anwar et al. (2021) [76]	aluminum, Silver	-	-	Aluminum reflectors outperform stainless steel (34.8% vs. 31% efficiency).
6	Pal et al. (2021) [77]	-	0.95	-	The maximum circumferential temperature difference observed is 16K.
7	Nascimento et al. (2021) [78]	-	0.935	-	Water works effectively at outlet temperatures of up to 300°C.
8	Yuan et al. (2020) [68]	ETFE foil	-	-	PTC efficiencies of 63%, 55%, and 54% were recorded at 27 °C, 63 °C, and 81 °C, respectively.

9	Reddy et al. (2020) [79]	-	0.94	71	Peak optical efficiency was 70% for evacuated receivers and 66% for non-evacuated receivers.
10	Bellos et al. (2020) [80]	-	82.2	75.3	Optical efficiency is 75.3% for the bare tube.

2.3 Receiver/Absorber

The receiver functions to transform solar energy into thermal energy [81]. The receiver is placed at the focal point of the parabolic trough and captures solar rays and enables the transfer of heat to the thermal medium utilized within the system or tube [82]. To mitigate heat loss through convection, the absorber tube is surrounded by an evacuated glass [83]. A primary challenge associated with the receiver material is its expansion, which results from temperature fluctuations between non-operating and operating conditions [34,84,85]. The details of the Receiver/absorber and coating are given in Table 3.

The thermal performance of a parabolic trough solar collector with swirling flow inside the absorber tube was numerically investigated. Results showed that tangential inlet configurations, particularly a single downstream inlet, enhanced heat transfer by about 12.7% and 41.7%, respectively, compared to conventional axial flow [86]. Oketola et al. (2024) developed a validated model combining Monte Carlo ray tracing and CFD for PTC analysis, showing that using metal twisted tape inserts with CO_2 as the working fluid can enhance heat transfer by up to 73% and improve thermal efficiency by 6% [47].

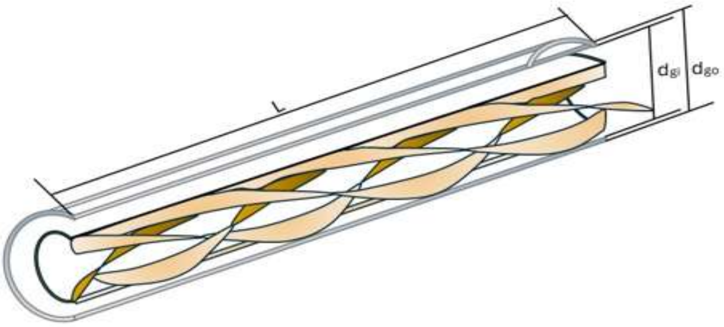
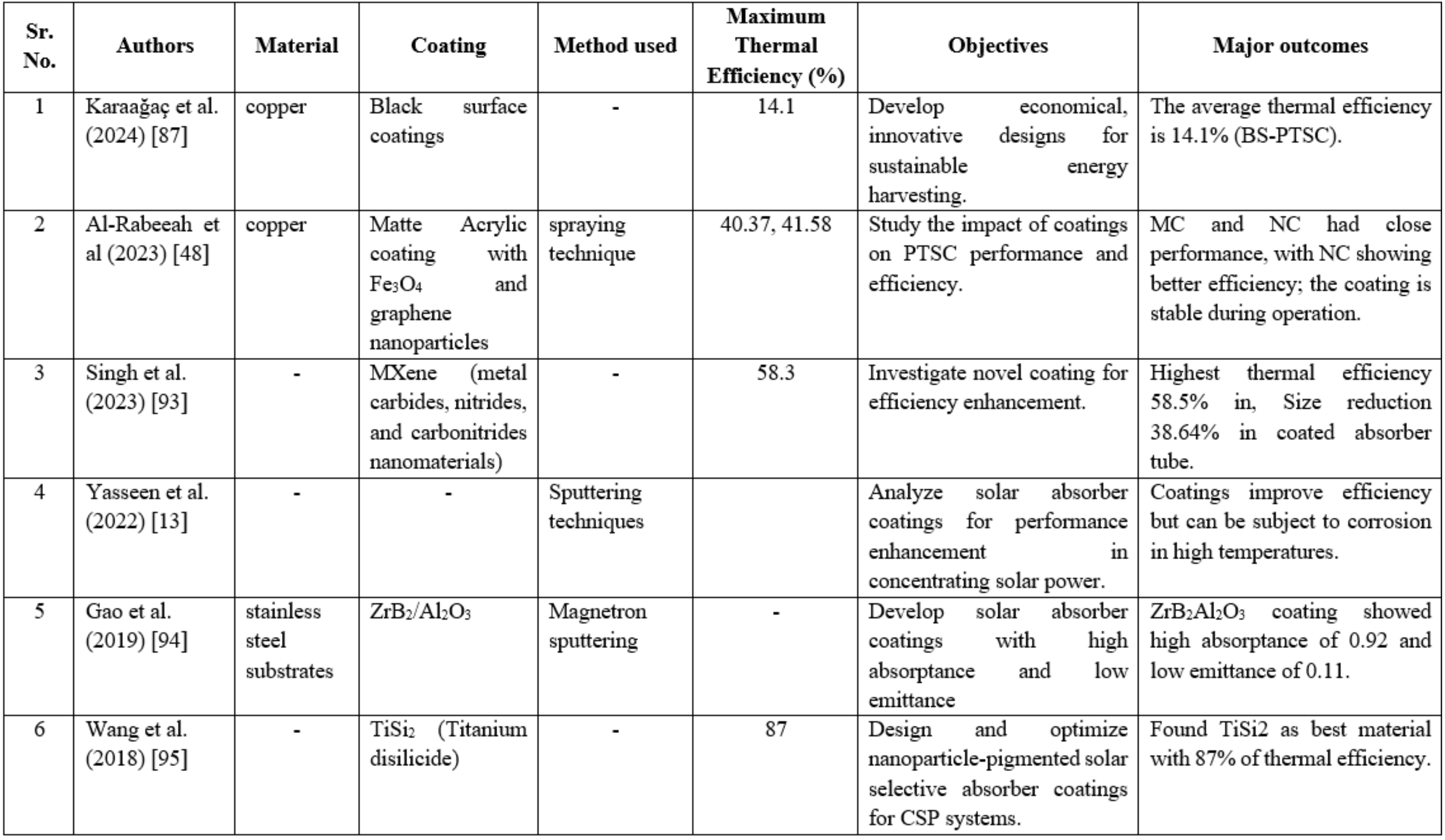


