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Review

Next-Generation CSP: The Synergy of Nanofluids and Industry 4.0 for Sustainable Solar Energy Management

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Abstract: The growing demand for efficient and sustainable energy solutions underscores the importance of advancing solar energy technologies, particularly Concentrated Solar Power (CSP) systems. This review presents a structured evaluation of two key innovation domains in CSP: the application of nanofluids and the adoption of Industry 4.0 technologies. The first part analyzes experimental and simulation-based studies on nanofluid-enhanced CSP systems, covering four major collector types—parabolic trough, solar power tower, solar dish, and Fresnel reflectors. Nanofluids have been shown to significantly enhance thermal efficiency, with hybrid formulations offering the greatest improvements. The second part examines the role of Industry 4.0 technologies—including artificial intelligence (AI), machine learning (ML), and digital twins (DT)—in improving CSP system monitoring, performance prediction, and operational reliability. Although a few recent studies explore the combined use of nanofluids and Industry 4.0 tools in CSP systems, most research addresses these areas independently. This review identifies this lack of integration as a gap in the current literature. By presenting separate yet complementary analyses, the study offers a comprehensive overview of emerging pathways for CSP optimization. Key research challenges and future directions are highlighted, particularly in nanofluid stability, system cost-efficiency, and digital implementation at scale.

Keywords: nanofluids; concentrated solar power; Industry 4.0; artificial intelligence; digital twin; machine learning

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1. Introduction

The World Health Organization (WHO) has reported that 80% of urban residents worldwide are exposed to poor air quality, contributing to approximately 3 million premature deaths annually due to environmental pollution [1]. The CO_2 concentration in the atmosphere is expected to surpass current levels by 2030. As a result, government regulations have mandated the reduction of these pollutants. Numerous studies over the past two decades have focused on reducing emission levels [2].

Renewable energy is widely adopted worldwide for its environmental benefits [3]. Among various renewable energy technologies, solar energy has gained global attention due to its universal availability and the cost-free nature of sunlight. Within solar technologies, Concentrated Solar Power (CSP) stands out as a highly efficient solution for large-scale power generation [4]. Unlike photovoltaic systems, CSP uses thermal processes to convert solar radiation into electricity. The growing interest in CSP is driven by its ability to integrate thermal energy storage (TES) and provide stable power output, making it a promising option for sustainable energy systems [5,6]. Various solar energy utilization techniques, such as solar photovoltaic (PV), CSP, and solar thermal, have been developed based on the availability of space and technology [7]. It is important to distinguish between solar collectors and solar concentrators. Solar collectors generally refer to systems that absorb and transfer solar energy for thermal applications, including both non-concentrating (e.g., flat-plate and evacuated tube collectors) and concentrating types. In contrast, solar concentrators specifically refer to systems that focus solar radiation onto a smaller receiver area using optical components, thereby achieving higher temperatures. CSP systems, which are the focus of this review, utilize solar concentrators, such as parabolic troughs, solar towers, Fresnel reflectors, and dish collectors.

The dominance of fossil fuels in the global energy mix remained stubbornly high, hovering around 80% [8]. Global primary energy consumption set a record for the second consecutive year in 2023, increasing by 2% to reach 620 exajoules (EJ). The ongoing depletion of conventional energy resources underscores the escalating global demand for energy, necessitating a shift towards non-conventional energy sources. The global distribution of energy sources in 2023 has been recorded [8]. This growth rate exceeded both the ten-year average and pre-pandemic levels. Although a new record was set for absolute fossil fuel consumption in 2023, its share of global energy demand slightly declined to 81.5% from 81.9% in 2022. Renewable energy capacity, particularly solar and wind, continued to expand at a rapid pace in 2023. Surpassing the previous year's record of 276 gigawatts by approximately 186 gigawatts, the total increase was a substantial 67%. Solar accounted for 75% of these additions, with China contributing significantly. Europe also played a role, installing just over 56 gigawatts of solar capacity, representing 16% of the global solar capacity increase. Figure 1 provides a breakdown of global CSP installation growth, including the share of each region and the total installed capacity.

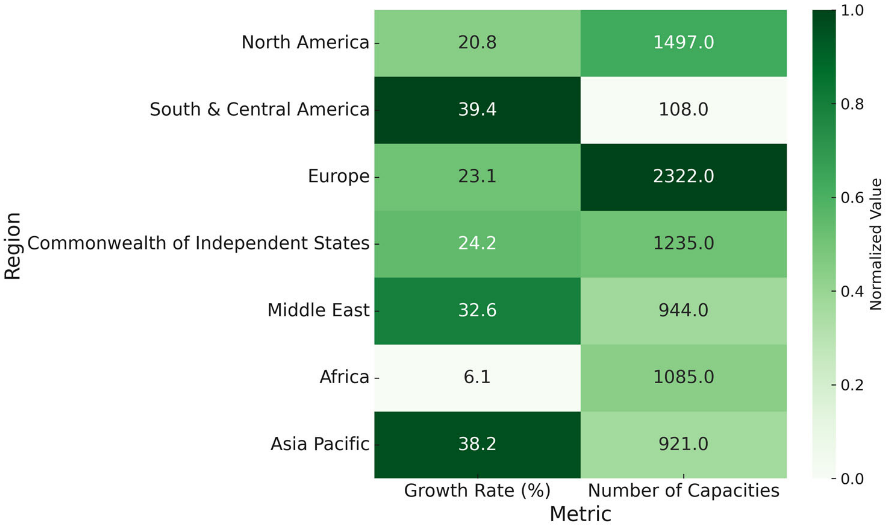

Figure 1. Global CSP installation growth share and the number of capacities [8].

Solar energy is recognized as having the greatest potential among all non-conventional energy sources to meet both present and future energy demands. Solar energy, once absorbed, is utilized in two primary forms: (a) through direct conversion into electrical energy via PV cells, and (b) as thermal energy through solar collectors. However, the high installation costs and relatively low conversion efficiency of PV cells continue to pose challenges [9,10]. The thermal energy produced by these systems can be utilized to power electrical generators. One significant advantage of using thermal energy compared to PV panels is its ability to be easily stored with higher thermal efficiency, particularly in regions with abundant solar radiation [11].

A novel approach for enhancing heat transfer efficiency involves dispersing nanoparticles within heat transfer fluids [12]. At Argonne National Laboratory in 1995, Choi introduced the term "nanofluid", by applying nano-powder suspensions as heat exchange media in intensified refrigeration equipment, which yielded promising results [13]. Nanofluid refers to a distinct fluid where nanoparticles, ranging in diameter from 1 to 100 nm, are dispersed within a base fluid. Studies have demonstrated that integrating nanomaterials into conventional base fluids can effectively mitigate problems caused by water-induced rust and corrosion. Nanomaterials hold great potential in solar applications due to their ability to enhance thermophysical properties, such as specific heat capacity, thermal conductivity, and heat transfer properties [14]. Subsequently, researchers have utilized nanofluids in solar collector systems to enhance thermal efficiency. Nanofluid-based solar systems not only facilitate applications at moderate to high temperatures, but also effectively harness the entire solar spectrum, offering versatile control owing to the outstanding spectral characteristics of nanofluids [15]. While our previous review article [16] provided a broad overview of nanofluids in various solar energy systems, the present work is distinct in its exclusive focus on nanofluid applications in CSP systems. Furthermore, this study uniquely reviews the role of Industry 4.0 technologies in optimizing the various CSP applications.

Traditional simulations like CFD, COMSOL, OpenFOAM, ANSYS, etc., facilitate numerical analysis, which is essential for optimizing solar energy systems, providing crucial insights into design, performance, and cost-efficiency. By employing simulation tools, researchers and engineers can model and predict system behavior under various conditions, leading to improved designs and operational strategies. For instance, simulations help optimize the placement and angle of solar panels and the design of solar collectors, enhancing system performance and efficiency [17]. Furthermore, simulations contribute to cost reduction by identifying optimal designs that minimize waste and streamline development [18]. They are crucial for analyzing the integration of solar components with storage systems and other energy sources, ensuring harmonious operation [19]. Thus, simulation is a key tool in advancing solar energy systems and enhancing design, performance, and research efficiency.

Industry 4.0 technologies are transforming renewable energy by optimizing generation, transmission, and trade, and by enhancing efficiency, cost-effectiveness, and sustainability through enabling tools such as digital twin (DT), artificial intelligence (AI), and machine learning (ML) [20], while addressing challenges like inefficiencies and grid constraints. This study explores their role in enhancing sustainability through data-driven solutions and circular economy models [21].

Solar energy, with its significant potential for sustainable development, requires accurate forecasting. Various methods have been explored for predicting global solar radiation, shifting from traditional models to Industry 4.0 techniques. ML has proven effective in modeling complex patterns and improving data-driven decision-making for solar energy optimization [22]. DT optimizes urban solar energy systems through real-time monitoring and performance analysis. Applied to five systems in Benguerir, Morocco, DT uses 3D models and data processing to simulate solar production and detect anomalies, ensuring optimal operation and system efficiency [23]. AI models enhance prediction accuracy in renewable energy systems. For instance, in solar thermal applications, AI models, like adaptive boosting and stacking ensemble learning, predict exergy efficiency in parabolic trough collectors (PTCs), improving performance by using input parameters such as temperature and nanoparticle types [24].

Traditional simulation methods have been widely used to model and optimize solar energy systems by providing detailed insights into heat transfer, fluid flow, and system performance. However, these methods can be computationally expensive and require an extensive manual setup. In contrast, Industry 4.0 technologies offer real-time monitoring and predictive analytics. DT creates virtual replicas of solar systems for continuous performance evaluation, while AI and ML enhance efficiency by identifying patterns and optimizing operations. Integrating these advanced technologies with traditional simulations can significantly improve the reliability, efficiency, and cost-effectiveness of solar energy systems.

2. Earlier Assessments and Developments in This Review

Compiling previous reviews provides a valuable overview of advancements in solar applications. This comprehensive analysis helps identify research gaps, successful methodologies, and challenges that require further investigation. CSP technology is increasingly being favored over other solar collector types due to its ability to generate electricity on a large scale with high efficiency [25]. Unlike PV panels, which convert sunlight directly into electricity, CSP systems use mirrors or lenses to concentrate sunlight onto a small area, generating high-temperature heat that drives a turbine to produce electricity. This concentrated heat can significantly enhance energy conversion efficiency and storage capability. One key advantage of CSP technology is its potential for higher efficiency in energy conversion compared to traditional solar thermal collectors [26].

The optical and thermal performance of PTCs has been studied. It analyzes various modeling approaches, including analytical and ray-tracing methods for optical analysis, and steady and transient heat transfer models for thermal analysis. Additionally, the review explores potential improvements to PTC design, such as novel designs, passive heat transfer enhancement, and nanoparticle-laden flows [27]. The use of nano-enhanced phase change materials (PCMs) in solar energy storage systems has been examined. While PCMs offer high storage capacity, their thermal conductivity can be improved through nanoparticle addition. This review analyzes recent studies on nano-enhanced PCMs in various solar technologies, highlighting potential benefits and challenges for practical implementation [28]. The use of nanofluids in PTCs to improve thermal efficiency has been reviewed. It analyzes the impact of various parameters, including nanoparticle type, size, and concentration, on PTC performance. Additionally, the study explores the potential benefits of using PCMs and nano-PCMs in these systems [29].