Figure 1 *Receiver with twisted tape insert [47]*

Karaağaç et al. (2024) designed receiver tubes with a Black surface (BS)-PTSC and the inclusion of Paraffin wax (PW). Results indicated an increase in thermal energy of 26.5% and 56.8%, respectively, which is more than conventional PTSC. These novel designs not only offer improved thermal efficiency but also contribute to sustainability by reducing CO_2 emissions without costly modifications [87]. Al-Rabeeah et al. (2023) compared matte coating (MC) and nano-coating (NC) enriched with Fe_3O_4 and graphene on absorber tubes of identical PTSCs. The NC showed superior performance, achieving a heat removal factor of 52.72% versus 50.33% for MC, with thermal efficiencies of 41.58% and 40.37%, respectively, at a mass flow rate of 120 L/h [48]. Nagamani Prabu et al. (2023) fabricated and evaluated an innovative PTC with a unique shell-type receiver made from aluminum and copper that utilized vegetable oil as the heat transfer medium. The novel design showed an initial efficiency of 58.61%, which is higher than the 36.5% efficiency of the traditional aluminum receiver [54]. Sharma et al. (2023), numerically studied heat transfer in a solar parabolic trough receiver using a rotating tube with hybrid nanofluid flow, showing that porous media significantly enhance heat transfer due to increased fluid–surface interaction under solar radiation [88]. Al-Rabeeah et al. (2023) discovered the double-evacuated U-shaped copper absorber tube as shown in Figure 2 with a flat plate, using a $NiFe_2O_4$/Water nanofluid as the heat transfer fluid, achieve the maximum thermal efficiency, reaching 52.7% and 59.05% at mass flow rates of 60 and 120 L/h, respectively [52].Shafiey Dehaj et al. (2022) experimentally investigated a parabolic trough solar collector using a novel U-tube absorber with $NiFe_2O_4$/water nanofluid as the heat-transfer fluid. Results showed that the U-tube design outperformed the conventional absorber, and the addition of $NiFe_2O_4$ nanofluid significantly enhanced thermal performance, achieving a maximum efficiency of 51% at a flow rate of 3 L/min and a volume fraction of 0.05% [89].Attaching triangular copper tape fins to receiver tubes significantly increased surface area, yielding efficiencies up to 87.12% at 3 L/min, though performance declined at higher flow rates [90]. Rotating absorber tubes reduced surface temperature and thermal stresses, improving overall efficiency by 17% [91],whereas optimizing tube diameter (0.016 m) increased efficiency to 79–81% and reduced heat losses [92].

Table 3 *Summary of the Receiver/absorber and coating used in previous investigations*



Sr. No.	Authors	Material	Coating	Method used	Maximum Thermal Efficiency (%)	Objectives	Major outcomes
1	Karaağaç et al. (2024) [87]	copper	Black surface coatings	-	14.1	Develop economical, innovative designs for sustainable energy harvesting.	The average thermal efficiency is 14.1% (BS-PTSC).
2	Al-Rabeeah et al (2023) [48]	copper	Matte Acrylic coating with Fe_3O_4 and graphene nanoparticles	spraying technique	40.37, 41.58	Study the impact of coatings on PTSC performance and efficiency.	MC and NC had close performance, with NC showing better efficiency; the coating is stable during operation.
3	Singh et al. (2023) [93]	-	MXene (metal carbides, nitrides, and carbonitrides nanomaterials)	-	58.3	Investigate novel coating for efficiency enhancement.	Highest thermal efficiency 58.5% in, Size reduction 38.64% in coated absorber tube.
4	Yasseen et al. (2022) [13]	-	-	Sputtering techniques		Analyze solar absorber coatings for performance enhancement in concentrating solar power.	Coatings improve efficiency but can be subject to corrosion in high temperatures.
5	Gao et al. (2019) [94]	stainless steel substrates	ZrB_2/Al_2O_3	Magnetron sputtering	-	Develop solar absorber coatings with high absorptance and low emittance	$ZrB_2Al_2O_3$ coating showed high absorptance of 0.92 and low emittance of 0.11.
6	Wang et al. (2018) [95]	-	$TiSi_2$ (Titanium disilicide)	-	87	Design and optimize nanoparticle-pigmented solar selective absorber coatings for CSP systems.	Found TiSi2 as best material with 87% of thermal efficiency.

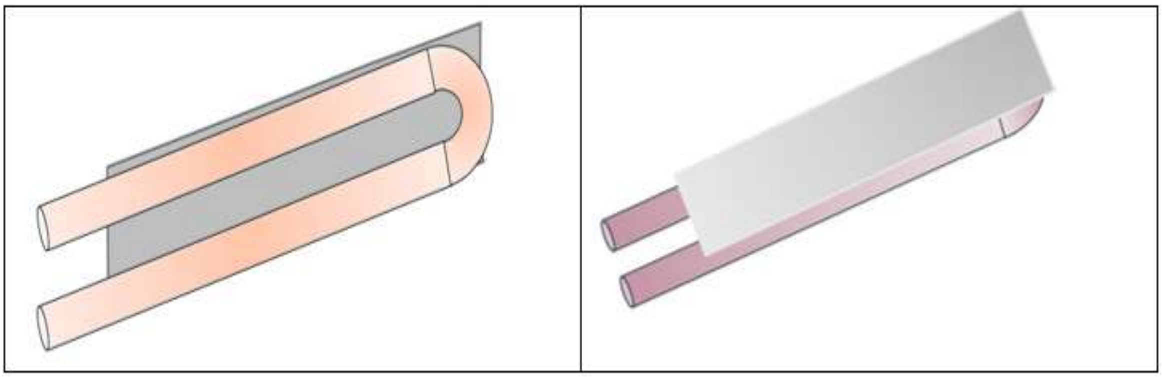


Figure 2 *Double evacuated absorber tube with flat plate*

Advanced absorber coatings such as ZrB_2/Al_2O_3, AlCrSiN-based nanocomposites, silicide cermets, and ZrOx/ZrC–ZrN multilayers exhibited high solar absorptance (0.88–0.96), low emittance (≈0.11–0.14), and excellent thermal stability at temperatures up to 750 °C, making them suitable for high-temperature applications [94,96,97], Additionally, nanoparticle - pigmented absorbers and evacuated receiver tubes improved optical-to-thermal efficiency by up to 94.4% and 70%, respectively, while nanofluids and flow inserts provided 15–60% heat transfer enhancement [95,98]. The study focused on a fabricated ZrOx/ZrC–ZrN/Zr tandem layered structure on SS and Cu absorber by the magnetron sputtering method. The best performance was achieved at 12.5 sccm nitrogen flow, with absorptance of 0.88 (SS) and 0.85 (Cu), exhibiting strong thermal stability at 700°C (vacuum) and 200°C (air). These designs are preferable in high temperature deployment in vacuum/inert environments [96,97]. Optical simulations further showed that S-curved receiver tubes offer more uniform heat flux distribution and reduced structural deflection compared to conventional straight tubes, indirectly improving system efficiency[99].

2.4 Heat Transfer Fluid

The solar heat is absorbed and then passed on to a hear transfer fluid (HTF), which then transfers the heat energy out of the solar collector. HTF is often pumped at increased flow rates to create turbulence.