The comparison between flat plate collectors and PTCs was included to provide a broader perspective on the performance of nanofluids across different collector types, as these collectors operate under varying temperature ranges and thermal conditions. This comparison allows us to examine how nanofluids affect the efficiency and heat transfer performance in both systems, helping to identify the conditions where nanofluids offer the most significant improvements in solar collector performance [30]. Nanofluids offer selective absorption properties and improved physical characteristics for enhanced performance in these systems. Future research should focus on optimizing systems and improving nanofluid stability for wider applications [31]. The use of hybrid nanofluids in solar-based TES systems has been explored. Hybrid nanofluids, particularly those containing multi-walled carbon nanotube (MWCNTs) and alumina nanoparticles, enhance heat transfer efficiency. Combined with PCMs like erythritol and nitrate salt, these systems offer a reliable energy supply during non-sunlight hours. Future research should focus on optimizing hybrid nanofluids and integrating improved PCMs for further efficiency gains [32].

Moreover, this review explores how Industry 4.0 technologies can transform traditional factories into smart factories. It also addresses challenges like intermittent power supply, low efficiency, and grid bottlenecks, while highlighting the role of digital technologies in advancing energy generation, transmission, and trade, alongside contributing to circular economies and sustainable development goals [21]. The use of the ML model to predict key parameters in solar thermal collector efficiency has been reviewed. It also discusses challenges, accuracy issues, and future research opportunities in applying AI to solar thermal systems [33].

While challenges like high implementation costs and lack of standardization exist, this study highlights the transformative impact of DTs on improving the reliability and cost-efficiency of solar power plants, urging further research to overcome adoption barriers and maximize its benefits [34]. It provides a comprehensive overview of the applications of AI in renewable energy systems, consolidating many reports across various energy sources, including solar power, wind, geothermal, and energy storage. It discusses current advancements, research outcomes, and case studies, addressing challenges and offering potential solutions while exploring future trends and opportunities for further advancements in AI-driven renewable energy technologies [35].

A comprehensive review, as explored above, has been listed in Table 1, revealing a dearth of studies that concurrently explore the integration of CSP, nanomaterials, traditional simulation, and Industry 4.0 technologies. This review uniquely builds upon three foundational aspects—CSP, nanofluids, and traditional simulation techniques—commonly addressed in earlier works, and extends the scope by incorporating a dedicated focus on Industry 4.0 tools for optimizing various CSP types. While previous reviews have explored one or more of these aspects separately, no study has integrated all these components. Some entries lack data due to the specific focus of each study, as authors prioritized certain aspects while omitting others based on their research objectives. This review paper presents a comprehensive analysis of the integration of CSP, nanofluids, traditional simulation techniques, and Industry 4.0 technologies—a combination not previously explored in detail. While previous studies have examined aspects of CSP and nanofluids individually or in combination, there is a lack of research that concurrently addresses the synergistic potential of AI, ML, and DT technologies within CSP systems. Furthermore, existing reviews have typically focused on one or two of these components, without considering their collective impact on enhancing CSP performance. This study fills this gap by offering a one-stop resource for understanding how these four factors can work to optimize CSP systems, providing readers with insights into both their individual and integrated roles in improving energy efficiency and performance. By combining traditional simulation techniques with cutting-edge Industry 4.0 tools, this review offers a more holistic view of the future of CSP technologies, positioning it as a novel contribution compared to prior works in the field.

Table 1. Review articles on nanofluid, traditional simulations, and Industry 4.0 applications in solar energy research.

Ref	Review Focus on	Year	CSP	Nanomaterial	Simulation	Industry 4.0
[27]	Performance and optimization of PTC	2018	✔	-	✔	-
[28]	Nano-enhanced PCMs for solar energy storage	2022	-	✔	-	-
[29]	Enhancing the performance of PTCs using nanofluids	2022	✔	✔	-	-
[30]	Comparing the performance of mono and hybrid nanofluids with conventional fluids in solar thermal collectors.	2022	✔	✔	-	-
[31]	Nanofluid-driven multifunctional systems in solar energy	2022	✔	✔	-	-
[32]	Hybrid nanofluids for solar TES	2024	-	✔	✔	-
[36]	NEPCMs for solar heat collection	2023	-	✔	✔	-
[37]	Enhancing solar thermal collector efficiency using nanomaterials	2024	✔	✔	-	-
[38]	The application of nanofluids in various solar energy systems	2018	-	✔	-	-
[39]	The application of nanofluids in solar thermal collectors other than CSP	2018	-	✔	-	-

Table 1. *Cont.*

Ref	Review Focus on	Year	CSP	Nanomaterial	Simulation	Industry 4.0
[40]	It examines the technology's cost evolution, the role of thermal storage, and the properties of molten salts used in CSP plants.	2019	✔	-	-	-
[18]	Modeling and simulation of PCM-based solar energy storage systems	2019	-	-	✔	-
[41]	The application of hybrid nanofluids in solar energy collectors	2021	✔	✔	-	-
[42]	The sustainability of nanofluids in thermal systems	2021	-	✔	✔	-
[43]	Hybrid nanofluids for solar thermal energy systems	2021	-	✔	-	-
[44]	Enhancing the thermal efficiency of parabolic solar collectors using hybrid nanofluids.	2024	✔	✔	✔	-
[45]	Enhancing solar still performance using nano-enhanced PCMs	2024	-	✔	-	-
[21]	Industry 4.0 technologies optimize renewable energy production and improve system efficiency	2023	-	-	-	✔
[33]	Use of ML techniques to improve solar thermal collector modeling and performance	2023	-	-	-	✔
[34]	Challenges and opportunities in applying DT technology to solar energy systems	2024	-	-	-	✔
[46]	The potential of DT technology in addressing the challenges associated with solar energy resources	2024	✔	-	-	✔
[47]	DT impact on solar energy research	2025	✔	-	-	✔
[48]	Application of AI technology in solar tower systems	2021	✔	-	-	✔

"✔" = reviewed by authors, "-" = not reviewed by authors.

3. Concentrated Solar Power Collectors

3.1. Parabolic Trough Collector (PTC)

PTCs are a leading technology CSP, offering a cost-effective and widely implemented large-scale solution for generating electricity from the sun. These systems are foundational to renewable energy production. PTC power plants harness solar energy by using a heat transfer fluid (HTF) to capture heat, which is then converted into electricity through a Rankine cycle. This process involves heating water to produce steam, which drives a turbine to generate power [49]. PTCs employ parabolic mirrors to concentrate sunlight onto a central receiver tube. HTF circulates within this tube, absorbing the concentrated solar energy. The heated HTF is then transported to the power block where it transfers its heat to generate high-temperature superheated steam in a series of heat exchangers. This steam subsequently drives a turbine to produce electricity [50]. A thermal oil commonly serves as HTF, capturing solar energy and transferring it to heat exchangers for steam generation and subsequent power production.

The PTC's receiver tube is constructed from stainless steel, coated with a selective metal-ceramic material for optimal heat absorption, and enclosed within an evacuated glass tube. This vacuum environment safeguards the absorber from oxidation and significantly reduces heat loss at high operating temperatures. To minimize convective heat loss within the annular space, the receiver tube is maintained at a vacuum below the conduction band Knudsen gas limit, typically around 0.0001 mm Hg. A metal-ceramic multilayer coating applied to the steel tube optimizes solar energy absorption by exhibiting low thermal emissivity and high optical absorptivity while reducing radiative heat loss. The outer anti-reflective coating on the glass envelope further enhances light transmission by minimizing reflection and Fresnel losses [51]. Extensive research on PTCs is being conducted globally to explore diverse applications. These research areas could be included in future nanomaterial incorporation studies.

3.2. Solar Power Tower Collector (SPTC)

SPTC is a CSP technology that uses a central tower to gather focused sunlight. They excel at generating electricity at high temperatures [52]. These systems employ an array of sun-tracking mirrors, called heliostats, to concentrate sunlight onto a central receiver positioned atop a tall tower. Heliostats precisely follow the sun's path, directing solar energy to create a high-temperature zone. The design and arrangement of the heliostat field, accounting for 40–50% of total system cost, significantly impacts the tower's efficiency and economic viability [53].

Heliostats, the sun-tracking mirrors in SPTC, typically use mirrored glass or reflective film for their reflective surfaces. Smaller heliostats often outperform larger ones due to reduced shading, blocking, and wind load [54]. Tubular receivers, equipped with internal vertical pipes acting as heat exchangers, capture and transfer absorbed solar energy to the heat transfer fluid [55]. These receivers are housed within the tower, which can reach heights of 100 to 300 m, facilitating large-scale power generation on extensive land areas [56]. The high concentration of sunlight achieved in these towers, reaching up to 1000 times, enables extremely high operating temperatures [57]. To harness this intense heat, molten salts or water/steam mixtures are typically used with Rankine cycles, while higher temperatures necessitate gas or particle-based fluids and Brayton cycles [58]. SPTCs have been the subject of extensive global research, exploring a wide range of potential applications. This research area could benefit significantly from incorporating insights emerging from recent studies.

3.3. Solar Dish Collector (SDC)

SDC is a CSP system featuring a single-point focus and a precise dual-axis tracking mechanism. Its compact design, independence from cooling water, and limited integration capabilities with thermal storage or other renewable energy sources significantly influence its competitive standing in comparison to other concentrated solar power technologies [59]. An SDC system comprises a receiver positioned at its focal point, a parabolic reflector equipped with solar tracking capabilities, and a network of pipes to circulate heat transfer fluid. The parabolic reflector can be constructed as a continuous surface or assembled from discrete segments to achieve the desired parabolic shape.

The receiver is securely mounted to the reflector's support structure, ensuring both components remain aligned with the sun's position. By optimizing the receiver's dimensions, shadowing can be minimized, and the receiver's support structure can be integrated into the reflector design. The receiver's weight can be optimized to reduce the energy required for solar tracking. The most common approach integrates a Stirling engine directly into the receiver [60]. SDCs have been extensively researched globally for diverse applications. This field stands to gain substantially from recent advancements in research.

3.4. Fresnel Reflector Collector (FRC)

FRC simplifies the parabolic trough design by replacing curved mirrors with a linear arrangement of flat or nearly flat mirrors [61]. This innovative approach, pioneered by Giovanni Francia in 1961 [62], offers a more cost-effective method for concentrating solar energy. FRC systems typically employ 10–20 elongated mirror segments to form a linear collector, replacing the single parabolic trough design. These mirrors are aligned north–south and can rotate along their length to track the sun's movement.

Employing flat mirrors instead of parabolic reflectors significantly reduces the cost of the collector field [63]. Additionally, FRC can concentrate sunlight onto a single receiver over a larger area compared to PTC. This design characteristic often reduces the number of collector loops required for a given field size, potentially leading to lower system costs. The literature suggests that the investment cost of a FRC should be no more than 67%

of that for a PTC to be economically feasible [64]. Additionally, ground-level mounting of Fresnel mirrors reduces wind resistance [65], a significant advantage in windy desert regions where solar energy is abundant. In addition to simplifying the reflector design, FRC systems also streamline the heat-receiving process by using a fixed array of absorber tubes relative to mirrors. The stationary nature of the heat receiver in Fresnel systems simplifies construction, reduces maintenance requirements, and lowers the risk of working fluid leaks compared to PTC, where the receiver moves along with the focused sunlight [66]. FRCs have been extensively studied globally for diverse applications. The field can benefit significantly from continued research.