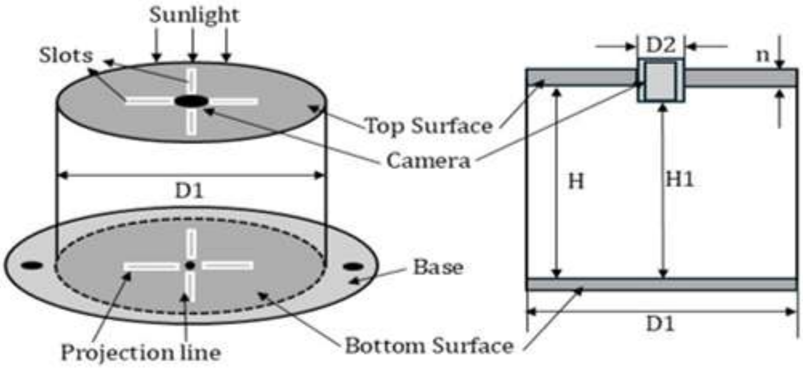
Selection of HTF type is crucial for optimizing the overall heat transfer efficiency. Water is often selected for temperatures below 100 °C due to its cost-effectiveness and favourable transport properties, and for temperatures exceeding 100 °C, synthetic oil, Therminol VP-1, Syltherm-800, and Al_2O_3 $-TiO_2$ nanofluid are preferred [31,100]. Detailed information on HTF is given in **Hata! Başvuru kaynağı bulunamadı.**. A detailed thermal model using 4% Metallic Oxide Nanofluids (CuO, SiO_2, Al_2O_3, TiO_2) with Therminol VP-1™ was developed and validated via experimental and theoretical investigations. A validated thermal model results indicate that nanofluids improve thermal efficiency, with CuO achieving the highest increase at 1.03% and outlet temperature rises of 9.57% (CuO), 6.04% (TiO_2), 5.21% (Al_2O_3), and 3.08% (SiO_2) [101]. A mathematical model using Decision Tree, SVM, and ANN was developed to predict PTSC thermal performance with hybrid nanofluids, showing that Syltherm-800 with 2% Al_2O_3 and 1% MWCNT achieved an average thermal efficiency of 70.54%.[44]. Through computational and experimental methods, Arun et al. (2024) have investigated the application of TiO2 nanofluids and dimpled tubes in parabolic solar trough collectors. The outcome shows that the coefficient of convective heat transfer increased by 34.25% at a mass flow rate of 2.5 kg/min and 0.3% TiO_2 volume concentration, and 11% rise in the total effectiveness of collector [46,102]. A one-dimensional quasi-static thermal model was used to evaluate PTSC performance with green and conventional nanofluids using water and Syltherm 800 as base heat-transfer fluids. Results showed that Syltherm 800 increased energy production by about 1 MWh and reduced operating costs, but resulted in higher CO_2 emissions compared to water-based HTFs [31]. A numerical study showed that Therminol VP-1/Al_2O_3–TiO_2 achieved the highest thermal efficiency (71.68%), Syltherm-800/Al_2O_3–TiO_2 provided peak exergy efficiency (24.1%), and Solar Salt/Al_2O_3–TiO_2 delivered balanced thermal and exergy efficiencies of 61.8% and 36.1%, respectively [103]. Vegetable oils can serve as eco-friendly, low-cost alternatives to synthetic oils as heat transfer fluids in PTC systems, enabling continuous operation at around 200 °C with a mass flow rate of 0.04 kg/s while improving sustainability and supporting local resources [104]. The authors discovered that a hybrid nanofluid can increase the thermal efficiency of solar parabolic trough systems by 80 %, especially when Al_2O_3-MWCNT/water is used [105]. Al-Aloosi et al. (2023) found via CFD analysis that circular, elliptical, and square fins delivered optimal thermal performance in PTCs, with performance factors up to 1.4 at Re = 4000. Likewise, Shaker et al. (2022) reported that using an Al_2O_3–Syltherm oil nanofluid with a flange-shaped turbulator improved heat transfer efficiency by up to 5%, depending on inlet temperature [57] [106]. Bamisile et al. (2022) used mathematical modeling to compare mono and hybrid nanofluids with conventional HTFs in PTCs and found that molten salt ($7NaNO_3$–$40NaNO_2$–$53KNO_2$) achieved the highest outlet temperature and an exergy efficiency of 37.93% [90][107]. The PTSC performance with TiO_2–H_2O nanofluid showed maximum temperature difference and useful heat gain at a flow rate of 160 LPH and a nanoparticle concentration of 0.15% [108].