4. Nanofluids in CSP Systems

Nanofluid incorporation enhances the efficiency of CSP systems by improving thermal conductivity, heat capacity, and stability. While this review paper primarily focuses on the integration of CSP technologies, nanofluids, traditional simulation techniques, and Industry 4.0 tools, a more detailed analysis of the characteristics and performance of individual nanofluids can be found in our recent publication [16]. In that paper, we provide an in-depth examination of nanofluid properties, including thermal conductivity, particle concentration, and their impact on the performance of energy systems. For a more detailed numerical interpretation of how specific nanofluids influence CSP systems, readers are encouraged to refer to this publication. The mechanisms by which nanofluids enhance thermal conductivity and heat transfer, including the relevant equations and results, were discussed in detail in our previous review article [16]. In our previous publication [16], we presented a comprehensive review on nanofluids in TES systems, emphasizing their ability to enhance thermal conductivity, phase change behavior, and overall energy storage efficiency. We analyzed different types of nanofluids, such as metal oxides and carbon-based materials, and their effects on latent heat and melting/solidification rates. The paper highlighted key challenges, including nanoparticle agglomeration, environmental concerns, and cost-related issues. These findings form a foundation for the present review, which expands the discussion beyond TES to explore the integration of nanofluids in CSP systems, and how their performance can be further optimized using simulation tools and Industry 4.0 technologies. This connection gives the current review its own identity, building upon earlier insights while providing a broader and more integrated perspective. Nanofluid integration in PTC, SPTC, SDC, and FRC boosts heat absorption and storage, reducing thermal losses. Current research efforts aim to optimize their role in advancing next-generation solar energy technologies. The following section explores their impact on various CSP configurations, highlighting performance enhancements and potential advancements.

4.1. Nanofluids in Parabolic Trough Collectors

The integration of nanofluids into PTC systems has been extensively studied due to their potential to significantly enhance heat transfer characteristics. The improved thermal conductivity and specific heat capacity of nanofluids enable more efficient energy absorption and heat exchange within the collector's receiver tubes. Numerous studies, employing both numerical simulations and experimental approaches, have quantified these thermal benefits which often link them to nanoparticle type, size, and concentration, demonstrating measurable improvements in system thermal efficiency and energy yield. The potential of nanofluids in enhancing the performance of PTC has been investigated. By incorporating CuO, TiO_2, Al_2O_3, and SiO_2 nanoparticles into Therminol VP-1, the study observed a temperature increase of up to 9.57% and a maximum thermal efficiency of 1.03%. While this improvement came with increased pressure drop, the overall findings highlight the potential of nanofluids in optimizing solar energy systems [67]. Abu-Zeid et al. integrated MWCNT nanofluid into a PTC system to enhance residential water heating performance [68]. By optimizing nanofluid concentration and system parameters, a significant 25% increase in thermal efficiency was achieved compared to traditional flat plate collectors. This improvement can be attributed to factors such as enhanced heat transfer, reduced thermal losses, and improved solar energy absorption. The resulting higher hot water temperatures and substantial reduction in CO_2 emissions demonstrate the potential of nanofluids and PTC technology in advancing sustainable water heating solutions [68]. Table 2 provides a comprehensive overview of experimental and numerical studies investigating the impact of nanofluids on PTCs.

Table 2. Impact of nanofluids on PTCs.

Ref	Location	Analysis	Base Fluid	Nano Material	VF (%)	PS (nm)	η_{th} ↑ (%)	Findings
[67]	Algeria	EXP	Therminol-VP-1	CuO, TiO_2, Al_2O_3, SiO_2	4	-	1.03%, 0.97%, 0.97%, 0.81%	Nanoparticles boosted PTC outlet temperature by up to 9.57%, enhancing efficiency by 1.03%. An increased pressure drop was observed.
[69]	Greece	EXP	Syltherm 800	Al_2O_3, TiO_2	3	-	0.7	The hybrid nanofluid composed of TiO_2 and Al_2O_3 outperformed both individual TiO_2 and Al_2O_3 nanofluids in the studied parameters.
[68]	Egypt	EXP	Water, EG	MWCNT	-	50	28%	Integrating MWCNT nanofluid into a PTC significantly enhanced thermal efficiency, leading to substantial reductions in CO_2 emissions.
[70]	Saudi Arabia	NUM	Syltherm-800	Al_2O_3, MWCNT	1–2	21	2.3	The optimal combination of 2% Al_2O_3 and 1% MWCNT nanofluids within a PTC yielded the highest thermal efficiency of 70.54%.
[71]	India	EXP	Water	CuO	0.05, 0.075, 0.1	10	5.15%, 51.19%, 53.26%	Enhanced efficiency by up to 53.26% compared to water, with a corresponding 1.08% increase in cost.
[72]	China	NUM	Therminol-VP-1 Syltherm-800	Cu	<10	100	7.99	Nanoparticles enhance heat transfer but also increase pressure drop, with Syltherm 800 demonstrating better performance than Therminol VP1.
[73]	Saudi Arabia	EXP	Water	Al_2O_3, MWCNT	0.1–0.3	<100	18	Enhanced thermal conductivity and heat transfer capabilities of the nanofluid, resulting in higher energy storage capacity and overall system performance.
[74]	Saudi Arabia	EXP	Therminol VP-1, Therminol 75, Syltherm-800	TiO_2, Al_2O_3	1.5	-	0.48%, 1.61%, 0.87%	Al_2O_3-TiO_2 hybrid nanoparticles with Syltherm-800 as the base fluid in a PTC improved thermal and exergy efficiency.
[75]	India	EXP	Water	CuO, Al_2O_3	0.05	20 to 40	44	Among all the materials tested, CuO exhibited the highest thermal efficiency.
[76]	India	EXP	Water	Al_2O_3	0.06	<20	29	The improved thermal efficiency was primarily due to a decrease in energy losses and the prevention of nanoparticle sedimentation.
[77]	Iran	EXP	Water	CuO	0.08	<100	52	A general upward trend in thermal efficiency, ranging from 18 to 52%, was observed as the nanoparticle volume fraction increased.
[78]	South Korea	EXP	Water	CeO_2, Al_2O_3, TiO_2	3	-	27	Among the nanofluids tested, CeO_2/water exhibited the most significant enhancement in thermal efficiency, followed by TiO_2 and Al_2O_3.
[79]	Iran	EXP	EG	MWCNT, SiO_2	0.3	4,6	30	MWCNT/EG nanofluid demonstrated a superior thermal efficiency compared to its SiO_2/EG counterpart.
[80]	Mexico	EXP	Water	Al_2O_3	3	10	28	The thermal performance of a solar collector is significantly influenced by its incidence angle, with even slight increases leading to appreciable improvements in thermal efficiency.
[81]	India	EXP	Water	Fe_3O_4	0.6	-	1.6	The combined application of fins and nanofluid resulted in an 87% increase in the heat transfer coefficient.
[82]	Iran	EXP	Mineral oil	MWCNT	0.03	10	7	The incorporation of MWCNTs into mineral oil significantly enhanced the overall efficiency of PTC systems compared to those utilizing pure mineral oil.

Table 2. *Cont.*

Ref	Location	Analysis	Base Fluid	Nano Material	VF (%)	PS (nm)	η_{th} ↑ (%)	Findings
[83]	Turkey	EXP	Therminol-VP-1	CuO, Al_2O_3, Fe_3O_4	3	-	0.2	In terms of thermal efficiency, Al_2O_3/Therminol nanofluid demonstrated superior performance compared to CuO/Therminol, while Fe_3O_4/Therminol exhibited the lowest efficiency among the tested nanofluids.
[84]	Greece	NUM	Syltherm 800	CuO, Al_2O_3	4	-	1.3	The CuO/Syltherm nanofluid exhibited the highest thermal efficiency among all fluids tested.
[85]	Pakistan	EXP	Water	Al_2O_3, Fe_2O_3	0.30	20 to 40	13	Al_2O_3/water nanofluid outperformed Fe_2O_3/water nanofluid in terms of overall performance.
[86]	Iran	EXP	Water	CuO	0.01	30	79	The combined use of CuO/water nanofluid and metal foam within a PTC system resulted in superior thermal efficiency when compared to the individual application of either component.

"VF"—volume fraction, "PS"—particle size, "η_{th}"—thermal efficiency, "↑"—Increased.

Alhamayani et al. optimized a PTC using a hybrid nanofluid comprising 2% Al_2O_3 and 1% MWCNTs in Syltherm-800 [70]. An artificial neural network (ANN) model accurately predicted system performance with an R^2 value of 99.99%. R^2 is a statistical measure that indicates the proportion of variance in the dependent variable (system performance) that is predictable from the independent variables (input features). An R^2 value of 99.99% implies that the model explains nearly all the variation in the system's performance, reflecting a high degree of accuracy in the predictions. The optimized system demonstrated an 8% increase in dynamic viscosity and a 9% increase in thermal conductivity compared to the base fluid, leading to a 70.54% thermal efficiency. While this improvement was accompanied by a 26.2% increase in pressure drop, the overall enhancement in energy conversion efficiency highlights the potential of nanofluids in optimizing solar energy systems [70]. A study investigated the influence of CuO-H_2O nanofluid on PTC performance. By varying nanofluid concentrations and mass flow rates, efficiency increases of up to 53.26% were achieved compared to water. The enhanced performance is attributed to reduced radiation and convection losses, despite a 1.08% increase in cost. Future research should focus on long-term stability and pressure drop analysis for large-scale systems [71]. The efficiency enhancements of approximately 0.48%, 1.61%, and 0.87% were reported using TiO_2 and Al_2O_3 nanoparticles dispersed in Therminol VP-1, Therminol 75, and Syltherm-800, respectively, at a volume fraction of 1.5%. These variations in thermal efficiency are primarily attributed to the differences in base fluid types used in the study [74].

These improvements were primarily achieved due to the enhanced thermophysical properties of nanofluids, such as increased thermal conductivity, higher specific heat capacity, and improved thermal stability. These properties promote more efficient heat transfer between the working fluid and the absorber tube, leading to faster energy absorption and reduced heat losses. Moreover, the uniform dispersion of nanoparticles minimizes thermal resistance and facilitates better energy conversion. The optimization of nanoparticle type, concentration, and base fluid also played a crucial role, enabling fine-tuning of fluid behavior to maximize thermal efficiency while managing pressure drop and viscosity challenges.

4.2. Nanofluids in Solar Power Tower Collectors

Although fewer in number compared to PTC studies, investigations on the application of nanofluids in SPTC systems have shown promising results. Enhanced thermal transport properties of nanofluids support higher receiver temperatures and better energy absorption in central receivers. Section 6 compiles various simulation-based studies that evaluate how nanofluid parameters impact the thermal efficiency and operational performance of SPTCs. Abu et al. numerically explored an SPTC thermal power plant, analyzing the performance of a thermal storage tank and heat exchanger using nanofluids [87]. Numerical results showed that the temperature profiles of the melted salt and steam fluctuated slowly due to the high thermal capacitance of the tanks. While the graphen oxide-distilled water (GO-DW) mono nanofluid exhibited superior performance, the GO/SiO_2-DW hybrid nanofluid offered a more cost-effective solution [87]. Table 3 provides a comprehensive overview of experimental and numerical studies investigating the impact of nanofluids on SPTCs.

Table 3. Impact of nanofluids on SPTCs.

Ref	Location	Analysis	Base Fluid	Nano Material	VF (%)	PS (nm)	η_{th} ↑ (%)	Findings
[87]	Saudi Arabia	NUM	Distilled Water	SiO_2, GO	-	-	-	GO-DW mono nanofluid exhibited superior performance and GO/SiO_2-DW hybrid nanofluid offered a more cost-effective solution.
[88]	Malaysia	NUM	0.6 $NaNO_3$ + 0.4 KNO_3	Al_2O_3	0.5	<20	14	The addition of 0.5% Al_2O_3 nanoparticles to molten salt increased thermal efficiency at a Reynolds number of 38,000.
[89]	Arizona	EXP	Therminol VP-1	GNP	0.001	-	10	Nanofluids offer a 5–10% efficiency boost.

"VF"—volume fraction, "PS"—particle size, "η_{th}"—thermal efficiency, "↑"—Increased.

A study investigated the enhancement of solar receiver tube performance in SPTC through the addition of internal fins and nanofluids. The use of cosine heat flux distribution resulted in a 102% improvement in receiver efficiency compared to Gaussian distribution. Shifting the heat flux aiming point to the middle of the receiver increased thermal efficiency by 10%. Furthermore, the incorporation of Al_2O_3 nanoparticles at 0.5 wt.% concentration led to a 14% increase in overall efficiency, while internal fins reduced tube deformation and thermal stresses, improving the receiver's durability [88]. Taylor et al.'s study explored the potential benefits of using nanofluids in SPTC [89]. By analyzing a notional nanofluid receiver design, the researchers found that efficiency could be improved by up to 10% compared to conventional systems, especially for power plants in the 10–100 MWe range. Graphite nanofluids with low volume fractions (0.001% or less) were found to be suitable for these applications. Laboratory-scale experiments further supported these findings, demonstrating an efficiency increase of up to 10% under optimized operating conditions. A financial analysis revealed that a 100 MWe SPTC in Tucson, Arizona, could generate an additional \$3.5 million per year by incorporating a nanofluid receiver [89].

4.3. Nanofluids in Solar Dish Collector

In SDC systems, the role of nanofluids is increasingly recognized for their ability to improve thermal performance under high-concentration solar flux. Current research focuses on optimizing nanoparticle type, size, and concentration to enhance heat transfer rates, reduce thermal resistance, and increase the overall energy conversion efficiency. These enhancements can make SDCs more viable for both power generation and industrial heat applications. A numerical and experimental study employed MWCNT/thermal oil nanofluid as the heat transfer fluid in a cylindrical cavity dish collector. Under steady-state conditions, the thermal efficiency of the cavity receiver increased by 13.12%, and the overall thermal performance of the MWCNT/thermal oil nanofluid improved by 4.72% [90]. A parabolic dish solar collector was studied using Al_2O_3, CuO, and TiO_2 oil-based nanofluids in conjunction with a Brayton cycle re-heater. Among the nanofluids tested, Al_2O_3 oil-based nanofluid exhibited the highest energy and exergy efficiencies at 33.73% and 36.27%, respectively. The results indicated that increasing the concentration of nanoparticles within the receiver tube enhances convective heat transfer efficiency. Additionally, the geometry and dimensions of the cavities in the solar dish significantly influence its overall performance [91].

Evaluation of cubical, hemispherical, and cylindrical SDC cavity receivers using alumina/oil nanofluids was performed, applying the first and second laws of thermodynamics.

Their findings revealed that decreasing nanoparticle size and increasing nanofluid concentration led to enhanced cavity thermal performance and electricity generation. Among the cavity shapes tested, the hemispherical receiver demonstrated the highest thermal efficiency, reaching 66.24% [92]. A numerical examination of an SDC with a spiral cavity absorber was conducted, using four different nanoparticles: CuO, Al_2O_3, SiO_2, and Cu. The results indicated that Al_2O_3 nanoparticles exhibited the highest thermal performance, while CuO nanoparticles outperformed the others in terms of exergy efficiency. In this study, Al_2O_3/thermal oil and SiO_2/thermal oil have been utilized in an SDC with a cylindrical cavity receiver. The findings revealed that Al_2O_3/thermal oil demonstrated the highest average thermal efficiency under steady-state conditions. Additionally, the heat loss coefficient for Al_2O_3/thermal oil was lower compared to SiO_2/thermal oil and pure thermal oil [93]. A comprehensive overview of nanofluid-based SDCs is presented in Table 4.

Table 4. Impact of nanofluids on SDCs.

Ref	Analysis	Nano Material	Cavity Shape	VF (%)	η_{ex} (%)	η_{th} (%)	η_{en} (%)	Findings
[90]	NUM & EXP	MWCNT/oil	Cylindrical	0.8%	-	4.72	-	The thermal efficiency of the cavity receiver increased by 4.72% using nanofluid.
[94]	NUM	CuO-H_2O	Cylindrical	0.1–0.4%	-	25.6	-	Employing a 0.1% CuO nanofluid at a flow rate of 0.0083 kg/s, the collector's maximum thermal efficiency was enhanced.
[95]	EXP	MWCNT/thermal oil	Hemispherical	0.8%	-	13	-	Exergy and energy efficiencies were calculated to be approximately 60.48% and 12.94%, respectively.
[96]	EXP	Al_2O_3/oil & SiO_2/oil	Hemispherical	-	16 & 12	74.41 & 68.86	-	Al_2O_3/oil nanofluid outperformed SiO_2/oil and pure oil in reducing heat loss from the hemispherical cavity receiver.
[97]	NUM	Soybean oil-based MXene	Hemispherical, cubical & cylindrical	0.025–0.125%	-	0.6	-	The equivalent efficiency demonstrated that the thermal benefits of using nanofluids surpassed the additional pumping energy, resulting in a net increase in overall solar collector performance.
[98]	NUM& EXP	Water/Al_2O_3	Parabolic	-	17.3	62.65	-	Nanofluids enhance heat transfer, leading to improved efficiency and performance.
[99]	EXP	Water/Al_2O_3, ZnO	Parabolic	-	22.72, 15.90	-	20.06, 12.55	Al_2O_3 enhanced energy, exergy, economic, exergo-economic, and enviro-economic aspects.
[100]	NUM& EXP	Oil/Al_2O_3	Hemispherical, cubical & cylindrical	0.01–0.2%	-	12.9, 5.84, 1.44	-	The thermal enhancement is most pronounced at higher temperatures, making nanofluids a promising choice for high-temperature applications.
[101]	EXP	Water/SiC	Parabolic	1%	37.06	-	-	SiC/water nanofluid exhibited higher exergy efficiency.

"VF"—volume fraction, "PS"—particle size, "η_{th}"—thermal efficiency, "η_{ex}"—exergy efficiency, "η_{en}"—energy efficiency.

Nanofluids significantly enhance the thermal performance of cubical and hemispherical cavity receivers in SDC, with greater efficiency compared to cylindrical cavities. The thermal enhancement is at higher temperatures, making nanofluids a promising choice for high-temperature applications. The thermal enhancement is estimated at 5%. Nanofluids increase thermal efficiency by up to 12.90% in hemispherical cavities, 5.84% in cubical cavities, and 1.44% in cylindrical cavities. Thermal enhancement is more significant at higher temperatures [100]. An experimental study compared the exergy efficiencies of water and SiC nanofluids in a parabolic dish reflector receiver system. The study focused on the impact of thermal conductivity and specific heat capacity on system performance. SiC nanofluids exhibited a higher thermal conductivity (0.800115 W/mK) compared to water, leading to a 17.59% increase in effective thermal conductivity. SiC nanofluids achieved a significantly higher average exergy efficiency (37.06%) than water (21.08%). Nanofluids carried 0.2378 kW more energy and 0.7593 kW more exergy than water for most flow rates, contributing to the higher exergy efficiency. Overall, the study demonstrates the potential of SiC nanofluids to significantly improve the energy and exergy efficiency of parabolic dish reflector receiver systems [101].

4.4. Nanofluids in Fresnel Reflector Collector

FRC, known for its lightweight and compact design, has proven to be promising technology for CSP systems. To boost their efficiency and competitiveness, further advancements are needed in energy conversion. Utilizing the distinctive properties of nanofluids, including improved heat transfer and lower fluid viscosity, is expected to lead to considerable enhancements in the overall performance of these systems. Few investigations have explored the potential of nanofluids to enhance FRC performance.

The FRC system was analyzed using nanofluids to enhance heat transfer and performance. The study compared four working fluids: DW and MWCNT/DW nanofluids with volume fractions of 0.05%, 0.1%, and 0.3%. A finite difference method was employed to numerically solve the energy balance equations. The MWCNT/DW nanofluids exhibited stable properties over six months without aggregation. Their thermal conductivity increased by 3%, 6%, and 7% at 25 °C compared to DW, respectively, and further improved with rising temperatures. Density and viscosity increased with higher volume fractions but decreased with temperature. The MWCNT/DW nanofluid with a 0.3% volume fraction achieved the highest thermal efficiency (33.81%), but also recorded the highest pressure loss (2.31–4.625 Pa). All MWCNT/DW nanofluid concentrations demonstrated lower entropy generation, making them advantageous for the system [102]. Huang et al. conducted a numerical study on the performance of an FRC collector at a concentration ratio of 28, utilizing thermal oil-based CuO and Al_2O_3 nanofluids [103]. The FRC was compared to PTC. The results demonstrated that the FRC outperformed the others in terms of energy, exergy, and entropy efficiency. When considering nanofluids as heat transfer fluids, water + Al_2O_3 offered the lowest levelized cost of energy (LCOE), which was 28.7% lower than water + CuO due to CuO's higher purchase cost. Conversely, Thermia Oil B had the highest LCOE at $0.48/kWh, primarily attributed to its higher fixed production costs [103]. Table 5 provides a comprehensive overview of experimental and numerical studies investigating the impact of nanofluids on FRCs.

Table 5. Impact of nanofluids on FRCs.

Ref	Location	Analysis	Base Fluid	Nano Material	VF (%)	PS (nm)	η_{th} ↑ (%)	Findings
[102]	Algeria	EXP	DW	MWCNT	0.05–0.3	8–15	33.81 ↑	The nanofluids exhibited a 3%, 6%, and 7% increase in thermal conductivity at 25 °C for volume fractions of 0.05%, 0.1%, and 0.3% respectively.
[103]	Iran	EXP & NUM	Water/Thermal Oil B	Al_2O_3, CuO	1–5	20–50	5.95 ↑	Al_2O_3, which is 28.7% cheaper LCOE than water + CuO due to the significantly higher purchase cost of CuO.
[104]	Greece	EXP	Syltherm 800	CuO	2,4,6	-	0.82 ↑	The optimum nanoparticle concentration is about 4% because a higher concentration does not lead to significant thermal efficiency enhancement.
[105]	Iran	EXP	Water	Al, Ag, Ni, TiO_2	0.01–2	20	10.8–11.3 ↑	Ni at a volume concentration of 0.5% led to thermal efficiency of 11.2% in June, 10.8% in July, and 11.3% in August.
[106]	Algeria	NUM	Therminol 66 Oil	MXene (Ti_3C_2)	0.05–0.1	-	29.38 ↑	Nanofluid with a 0.1 wt% concentration achieved an average thermal efficiency of 58.07%, an exergy efficiency of 12.21%, and a performance evaluation criterion (PEC) of 15.50%.
[107]	China	EXP	Thermal oil	CuO	0.05, 0.1, 0.2	60	67.6	The thermal conductivity of CuO/oil nanofluids with a 0.2% volume fraction was 3.8% higher than that of the pure oil-based fluid.
[108]	Iran	EXP	Water	Gold	0.01–2	-	-	At a mass flux of 100 kg/m^2s, critical heat flux (CHF) increased by 91.01%, while at 500 kg/m^2s, it increased by 114.1%.

"VF"—volume fraction, "PS"—particle size, "η_{th}"—thermal efficiency, "↑"—Increased.