2.5 Tracking System

Parabolic trough collectors cannot use diffuse radiation, so solar tracking systems are used to maintain focus on the absorber tube throughout the day [109]. A tracking system comprises a controller module, electro-pneumatic drive assembly, and a geared electric actuator [110]. There are two major types of tracking systems, that is, one axis and two axis tracking. One-axis trackers rotate around north-south for the highest annual energy yield. Moreover, two-axis trackers maximize incident irradiation by keeping the collector surface parallel to the sun, eliminating incidence angle losses [3]. Table 5 are summarized in various tracking systems used in the PTC system. Kapsikar et al. (2023) showed that a 15-day tilt adjustment for an east–west facing mini-PTC results in only a 0.11% reduction in absorbed flux compared to daily tracking. Since the tilt change remains within half the acceptance angle (±4.35°) and requires just 16 adjustments per year, this approach significantly reduces system cost by eliminating continuous active tracking [37].As illustrated in Figure 6, a solar tracking sensor based on image recognition improves tracking accuracy by capturing sunlight projections through two vertical slots, processing them with a Hough transform, and adjusting the position accordingly [112].Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Teaching-Learning Based Optimization (TLBO) algorithms were tested and compared to find the optimal position of the parabolic trough. The PSO algorithm more accurately tracked the trough position than other algorithms [113]. Advanced control strategies, such as dual closed-loop tracking, reduced sun-tracking error by 78% [115]. Studies also show that collector performance is highly sensitive to tracking errors, especially for smaller-diameter receivers [59].

Table 4 *Summary of Heat Transfer Fluid (HTF) used in previous investigations*

Sr. No.	Authors	HTF	HTF Flow rate	Inlet fluid Temperature	Outlet fluid Temperature	Thermal conductivity	Maximum Thermal Efficiency	Major Outcomes
				°C	°C	(W/m.k)	%	
1	Alhamayani (2024) [44]	Syltherm-800 with a combination of 2% Al_2O_3 and 1% MWCNT	-	-	-	-	70.54	Highest density enhancement with 2% Al_2O_3 and 1% MWCNT
2	Benrezkallah et al. (2024) [101]	Therminol VP-1™ with 4% of, Al_2O_3 , SiO2, CuO,TiO2,	-	-	-	40, 1.4, 33, 8.4	-	The PTSC system gained thermal efficiency of 1.03, 0.97, 0.97 and. 0.81 %, respectively.
3	Gupta et al. (2023) [105]	Al_2O_3 -MWCNT	-	-	-	40	80	Achieved higher efficiency over traditional heat transfer fluids.
4	Dou et al. (2023) [50]	Syltherm 800, Therminol VP1	-	-	-	-	-	Syltherm 800 is a better choice for a base fluid due to higher efficiency enhancements.
5	Ram et al. (2023) [53]	CuO–H2O based nanofluid (0.05%, 0.075%, 0.1% conc.)	70 L/h, 140 L/h	-	-	0.938, 1.088, 1.245	53.26, 69.07	Efficiency increased with CuO-H_2O nanofluid compared to water.
6	Praveen et al. (2022) [56]	Hitec solar salt	-	293	525	-	-	The plant efficiencies of 16.53% and 17.42%, respectively.
7	Shafiey Dehaj et al. (2022) [89]	Ni-Fe2O_4/Water nanofluid	3 L/min	50	54.1	-	51	Higher flow rates that are more effective and suitable for the PTSC.
8	Bamisile et al. (2022) [114]	Salt (7$NaNO_3$_ 40$NaNO_2$_ 53KNO_2)	-	-	491	-	66.27	Nano fluids outperformed base fluids in energy and exergy efficiencies.



(a) Overall Structure (b) Cutaway view

Figure 3 *Structure of Tracking Sensor [112]*

Elsayed et al. (2021) developed a novel 3-D model and built a single-axis tracking mechanism from inexpensive materials. Mechanism accuracy showed a maximum tracking deviation of (3.36° to -1.65°) with a mean of less than 0.5° and a standard deviation of under 0.75° annually. PTC achieved a stagnation temperature of 185.5 °C for synthetic oil in fall weather [116]. Ghassoul (2020) presented a new (single/dual axis) sun-tracking system that harvests more energy than fixed panels. They implement a Pilot control interface that effectively tracks the sun's movement and adjusts the panel position based on light to frequency (LTF) comparisons. This method achieves 98.36% energy extraction with low energy consumption [117]. A parabolic trough collector using north–south, rotatable-axis tracking reduces cosine losses by adjusting the surface azimuth angle, with experimental results showing an increase in daily average efficiency from 43% to 48% [118].

2.6 Thermal Energy Storage Device

Solar thermal storage is one of the important technological solutions by which solar energy can be captured and stored in the form of thermal

Table 4 *Summary of the Tracking system used in previous investigations*

Sr. No	Authors	Tracking System	Observations
1	Kapsikar et al. (2023) [37]	15-day tilt adjustment.	The mini PTC cost was reduced by replacing the active tracking system with a periodic 15-day tilt adjustment.
2	Lan J (2023) [112]	Novel Image base Tracking sensor.	Get precise measurements of azimuth and altitude with an accuracy of 0.05°.
3	Al-Rabeeah et al. (2023) [52]	Manually adjust the collector position to the correct angle in every 10 minutes.	It is more convenient, cost-effective, and produces comparable results to automated tracking.
4	Saldivar-Aguilera et al. (2023) [115]	Novel closed-loop dual control algorithm.	The suggested strategy reduced the mean solar tracking error from 0.97° to 0.21°, a 78% improvement, enhancing accuracy and stability.
5	Elsayed et al. (2021) [116]	Mechanical solar tracking system for a small Parabolic Trough Collector.	Stagnation temperature 185.5 ℃ for small PTC in the fall season.
6	Ghassoul (2020) [117]	Light-to-frequency conversion technique for accurate and sensitive tracking.	Energy extraction up to 98.36% with minimum energy consumption.
7	Qu et al. (2017) [118]	Rotatable axis tracking system.	It reduced daily average cosine loss by 10.3% and improved daily collector efficiency by 5.0% compared to north–south axis tracking.
8	Ruelas et al. (2017) [119]	Solar tracking system based on Image vision.	Sun's position can be obtained with an accuracy of 0.0426°.

energy to be used later [120,121].These systems, which use different materials, such as molten salts or phase change materials, to absorb and store the heat, usually receive it during sunlight hours and are used at night or when the weather is cloudy [122–124]. Stored heat can be used to generate electricity on demand or in industrial processes [125]. Table 5 Contains a summary of thermal energy storage systems.Bagherzadeh et al. (2024) compared and evaluated the cascaded latent heat storage (CLHS) and non-cascaded setup using phase change materials (PCMs) with a small parabolic trough collector. Experiments were performed using three different paraffin waxes, showing that the CLHS increased latent heat storage capacity by 10%, 47%, and 5% and increased exergy storage by up to 27.4% with an average thermal efficiency of 73.5% [126]. An experiment involving parabolic trough solar collector with porous discs manufactured from silicon and filled with phase change (PCM-paraffin) material determined that at 200 LPH flow rate system achieved fluid and PCM temperatures of 84.2 °C and 98.5 °C, energy storage of 599.7 kJ and mean thermal and exergy efficiencies of 73.8% and 15.1%, which indicating significant improvement over conventional absorber systems [127]. Koželj et al. (2021) experimentally investigated the efficiency of heating systems incorporating phase change material (PCM). The results indicate that 15% of the PCM in the water storage tank offers 70% more heat storage than a traditional heat storage tank. [128]. Crespo et al. (2019) suggested that novel Organic PCM possess higher heat of fusion (134.8-339.8 kJ/kg) than inorganic materials (20.9-266.1 kJ/kg) within the temperature range of 100-400°C but exhibit low thermal conductivity and large volume change. An inorganic eutectic composition has additional available PCMs for 120–400 °C, with heat of fusion values ranging from 74–535 kJ/kg, exceeding organic and other inorganic substances. The KOH/LiOH (54/46) mixture gives maximum heat of fusion at 535 kJ/kg [129].

Table 5 *Summary on Thermal Storage*

Sr. No.	**Authors**	**Objectives**	**Major Outcomes**
1	Bagherzadeh et al. (2024) [126]	Compared PCM performance with cascaded latent heat storage (CLHS) and a non-cascaded setup.	CLHS improves latent heat storage by 10–47%.
2	Mhedheb et al. (2023) [130]	Test the thermal performance of hybrid-nano PCM storage TES units.	1% TiO_2–CuO hybrid nanoparticles enhance storage temperature and reduce PCM melting time.

3	Yeh et al. (2022) [131] Hinojosa et al. (2023) [132]	Improve thermal performance by using shape-stabilized phase change material (SSPCM).	SSPCM increases discharge duration by 2.6× with a 55 °C outlet temperature.
4	Helmi et al. (2022) [133]	Test the behavior of porous fin materials (copper, aluminum, bronze, steel) with different porosities.	97% porous fins raise heat transfer 3.7 times with a 2.6 times pressure drop.
5	Koželj et al. (2021) [128]	PCM integration in a water tank for improved heat storage efficiency.	Adding 15% PCM boosts tank heat storage by 70%.
6	Algarni et al. (2020) [134]	Enhances heat transfer efficiency by combining Ne-PCM.	0.33 wt% Cu improves PCM efficiency by 32% and supplies 50 °C water for 2 h.
7	Lamrani et al. (2020), [135]	To increase the effectiveness of latent heat storage for large buildings.	RT-55 PCM enables effective night-time hot water delivery for buildings.
8	Crespo et al. (2019) [129]	To evaluate the thermophysical properties of selected organic PCM.	The most promising PCMs at medium-high temperatures (120–400 °C) are inorganic eutectic compositions.
9	Mao et al. (2019) [136]	To investigate the charging and discharging performance of TES systems.	Truncated cone TES tanks shorten charging/discharging time by 21–32%.