Bellos et al. explored two common thermal efficiency enhancement techniques for a linear FRC: the use of nanofluids (CuO in thermal oil up to 6%) and internal longitudinal fins in the absorber. The study compared these techniques individually and in combination. For a 600 K inlet temperature, the final evaluation revealed the following: a smooth absorber with 4% nanofluid: 0.28% thermal efficiency enhancement; internal fins with pure oil: 0.61% thermal efficiency enhancement; and internal fins with 4% nanofluid: 0.82% thermal efficiency enhancement. While these enhancements are relatively small, they highlight the potential benefits of these techniques. However, before adopting them in LFRs, it is crucial to consider additional factors discussed in this paper [109]. This study calculates the CHF of the FRC system. The effects of nanofluids (Al, Ag, Ni, and TiO_2) on critical heat flux length and convection heat transfer coefficient were investigated at various concentrations (0.01–2%). Modeling results indicated that increasing nanoparticle volume concentration improved the heat transfer coefficient. Nickel nanoparticles at 2% volume concentration achieved a 10.6% increase compared to pure water. Dispersing nickel nanoparticles in pure water also enhanced thermal efficiency. In June, July, and August, thermal efficiency increased by 11.2%, 10.8%, and 11.3%, respectively, at a 0.5% nanoparticle concentration [105].

5. Traditional Simulation-Based Evaluation of Nanofluids

Numerical modeling offers a complementary approach to experimental studies for investigating nanofluid applications in solar collectors. Its advantages include cost-effectiveness, time efficiency, and flexibility. Popular simulation software such as CFD, COMSOL, OpenFOAM, ANSYS, etc., facilitate numerical analysis. The relative ease, lower cost, and shorter timeframes associated with numerical modeling have contributed to its prevalence in nanofluid-based solar concentrators' research.

Traditional analytical approaches in CSP systems have primarily focused on simplified geometries and steady-state assumptions, offering limited applicability when dealing with complex phenomena, such as transient heat transfer, nanofluid dynamics, or heterogeneous material properties. As these analytical models fail to capture the real-time operational behavior of advanced CSP setups, particularly when nanomaterials are involved, numerical simulations become indispensable. The following section explores how these simulations have been employed to investigate nanofluid-enhanced CSP systems across different configurations. Table 6 presents a compilation of simulation studies examining the integration of nanofluids with all types of CSP.

Table 6. Traditional simulation studies on various types of CSP using nanofluids.

Ref	CSP/ Location	Simulation Tool	Base Fluid	Nano Material	VF (%)	PS (nm)	η_{th} ↑ (%)	Findings
[110]	SDC Kuwait	Eulerian two-phase model	Thermal oil	MgO, MWCNT	-	30, 20–30	41	Nanofluids boost thermal performance and exergy efficiency but increase pressure loss.
[111]	PTC India	COMSOL	Water	TiO_2	0.2–0.5	20	11	The optimal configuration was achieved using a nanoparticle volume percentage of 0.5% and a 45-degree inclination angle, resulting in superior heat transfer and overall system efficiency.
[112]	PTC Saudi Arabia	CFD	Water	CuO, Al_2O_3	3–7	-	7.2	Incorporating porous obstacles and CuO nanofluids boosted efficiency by 7.2%.
[113]	PTC Saudi Arabia	CFD	Therminol-VP-1	Cu	-	-	1.6	Increasing fin height enhances thermal efficiency but also leads to higher pressure losses.
[114]	PTC Morocco	CFD	Syltherm 800	MWCTN, TiO_2	-	-	2.5	MWCTN-TiO_2/Syltherm800 hybrid nanofluid significantly improved thermal performance.
[115]	PTC Hungary	ANSYS Fluent	Water	Fe_3O_4 Graphene	0.01, 0.05, 0.1, 0.2	20–30, 1–5	0.11	Higher thermal efficiency is attributed to the improved thermophysical properties of the G-Fe_3O_4/water hybrid nanofluid, specifically its higher thermal conductivity and lower viscosity compared to water.

Table 6. *Cont.*

Ref	CSP/ Location	Simulation Tool	Base Fluid	Nano Material	VF (%)	PS (nm)	η_{th} ↑ (%)	Findings
[116]	PTC Iran	CFD	Therminol-VP-1	Al_2O_3	4	20	0.5	Application of nanofluid led to an appreciable increase in Nusselt number compared with the base fluid
[117]	PTC South Africa	CFD	Therminol-VP-1	Cu, Al_2O_3, Ag	6	<100	14	Among the tested nanofluids, Ag-Therminol exhibited the highest thermal performance, while Al_2O_3-Therminol demonstrated the lowest.
[118]	PTC Tunisia	Python	Syltherm-800 Therminol-VP-1	CuO, CeO_2	1	-	34.82, 1.58	Syltherm-800 demonstrates superior performance compared to Therminol VP1 in terms of heat transfer enhancement.
[119]	PTC Iran	3D Numerical	Water	Al_2O_3, Cu	-	-	-	Inserting turbulators in the form of conical helical gear rings increased the heat transfer coefficient by up to 57.3% while reducing total entropy generation by 32.8%, despite a rise in pump power consumption.
[120]	PTC China	FlexPDE	Water	Cu, Al_2O_3, Fe_3O_4, TiO_2	8	-	-	Among the nanoparticles tested, CuO demonstrated the highest thermal performance compared to Al_2O_3, Fe_3O_4, and TiO_2.
[121]	PTC Iran	CFD	Water	Al_2O_3	1–2	-	-	Al_2O_3 nanofluid in a PTC with direct steam generation enhanced vapor volume fraction by 8.64% compared to water, while increasing Nusselt number by up to 544% under non-uniform heat flux
[109]	PTC Greece	CFD	Syltherm 800	CuO	6	-	1.5	The synergistic combination of nanofluids and finned surfaces led to a substantial enhancement in both thermal efficiency and convective heat transfer.
[122]	PTC Greece	CFD	Therminol-VP-1	SWCNT	2.5	10	4	Specific heat capacity also plays a critical role in determining overall thermal performance.
[123]	SPTC Saudi Arabia	COMSOL	Water	Al_2O_3	1, 2	47	19	Adding 2% nanofluids to water can increase PEC by up to 16%.
[124]	SPTC China	EES	Water	CuO	-	-	-	CuO increases the ERTE of a solar collector by 5.6% under the maximum available DNI of 1000 W/m^2.
[125]	SDC Iran	MATLAB	Engine oil	MWCNT, SiO_2, Al_2O_3, TiO_2, Fe_2O_3, CuO	0.01–0.05	-	12	CuO shows the highest efficiency
[126]	SDC China & Iran	Numerical	Water/Dowtherm	MWCNT	0–0.04	20–50	-	LCOE of SDC with nanofluid increased 5.5 times
[127]	FRC Greece	SolidWorks Flow	Syltherm 800	CuO	6	-	0.22–0.78	The nanofluid's positive impact on thermal efficiency, reaching 0.8%, was offset by a substantial 50% rise in pumping energy demand.
[128]	FRC UAE	MATLAB Numerical	Water	rGO-Co_3O_4	0.05, 0.1, 0.2	-	2.75–31.95	The mean exergy efficiency increased by 2.27%, while the FRC optical efficiency was 41.97%. PEC values higher than 1.
[129]	FRC Ecuador	PYTHON Numerical	Therminol VP 3	Graphite	-	10–45	94	Within the temperature range of 403 K to 343 K, receiver efficiencies were consistently high, reaching values between 92% and 96% with nanofluid.
[130]	FRC China	CFD	-	Ag/propylene glycol	-	-	49.3	Increasing the inlet nanofluid flow velocity or decreasing the inlet nanofluid temperature can lead to improved thermal efficiency.
[26]	FRC China	Aspen-HYSYS	Water	Al_2O_3, CuO	0.001–0.2	-	-	The economic analysis of the proposed hybrid system revealed an LCOE of 0.0446 Euro/kWh and an SPT of 7.74 years.

"VF"—volume fraction, "PS"—particle size, "η_{th}"—thermal efficiency, "↑"—Increased.

5.1. Parabolic Trough Collector

Arun et al. investigated the influence of TiO_2 nanofluid on PTC performance. By varying nanoparticle concentrations and mass flow velocities, researchers optimized heat transfer properties and efficiency. CFD simulation revealed that the combination of a 0.5% nanoparticle volume fraction and a 45-degree inclination angle yielded the best results, enhancing the collector's performance by 11% compared to the base fluid. This research underscores the potential of nanofluids in improving solar collector efficiency [111]. Numerical simulations using CFD were conducted on a PTC equipped with inner longitudinal fins and a porous tube receiver using a Cu-Al_2O_3/synthetic oil hybrid nanofluid. At lower Reynolds numbers, copper nanoparticles significantly increased outlet temperature compared to aluminum oxide, which had a minimal effect. Convective heat transfer improved with higher nanoparticle concentrations, with Cu nanoparticles demonstrating three times the effectiveness of Al_2O_3 [112].

The study found that using Al_2O_3 nanofluids in a PTC with direct steam generation enhanced vapor volume fraction by 8.64% compared to water. CFD simulation was implemented. This improvement is attributed to the enhanced heat transfer and nucleation site properties of the nanofluids, which facilitated more efficient bubble formation and growth. Consequently, the Nusselt number, a key indicator of heat transfer performance, increased by up to 544% under non-uniform heat flux conditions. However, the addition of nanoparticles also introduced complexities, such as increased pressure drop and potential for fouling, which require further investigation. Despite these challenges, the study demonstrates the potential of nanofluids to significantly enhance the performance of PTC for direct steam generation applications [121]. Simulation studies on PTCs show significant improvements in convective heat transfer, TES efficiency, and receiver tube performance when using nanofluids. These models validate the potential of nanomaterials to reduce temperature gradients and improve collector efficiency under variable solar input.

5.2. Solar Power Tower Collector

Salilih et al. evaluated a study on the impact of Al_2O_3 nanofluids with water on a small-scale heliostat thermal power plant [123]. By incorporating nanofluids into the condenser cooling system, the researchers achieved a 5% increase in cycle efficiency through COMSOL simulation. This improvement is attributed to the reduced water temperature at the condenser outlet and enhanced heat transfer properties of the nanofluid. The study also demonstrated that increasing the nanofluid flow rate can further improve efficiency, with a maximum enhancement of 16% observed at a 2% nanoparticle concentration [123]. EES simulation study found that using nanoparticles in the base fluid can increase the exergetic efficiency (ERTE) of a solar collector by 5.6% under the maximum available direct normal irradiance (DNI) of 1000 W/m^2. Additionally, the use of nanoparticles can boost hydrogen production by 5.3% compared to the base fluid. However, increasing receiver temperature leads to higher output power but reduces hydrogen production, potentially increasing unit product cost. The optimal operating point for maximizing both output power and hydrogen production was found to be at 2420 kW and 148 kg/h, respectively [124]. In SPTCs, numerical models illustrate that nanofluids enhance the volumetric absorption and thermal stratification within central receivers. These findings demonstrate the ability of nanofluids to support high-temperature operations and optimize the performance of the TES system.

5.3. Solar Dish Collector

SDCs offer a promising solution for harnessing solar energy on a large scale. However, optimizing their performance requires a deep understanding of the complex interactions between the solar dish components, the working fluid, and the operating environment. Simulation studies provide a valuable tool for investigating these interactions and identifying potential improvements. Askari et al. investigated the impact of six engine oil-based nanofluids (MWCNT, SiO_2, Al_2O_3, TiO_2, Fe_2O_3, and CuO) on a solar concentrating photovoltaic thermal collector [125]. The performance of the system was evaluated under various operating conditions, including nanoparticle concentration, receiver tube diameter, concentrator surface area, receiver length, channel ratio, beam radiation, and volumetric flow rate. MATLAB simulation and two ML models were used to predict the system's first and second law efficiencies [125].

Ouyang et al. investigated the impact of a hybrid nanofluid (MgO, MWCNT) on a semi-cone parabolic dish solar collector [126]. Results showed that nanofluids significantly enhance thermal and exergy efficiency, although they increase pressure loss. This improvement is attributed to the enhanced heat transfer properties of nanofluids, which allow for more efficient absorption and transfer of solar energy. While the use of nanofluids offers several benefits, it is important to note that they can also increase pressure loss within the system. This is due to the increased viscosity of nanofluids compared to base fluids.

However, the overall benefits of using nanofluids often outweigh the drawbacks, making them a promising option for enhancing the performance of SDCs. The use of nanofluids in solar collectors can significantly improve heat transfer and overall performance which has been numerically simulated. In Iran, solar collectors using nanofluids may have better exergy efficiency during certain months compared to China. However, using nanofluids can increase the LCOE by more than 5.5-fold in Tehran. Further research is needed to optimize the use of nanofluids in solar collectors to balance performance gains with cost considerations [126]. Simulations of dish collectors indicate improved thermal conductivity and reduced heat loss at the receiver, especially in high-flux concentration zones. These studies support the application of nanofluids for enhancing compact, high-efficiency solar receivers.

5.4. Fresnel Reflector Collector

In a study by Bellos et al., an FRC system was evaluated using CuO nanofluid dispersed in Syltherm 800 (6% volume concentration) as a heat transfer fluid [127]. The collector, with a net aperture of 154 m^2 and a concentration ratio of 58.36, employed curved primary mirrors, compound parabolic secondary reflectors, and an evacuated tube receiver. Nanofluid performance was compared to pure thermal oil at various inlet temperatures (350–650 K) and a flow rate of 200 L/min. While the nanofluid increased thermal efficiency by nearly 0.8%, it also required up to 50% more pumping work. To comprehensively assess nanofluid utilization, various criteria such as exergy efficiency, overall efficiency, and entropy generation were applied. The analysis, conducted using SolidWorks Flow Simulation with a validated model, concluded that nanofluid operation, particularly at higher temperatures, is beneficial [127].

A MATLAB simulation was conducted to analyze the energetic behavior of a small-scale FRC prototype using rGO-Co_3O_4/water hybrid nanofluids at various concentrations (0.05, 0.10, and 0.20 wt%) and temperatures in Blida, Algeria. At 0.20% particle loading and 60 °C, thermal conductivity increased by 19.14%, while viscosity rose by 70.83% [128]. The mean heat loss coefficient decreased by 5.49% to 0.921 W/m^2K. Entropy generation decreased with higher hybrid nanoparticle concentrations, with an average reduction of 59.48% to 0.55 J/K. The FRC prototype equipped with rGO-Co_3O_4/water hybrid nanofluids reduced electrical energy consumption by 19.90% to 20.30%, equivalent to an electrical capacity increase from 549.72 to 560.69 kWh. This resulted in a CO_2 mitigation from 248.97 to 253.94 kg. The LFR reflector with rGO-Co_3O_4/water hybrid nanofluids is a cost-effective and environmentally friendly device [128].

Finite volume discretization and Python coding were used to solve the equations. Receiver efficiencies of 92–96% were achieved at temperatures ranging from 403 K to 343 K. The volumetric fraction (optical depth) significantly influenced radiation absorption, temperature profiles, and receiver efficiency. Low optical depths resulted in low solar absorption and high reflected radiation losses, while high optical depths led to increased solar absorption, higher temperatures near the glass, and higher convection losses. Optimum receiver efficiency was found at an optical depth close to 2.3 [129]. Numerical models for FRC systems reveal enhanced heat transfer coefficients and reduced entropy generation when employing nanofluids. The findings highlight the ability of nanomaterials to mitigate performance losses due to receiver geometrical limitations and irregular solar flux distribution.

Overall, the reviewed simulation studies consistently demonstrate that the integration of nanofluids significantly improves heat transfer efficiency, reduces thermal losses, and enhances overall energy conversion in CSP systems. These findings not only validate the thermal advantages of nanofluids in concentrated solar configurations, but also highlight the limitations of conventional simulation approaches when addressing system-level complexity. This justifies the need to adopt advanced Industry 4.0 tools such as AI, ML, and DT in future studies to enable real-time monitoring, predictive modeling, and optimization of CSP operations.

6. Industry 4.0 in CSP Systems

Industry 4.0 technologies improve energy management and reliability. The following section explores their impact across various CSP configurations, optimizing performance and sustainability.

6.1. Parabolic Trough Collector

Table 7 compiles the implementation of Industry 4.0 technologies on PTCs. A study [24] focuses on utilizing AI models to predict exergy efficiency in PTC, which are vital components of solar thermal systems. A total of six AI models, including adaptive boosting (AdaBoost), stochastic gradient descent (SGD), and stacking regressor, were developed to predict the exergy efficiency of PTCs utilizing molten salt-based nanofluids (Al_2O_3, CuO, and SiO_2). Among these models, the stacking regressor showed the highest prediction accuracy (R^2 = 0.963), followed by AdaBoost (R^2 = 0.947). The results suggest that AI models, especially when applied with a combination of input variables, significantly improve the prediction accuracy of exergy efficiency in PTCs. These advancements enhance the energy management of CSP systems by optimizing performance, reducing inefficiencies, and supporting better energy forecasting. Future work includes exploring advanced AI techniques, expanding the input parameters, and incorporating experimental validations to further improve system performance and energy management strategies [24].

The potential of AI algorithms in predicting the energy and exergy efficiencies of PTCs using oil-based nanofluids has been analyzed. Three types of synthetic oils—Therminol VP-1, Syltherm 800, and Dowtherm Q—were mixed with metallic oxide nanofluids (Al_2O_3, CuO, and SiO_2) at varying volume fractions. The research applied multiple regression techniques, including tree-based, linear, and non-linear models, to predict the performance of PTCs. Among the nine models tested, the classification and regression trees (CART) and extra trees regressor (ETR) showed the highest prediction accuracy for energy and exergy outputs, with R^2 values up to 0.9999 and 0.9983, respectively. The study highlights the robustness of AI algorithms in optimizing energy and exergy performance, offering valuable insights into improving PTC system efficiencies. These advancements not only enhance energy management, but also contribute to cleaner production, sustainability, and environmental performance by reducing errors and increasing the reliability of predictions [131]. Recent studies have begun to explore the potential of AI and ML algorithms to optimize nanofluid parameters within CSP systems. These include the prediction of optimal nanoparticle concentrations, thermal conductivity behavior under varying conditions, and long-term dispersion stability, which significantly influence system performance. Such data-driven models reduce the need for extensive physical experimentation, accelerating development cycles.

Table 7. Integration of Industry 4.0 technologies in PTC systems.

Ref	Nanofluid Used	Industry 4.0 Tool	Application in CSP	Findings	Impact on Energy Management
[24]	Al_2O_3, CuO, SiO_2	AI	Exergy efficiency prediction using AI models	Six AI models (AdaBoost, MARS, SGD, Tweedie, Stacking, and Voting) were developed to predict the exergy efficiency of PTCs using molten salt-based nanofluids. The stacking regressor achieved the highest accuracy (R^2 = 0.963), followed by AdaBoost (R^2 = 0.947).	AI models, particularly Stacking and AdaBoost, enhance prediction accuracy, optimize performance, and contribute to more efficient management of energy in PTC systems.
[131]	Therminol VP-1-SiO_2, Dowtherm Q-SiO_2	AI	Energy and exergy efficiency prediction using oil-based nanofluids	AI algorithms to predict energy and exergy efficiencies in PTCs using oil-based nanofluids. CART and ETR models achieved the highest accuracy, with R^2 = 0.9999 for energy and R^2 = 0.9983 for exergy using Therminol VP-1-SiO_2 and Dowtherm Q-SiO_2 nanofluids.	AI models like CART and ETR optimize energy and exergy performance, leading to more efficient PTC operation, reduced environmental impact, and enhanced sustainability.
[132]	-	AI	Fault detection in PTC	Detects faults in optical efficiency, flow rate, and thermal losses with accuracy ranging from 71.72% to 90.62%.	Improved operational efficiency and reduced maintenance costs.
[133]	-	AI	Heat loss detection and monitoring in receiver tubes	The proposed Heat LOS system uses real-time infrared camera images and CNN deep learning to achieve 93% accuracy in detecting thermal	Reduced maintenance costs and optimized OPEX by enabling early intervention.
[134]	Graphene and silver	AI	Optimizing solar thermal collector efficiency	Key parameters (e.g., Deborah number, Darcy number) affect thermal profiles, Nusselt number, and entropy generation. ANN model improved prediction accuracy.	Enhanced thermal performance and heat transfer efficiency, optimizing energy use in solar thermal systems.
[135]	-	AI	Estimation of hourly electric production	ANN model outperformed analytical models with 96% accuracy, predicting annual energy production of 42.6 GWh/year.	Improved accuracy in energy production estimates, beneficial for optimizing performance in future solar power plants.
[136]	-	AI	Fault detection and isolation	A three-layer neural network methodology detected faults with over 80% accuracy, reaching 90% when all layers were used.	Enhanced fault detection and isolation, improving plant efficiency and reducing downtime.
[137]	Hybrid Non-Newtonian Nanofluids	AI	Optimizing PTC performance	Deep learning predicted the thermal efficiency of the system, showing higher efficiency with helical absorber tubes and optimized flow rates. The highest thermal efficiency was 58.2% at a 4% nanoparticle concentration and Re = 5000.	Demonstrated that deep learning can optimize CSP performance by predicting efficiency, and highlighted the benefits of using hybrid nanofluids and helical absorber tubes in enhancing heat transfer and energy efficiency.
[70]	Al_2O_3-MWCNT/Syltherm-800	ML	Optimizing PTC performance	The addition of 2% Al_2O_3, 1% MWCNT/Syltherm-800 yields the highest thermal efficiency (70.54%). ML showed an R^2 value of 99.99%.	Enhanced thermal efficiency and reduced computation time for outlet temperature prediction.
[138]	-	DT, ML	PTC in the Mexican dairy industry	DT model, combined with ML, accurately predicted energy and cost indicators. Optimization identified the best solar collector configurations for various climates.	Emphasized the value of DT models in optimizing energy systems, enhancing efficiency, and reducing environmental impacts in industrial applications.
[139]	-	ML	Predicting transient heat transfer in sensible heat storage	ML tool showed the best prediction accuracy with errors below 1.45%. The method reduces the computational time for transient simulations.	Reduces computational effort, improves site selection, and accelerates design processes.
[140]	-	ML	Enhancing efficiency with corrugated tube receivers	The Huber model predicted friction factors with R^2 = 0.97, the support vector regression (SVR) model predicted the Nusselt number with R^2 = 0.96. Enhancements in thermal efficiency (9%), Nusselt number (132%), and friction factor (38%).	Enhances CSP collector performance, optimizing energy transfer and reducing energy input needs.