2.7 Applications of PTC

PTC systems are suitable for various industries with high thermal energy demands, such as chemical, food and beverage, fabrics, textiles, laundries, water distillation, and air heating systems [137]. They contribute to thermal energy production, reducing economic, environmental, and social impacts. The system energy safety and short payback times can help mitigate global climate change by reducing fossil fuel consumption and environmental pollution, leading to a healthier living environment [55,138]. The Mekelle University student cafeteria replaced its existing electrical baking system with a solar thermal system to reduce its carbon footprint. The system uses 92 Anodized aluminum plate Mitads as heating elements, which are heated by hot oil from a parabolic trough solar collector. The system achieved a thermal efficiency of 57.4, satisfying the necessary heating capability and energy usage of 1216.5 MJ per hour [138]. Omidi et al. (2023) experimentally evaluate a hybrid solar energy system that simultaneously produces distilled water and hot water using a parabolic trough heat pipe solar collector, The highest daily distilled water production of 4940 ml/day, and an energy efficiency of up to 63.57% [55]. To address the problem with humidity, Buker et al. (2022) proposed a rotary desiccant dehumidification system powered by a solar collector. The performance of the system is measured on the basis of air flow rate, regeneration air temperature, inlet-outlet air temperature, and humidity ratio. It attains best performance at 45.8°C and 60 m^3/h flow rate, with high dehumidification efficiency at 80 m^3/h [74]. As shown in Figure 4. The innovative distillation system, combine with a parabolic trough collector, incorporates a conical coil heat exchanger submerged in the distillation reservoir, achieving a notable reduction in phenolic compounds by 95-97% and improved productivity. The system generated 19 MWh of thermal energy, avoiding approximately 12,660 kg of CO2 emissions [60]. Ktistis et al. (2021) reviewed a PTC system installed at the KEAN soft drinks factory in Cyprus and found that it reliably met industrial steam demand, producing about 940 L of steam per day with an average daily efficiency of 39% after two months of operation [137].

Advantages of solar energy as a method of heating an industrial process plant in Salt Lake City. The proposed 5 MW_t solar plant, using parabolic trough technology, would generate about 15,389 MWh_t of thermal energy each year. It would deliver this heat at a competitive cost of \$26.3 per MWh_t. By replacing natural gas, the plant could cut nearly 3.6 million kg of CO_2 emissions annually, along with other pollutants like PM, NO_x, and SO_2, and save \$99,900 to \$357,004 in external costs [139]. Upadhyay et al. (2021) demonstrated the novel PTC's promising results for low-temperature water heating systems. The price for water heating per kilogram costs 0.3 INR for the manual tracking system and 0.4 INR for the automatic tracking system. The expected return on investment was 4 years and 5 years for the manual tracking and automatic tracking systems, respectively [39]. A renewable energy system has been developed based on solar power and with the help of a parabolic trough collector, the existing process is to be replaced in an ice cream plant in Isparta, Turkey. Using energy and exergy analysis, the system will be able to save 1.235 kWh of energy, which will constitute 98.56 percent of the total daily energy consumption of 85.81 kWh [140].