An AI methodology for fault detection in a 50 MW PTC plant using a defocusing strategy has been investigated. The methodology detects faults in optical efficiency, flow rate, and thermal losses. Simulations demonstrate detection accuracies ranging from 71.72% to 90.62%, improving the operational efficiency of the plant and potentially reducing maintenance costs. Future work includes applying these methods to other plants and considering real plant testing [132]. The Heat Loss Out (Heat LOS) system for real-time, non-intrusive evaluation of thermal losses in PTC receiver tubes was analyzed. By using infrared camera images processed with deep learning, the system achieves up to 93% accuracy in identifying heat losses, reducing the need for manual inspections. This solution, tested at the Green Energy Park in Morocco, allows for efficient monitoring of absorber tubes, improving operational efficiency and reducing maintenance costs [133].

A study investigated the heat transfer performance of a Jeffrey hybrid nanofluid containing graphene and silver nanoparticles with gyrotactic microorganisms, flowing through a porous medium in a PTC. The study models the system using the principles of mass, momentum, energy, concentration, and microorganism concentration. The results reveal that various parameters, such as Darcy number, Deborah number, and thermophoretic diffusion, significantly affect thermal profiles and heat transfer. The ANN model, using the Levenberg–Marquardt algorithm, further enhances the accuracy of these predictions. The findings support improvements in the efficiency of solar thermal systems, especially for CSP applications [134].

Zaaoumi et al. investigated three models for estimating the hourly electrical output of a PTC solar thermal power plant located in Ain Beni-Mathar, Morocco [135]. The first two models are analytical, focusing on heat losses and thermal efficiency, while the third model uses an ANN. The ANN model demonstrated superior accuracy, with an R-value of 96%, providing an estimated annual energy production of 42.6 GWh/year, compared to the operational value of 44.7 GWh/year. The ANN model proves effective for estimating energy production, offering valuable insight for future projects in Morocco and similar regions [135].

A deep learning-based methodology for detecting and isolating faults in parabolic-trough plants was studied. The approach uses a three-layer hierarchical model that combines an ANN with an analysis of flow rate dynamics and thermal losses due to defocusing. The methodology was applied to a simulation model of the ACUREX plant, achieving over 80% accuracy in fault detection, with accuracy exceeding 90% when all layers were activated. The proposed methodology improves fault diagnosis, offering the potential for optimizing plant performance and reducing maintenance costs. Future work includes applying the methodology to real plants and enhancing it to handle multiple simultaneous faults [136].

Another study investigates the impact of using a helical absorber tube in a double-fluid PTC filled with hybrid non-Newtonian nanofluids. The research, employing AI tools such as ANN, successfully predicted the system's thermal efficiency. The helical absorber tube improved efficiency, reaching a maximum of 58.2% at a 4% nanoparticle concentration and Re = 5000. The findings highlight the effectiveness of using deep learning for optimizing energy systems and suggest that hybrid nanofluids and helical absorber tubes can significantly enhance heat transfer and overall energy efficiency in CSP applications [137].

Optimizing PTC performance using hybrid nanofluids (Al_2O_3-MWCNT/Syltherm-800) at varying concentrations [70]. A mathematical model and three ML models (decision tree, SVM, and ANN) were developed to predict PTC outlet temperature. The results show that 2% Al_2O_3 and 1% MWCNT/Syltherm-800 achieved the highest thermal efficiency of 70.54%. The ANN model proved most accurate, with an R^2 value of 99.99%. The study also demonstrated improvements in dynamic viscosity, thermal conductivity, and pressure drop with hybrid nanofluids, providing insights for better solar thermal energy management [70].

DT model along with ML and multi-objective optimization to improve a PTC system in the Mexican dairy industry were applied in a study [138]. The model, using the Gaussian process for prediction, effectively estimated performance indicators. The optimization process identified the most efficient solar collector configurations for various climates. The findings underscore the importance of DT models in optimizing industrial energy systems, enabling better decision-making, improving efficiency, and balancing economic and environmental factors [138].

ML methodology was developed for predicting the transient heat transfer performance in sensible heat storage systems used with direct steam generation in PTC thermal power cycles [139]. The Gaussian process regression model demonstrated high prediction accuracy, with a minimal error of 1.45% for a 14-day operation at Bawean Island. This approach significantly reduces computation time compared to traditional simulations, benefiting the site selection and plant design stages by improving temperature control management and enabling faster analysis [139]. ML models, specifically the Huber and SVR models, demonstrated high accuracy in predicting friction factors and Nusselt numbers, making them valuable for optimizing heat transfer processes in CSP systems [140].

6.2. Solar Power Tower Collector

An overview of how Industry 4.0 technologies are applied to SPTCs is presented in Table 8. The application of AI in optimizing heliostat calibration for SPTC systems was studied [141]. By using self-normalizing neural networks and transfer learning, the study achieved a 0.42 mrad precision—three times more accurate than the best existing regression algorithms. This method reduces tracking errors, enhancing the efficiency of solar energy generation in SPTCs. The research demonstrates that neural networks, when pretrained on suitable datasets, can optimize calibration and energy management in CSP systems [141]. The safety assessment of AI applications for heliostat calibration in SPTC systems has been analyzed. The authors performed a sensitivity analysis on a neural network, showing that errors caused by noisy data were kept below 0.02 mrad, even with small datasets. This ensures the reliability and safety of AI-driven calibration, addressing concerns about its deployment in critical infrastructure. The study emphasizes the potential for AI to improve operational efficiency and reduce risks in CSP systems [142].

Table 8. Integration of Industry 4.0 technologies in SPTC systems.

Ref	**Industry 4.0 Tool**	**Application in CSP**	**Findings**	**Impact on Energy Management**
[141]	AI	Optimizing heliostat calibration	A deep learning-based method using self-normalizing neural networks and transfer learning achieved a heliostat calibration accuracy of 0.42 mrad, three times more accurate than the best regression algorithm.	Improved heliostat calibration leads to enhanced accuracy and efficiency in SPTC operations, reducing tracking errors and improving energy generation efficiency.
[142]	AI	Safety assessment of AI in heliostat calibration	Sensitivity analysis of a neural network for heliostat calibration showed that measurement errors due to noisy data were guaranteed to be below 0.02 mrad, even with small datasets (as few as 30 data points).	Ensures reliable calibration, reducing risks and improving system efficiency.
[143]	AI	Optimizing heliostat surface prediction	The iDLR method predicted heliostat surfaces with high accuracy (MAE of 0.14 mm) based on target images, achieving 92% accuracy in flux density predictions.	Increases efficiency by improving flux density distribution, reducing the need for recalibration, and optimizing power plant operations.
[144]	ML	Optimizing hybrid performance	The GWO-HSVR ML model was the most accurate in predicting turbine and PV output. The SPTC-PV system outperformed both SPTC-PV and stand-alone PV modules, achieving an electrical output of up to 8.36 MW.	Enhances hybrid system efficiency, optimizes performance based on location, and increases overall electrical and thermal energy production.
[145]	ML	Optimizing the EOR factor with solar-assisted carbon capture	The integration of SPTC heliostats and PV systems reduced the energy penalty factor from 21.2% to 7.4%, while the decision tree model achieved an R^2 of 0.98, forecasting an increase in the EOR factor from 19% to 43.16%.	The solar-assisted system, coupled with ML, reduces energy consumption and enhances EOR performance, improving overall system efficiency.
[146]	DT	Optimizing solar chimney performance	DT model, using both multivariate regression and MLP-ANN, successfully predicted performance parameters. The optimized design through DT showed significant improvements in air changes per hour, energy efficiency, and environmental impact, with improvements of up to 87%.	Enhances building energy efficiency by integrating passive solar chimney systems, providing real-time optimization and performance projections, and reducing energy consumption and environmental emissions across different climatic zones.

A study introduces the Inverse Deep Learning Ray Tracing (iDLR) method, which uses deep learning to predict heliostat surfaces from target images obtained during calibration [143]. The method achieved high accuracy in predicting the heliostat surface with a median mean sbsolute error (MAE) of 0.14 mm. When integrated into a ray-tracing environment for flux density predictions, iDLR surpassed the ideal heliostat assumption, achieving 92% accuracy. The approach is cost-effective, as it requires only software and data already available from routine operations. By improving flux density distribution and optimizing the overall operation of CSP plants, iDLR enhances efficiency and energy output [143].

Salari et al. investigated the performance of a hybrid SPTC integrated with a photovoltaic thermal system, comparing it to conventional SPTC and SPTC-PV configurations [144]. The research applies ML models, specifically support vector regression (SVR) with various kernels, optimized by the Grey Wolf Optimizer (GWO), to predict and enhance system performance. Results indicate that the SPTC-PVT system outperforms both SPTC -PV and stand-alone PV modules, providing up to 8.36 MW of electrical output. The GWO-HSVR model showed the highest prediction accuracy. The hybrid system optimizes both electrical and thermal production, making it suitable for locations with varying weather conditions, with San Diego proving to be the most optimal location for this setup [144].

A solar-assisted approach to enhance the performance of Enhanced oil recovery (EOR) systems, integrating solar tower heliostats, photovoltaic systems, and energy storage to minimize the energy penalty of post-combustion carbon capture has been explored [145]. The hybrid system reduced the energy penalty from 21.2% to 7.4%, while ML models, particularly the decision tree, significantly improved the prediction accuracy (R^2 = 0.98) of the EOR factor, increasing it from 19% to 43.16%. The integration of solar energy with advanced carbon capture and predictive models presents an energy-efficient, sustainable solution for EOR, reducing carbon emissions by 64.76% and minimizing fossil fuel dependence. The results demonstrate a scalable and environmentally friendly pathway for oil recovery in high-emission regions, contributing to global sustainability goals [145].

DT models have been used to optimize the performance of building-integrated solar chimneys, incorporating both multivariate regression and multilayer perceptron artificial neural network (MLP-ANN) techniques. The DT model provided precise predictions of air changes per hour, energy efficiency, and environmental impact, achieving substantial performance enhancements of up to 87%. A multi-objective optimization approach was used with NSGA-II genetic algorithms and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to fine-tune solar chimney configurations, resulting in improved performance across various climatic zones. The findings highlight the potential of DT in real-time performance monitoring and optimization, contributing to improved building energy efficiency, reduced energy consumption, and a lower environmental footprint. The research advocates for the global integration of passive solar chimney systems, especially in regions with high air-conditioner usage, and for building retrofitting [146].

6.3. Solar Dish Collector

Table 9 provides an overview of the application of Industry 4.0 technologies to SDCs. The integration of AI models like Adaptive Neuro-Fuzzy Inference Systems-Particle Swarm Optimization (ANFIS-PSO) has been studied to optimize the performance of an SDC/Stirling system. The findings show that power generation increases with enhanced solar radiation and concentration factors. ANFIS-PSO demonstrated superior predictive accuracy for global efficiency and engine speed. The energy management improvements suggest optimized system operation, reduced energy consumption, and better resource allocation [147].

Table 9. Integration of Industry 4.0 technologies in SDC systems.

Ref	Nanofluid Used	Industry 4.0 Tool	Application in CSP	Findings	Impact on Energy Management
[147]	-	AI	Optimizing the SDC/Stirling system	The ANFIS-PSO method optimized power generation, global efficiency, and engine speed under various parameters.	The model improves system efficiency by optimizing power output, reducing heat loss, and enhancing performance.
[148]	-	AI	Exergo-economic analysis	The ANN-Improved Particle Swarm Optimization (ANN-IPSO) model provided highly accurate predictions for exergy efficiency (R^2 = 0.9903) and product cost (R^2 = 0.9948), outperforming ANN alone.	Enhances forecasting accuracy, leading to optimized system efficiency and reduced operational costs.
[149]	-	AI	Optimizing SDC performance for hydrogen production	ANN predicted heat flux with R^2 = 0.979, RMSE = 0.438, and MAPE = 0.32%. Uniformity parameter prediction achieved R^2 = 0.925.	AI-based modeling reduces computational costs and optimizes SDC configurations for efficient hydrogen production.
[150]	MWCNT-Thermal Oil	ML	Optimizing SDC performance	ANFIS-EO outperformed ANN and ANFIS, achieving an R^2 of 0.99999 and reducing RMSE by up to 91.86%. Thermal efficiency improved by 10% using nanofluid.	Enhances prediction accuracy, reducing experimental costs and optimizing CSP efficiency.
[151]	-	ML	Optimizing SDC performance	The integrated optical-thermal model combined with ANN Exponential Linear Unit (ELU activation) achieved R^2 = 0.97, RMSE = 0.49, and MAPE = 5.38%.	ML-assisted modeling reduces computational expenses and improves thermal performance predictions.