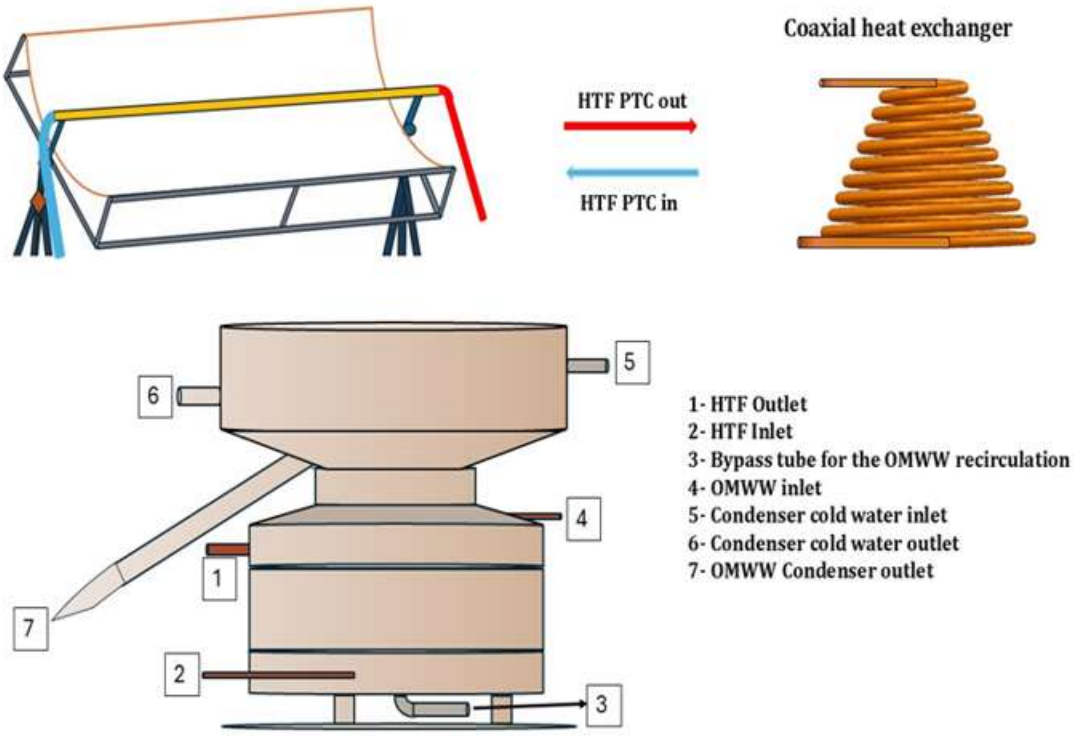


Figure 4 *Wastewater distiller [60]*

Table 6 *Summary on Application of PTC*

Sr. No.	Authors	Application	Remarks
1	Retta et al. (2024) [138]	Solar thermal system for Injera baking.	Produces 11,000 injera in 6 h, operating efficiently for 9 months/year.
2	Omidi et al. (2023) [55]	Heating and desalination of water.	Water distillation cost \$0.038/L; hot water cost \$1.01/m³.
3	Mistri et al. (2023) [141]	Cooking and water heating.	Delivers water at 91.9 °C under 642 W/m², with 5–40% efficiency.
4	Othman et al. (2022) [60]	Olive oil mill wastewater treatment.	Achieves 95–97% reduction in phenolic compounds from OMWW.
5	Chantasiriwan (2022) [142]	Combining parabolic trough collectors and biomass power plants in order to heat the feed water.	Feedwater heating increases power output by 8.86×10^7 kWh/year with LCOE of \$0.103/kWh.
6	Upadhyay et al. (2021) [39]	Water heating.	Enables low-cost low-temperature water heating with quick payback.
7	Mohammadi et al. (2021) [139]	Industrial process heat.	External cost savings range from 99,900 to 357,004 annually.
8	Kizilkan et al. (2016) [140]	Power an ice cream factory.	Reduces energy consumption by 98.56% (1.235 kWh).
9	Zou et al. (2016) [143]	Small-scale parabolic trough collector for water heating in cold climates.	Maintains 67% thermal efficiency even below 310 W/m² solar irradiance.

3. Conclusion

Solar trough collectors illustrate a compelling investment in clean energy technology characterized by substantial thermal efficiency, scalability, and environmental benefits. Continued technological advancements will enhance their viability while reducing costs, making solar collectors increasingly accessible and practical for diverse applications. As increasing popularity of renewable energy sources, solar trough collectors are set to make a considerable impact on the world energy scene, and they will prove to be an essential part of the future energy grid. In accordance with several numerous works, the following conclusions may be made.

- Structural analysis of PTC shows that key parameters such as length and width of collector aperture area, focal length, rim angle, trough material, etc, should be optimized to enhance PTC efficiency.
- Optical analysis of PTC shows that progressive improvement can be made in PTC efficiency by enhancing the key affecting elements such as reflectivity of the mirror, materials and coatings.
- Thermal analysis shows that PTC efficiency can be improved by optimizing the working fluid, absorber coating and material, absorber tube design, and by using fins or twisted tape inserts, highlighting the need for cost-effective and sustainable coating methods.
- Advances in tracking sensors, automation, and control algorithms have reduced energy losses and improved PTC performance, though further work is needed to lower costs and maintenance.
- The thermal energy storage system incorporated within PTC allows a diverse variety of thermal energy applications. The phase transition from solid to liquid stores a significant amount of energy that is available to use during nighttime or on cloudy days.
- Parabolic trough collectors can be applied in air heating, desalination, and industrial processes, reducing fossil fuel use while improving energy efficiency and environmental sustainability.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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