AI tools like ANN and IPSO were used for predicting the exergo-economic performance of a combined solar dish and desalination system. The hybrid ANN-IPSO model demonstrated superior accuracy in forecasting exergy efficiency and specific unit cost, outperforming traditional ANN models. The findings highlight the effectiveness of AI-driven modeling in optimizing system performance, improving energy efficiency, and reducing operational costs. [148].

A study integrated optical and thermal analysis with deep learning to optimize a solar parabolic dish cavity receiver system for hydrogen production [149]. The ANN model accurately predicted heat flux and uniformity parameters, reducing computational effort compared to iterative optical simulations. A 3D CFD model incorporating a non-uniform heat flux distribution was validated, showing a maximum cavity temperature deviation of 75 K over time. The ZnO dissociation process resulted in a zinc mass fraction of 0.71 and an oxygen molar flow rate of 1×10^{-5} mol/s. The findings support AI-assisted optimization for efficient solar-driven hydrogen production [149].

Another study employs ML tools of ANFIS integrated with the equilibrium optimizer (EO) to predict and optimize the thermal performance of SDC with a cylindrical receiver [150]. The ANFIS-EO model outperformed ANN and standalone ANFIS in prediction accuracy, achieving an R^2 of 0.99999 and significantly reducing RMSE. Using MWCNT thermal oil nanofluid resulted in a 10% thermal efficiency enhancement. The findings highlight the potential of ML-driven modeling in improving CSP performance while minimizing costly experimental efforts. Future work should explore additional metaheuristic approaches to further refine prediction accuracy [150].

A study developed an integrated optical-thermal model combined with an ML tool of deep learning to estimate the performance of a 40 m^2 parabolic dish collector under varying inclinations and wind conditions [151]. The deep learning model, using ELU activation, demonstrated high accuracy with $R^2 = 0.97$, RMSE = 0.49, and MAPE = 5.38 percent, effectively predicting thermal performance. This approach reduces computational expenses and provides a reliable alternative to complex simulations, enhancing CSP system efficiency [151].

The integration of Industry 4.0 technologies in SDC has seen significant advancements, particularly in the design, thermal performance, and techno-economic analysis of SDC. These systems have demonstrated high flexibility in distributed energy applications, with generation capacities ranging from 1.0 to 38.8 kW and overall efficiencies between 13% and 32%. Hybridization with micro gas turbines has further enhanced their performance, achieving efficiencies between 18.35% and 26.48%. These findings highlight the potential of SDC in providing sustainable, cost-effective solutions for energy generation, though further efforts are needed to promote their commercial viability [25].

In parallel, the application of hybrid AI models has proven to be a valuable tool for performance prediction in SDCs. The development of the RVFL-CHOA model, which integrates the Random Vector Functional Link (RVFL) network with the Chimp Optimization Algorithm (CHOA), has demonstrated superior prediction accuracy for both instantaneous power output and monthly power production. The model achieved determination coefficients of 0.9992 and 0.9108, respectively, alongside minimal error values, showcasing the effectiveness of AI in enhancing the prediction and optimization of SDC performance [152].

6.4. Fresnel Reflector Collector

Table 10 offers a summary of the integration of Industry 4.0 technologies into FRCs. The optimization of a linear FRC using an AI tool like Monte Carlo Ray Tracing (MCRT) and Improved Prey Predator Optimization Algorithm (IPPOA) have been implemented [153]. Three configurations—small, medium, and fully optimized—were analyzed, achieving efficiencies of 42%, 47%, and 48%, respectively. The IPPOA method consistently outperformed other algorithms in optimizing parameters such as mirror spacing. The thermal efficiency reached approximately 93%. The findings suggest that while the fully optimized model maximizes efficiency, the medium-sized model offers a balance between cost and performance [153].

Table 10. Implementation of Industry 4.0 technologies in FRC systems.

Ref	Industry 4.0 Tool	Application in CSP	Findings	Impact on Energy Management
[153]	AI	Optimizing FRC performance	IPPOA achieved efficiencies of 42%, 47%, and 48% in different cases. MCRT modeling had 97% precision.	AI-driven optimization enhances FRC efficiency, improving cost-effectiveness and thermal performance.
[154]	ML	Performance prediction	The Relevance Vector Machine–Simulated Annealing Algorithm (RVM-SAA) model outperformed RVM and ANN, achieving R^2 values of 0.9997 for thermal power and 0.9988 for outlet oil temperature. RMSE values were 0.4090 and 2.5150, respectively.	Enhanced predictive capabilities for FRC system performance, improving long-term operation monitoring and optimization.
[155]	ML	Performance prediction	K-nearest neighbors (KNN) demonstrated the highest R^2 of 98.81% and MAPE of 1.975%, outperforming other ML models for predicting output power.	Enhanced prediction accuracy for operational optimization, leading to better energy management and system efficiency.
[156]	DT	False data injection detection in outlet temperature sensor	The neuro-fuzzy detector, based on ANFIS, demonstrated over 97% detection accuracy in identifying false data injections affecting the outlet temperature sensor of FRC.	Improved system reliability and security by accurately identifying and mitigating cyber-attacks, ensuring continuous operation and performance of the solar plant.
[157]	DT	DT for solar cooling optimization	The DT models, both ANFIS and PDE-based, successfully simulated the operation of an FRC for cooling applications, achieving excellent accuracy with a worst-case mean absolute percentage error of 2.49%.	Enabled optimization and control of the cooling plant, offering enhanced predictive control, adaptation to plant aging, and faster twinning for operation improvement

The performance of a large-scale FRC system with an evacuated compound receiver and thermal oil energy storage was tested in Al-Khobar, Saudi Arabia, with the assistance of ML models [154]. The system achieved an energy efficiency of 35.10% and an exergy efficiency of 7.82%, with thermal oil temperatures reaching up to 213.25 °C. ML models, specifically the RVM and an enhanced version combining RVM with the SAA, were used to predict the system's performance. The RVM-SAA model significantly outperformed traditional models, providing high prediction accuracy for thermal power production and outlet temperature. The RVM-SAA model achieved the highest R2 values and lowest RMSE and other error metrics, demonstrating its superiority for performance prediction [154].

Meligy et al. investigated the predictive performance of six ML models (multilayer perceptron, LSTM, random forest, k-nearest neighbors, decision trees, and extreme gradient boosting) for forecasting the output power of a linear FRC solar plant in Nicosia, Cyprus [155]. The analysis, using data from May 2018 to September 2019, demonstrates that the k-nearest neighbors (KNN) model outperforms all other algorithms with an R^2 of 98.81% and a mean absolute percentage error (MAPE) of 1.975%. The KNN model's efficiency, both in accuracy and training time, makes it highly suitable for practical applications. Additionally, the KNN model was found to outperform the ISO9806 physical model, offering improved estimation accuracy and a simpler implementation process [155].

DT model based on Adaptive Neuro-Fuzzy Inference Systems (ANFIS) to identify false data injections (FDI) was employed in the outlet temperature sensor of an FRC system [156]. The proposed system detects three scenarios: normal operation, negative data injection, and positive data injection. Simulation results indicate that the detector performs with over 97% accuracy and precision in detecting FDI, providing a robust solution to safeguard against cyberattacks on the solar plant's control system. The approach, integrating ANFIS and Principal Component Analysis (PCA), proves reliable for maintaining operational integrity, with potential for future application to other variables and the development of an FDI-tolerant control system [156].

DT of a FRC has been integrated into an absorption cooling plant [157]. Two dynamic models are employed: one based on ANFIS and another using phenomenological modeling through Partial Differential Equations (PDE). Both models were validated with real operational data and demonstrated excellent accuracy, with ANFIS offering faster computational times. The models capture the effect of mirror defocus on temperature dynamics and are adaptable to changes such as plant aging or process modifications. This research contributes to advanced optimization and predictive control techniques for solar cooling systems, enabling better operation and future scientific advancements [157].

7. Challenges in CSP

7.1. Nanofluid Incorporation

Nanofluids face various challenges, including erosion, corrosion, high production costs, nanoparticle size and concentration effects, increased pumping requirements, pressure drop, instability, and changes in viscosity.

- Obstacles to nanofluid preparation: Nanofluids are prepared using one-step or two-step methods; the two-step method risks stability issues, while the one-step method may introduce impurities affecting performance [16].
- Selecting appropriate base fluids and nanoparticles: The selection of base fluid and nanomaterials in nanofluids depends on heat capacity, viscosity, and solubility; hybrid nanofluids improve heat transfer, with oil-based ones for lubrication and water/ethylene glycol-based ones for cooling, while performance depends on nanoparticle size, concentration, and pumping power [16].
- Substantial production costs: Nanofluid production is complex and costly; the one-step method ensures stability but has low yield and high costs, while the two-step method is efficient for large quantities but expensive, driving research toward more economical solutions [16].
- Stability: Nanofluid stability is crucial; surfactants enhance stability but may reduce thermal conductivity, while higher nanoparticle concentration boosts conductivity but can hinder stability [16].
- Sedimentation: It remains a key barrier to long-term nanofluid performance; however, recent advancements such as nanoparticle surface functionalization, use of advanced surfactants, and ultrasonication techniques have significantly improved dispersion stability [16].
- Erosion and corrosion: Erosion and corrosion are challenges in thermal nanofluids; studies show ZrO_2 and TiO_2 cause high corrosion, while SiC has minimal impact, with long-term effects in solar collectors linked to nanoparticle accumulation [16].
- Environmental consequences: The disposal of nanofluids, especially those containing hazardous nanomaterials, raises serious environmental concerns. Improper disposal, such as landfilling or incineration, can release toxic substances into the air, contributing to environmental degradation and posing risks to both human and biodiversity. To mitigate these concerns, further research is needed to explore alternative, eco-friendly disposal methods and develop biodegradable nanomaterials, which could help minimize the environmental footprint of nanofluids in energy systems and promote a more sustainable approach to their lifecycle [16].

7.2. Industry 4.0 Implementation

As already noted, the integration of Industry 4.0 technologies into the renewable energy sector presents significant opportunities for optimizing energy production, efficiency, and sustainability. However, the widespread implementation of these advanced digital tools faces a range of challenges, spanning technical, regulatory, economic, and social dimensions. Addressing these challenges is crucial to unlocking the full potential of digital technologies and ensuring their successful deployment across the renewable energy landscape.

- Technical and Regulatory Challenges: These include technical issues such as system malfunctions, interoperability problems, unreliable connectivity, and cybersecurity risks. Regulatory hurdles involve the lack of clear frameworks and standards for digital technology integration in renewable energy systems, as well as the challenge of keeping up with rapid technological advancements [20].

- Economic and Social Challenges: High capital costs, uncertain return of investment (ROI), and energy consumption of digital technologies are significant economic barriers. Social challenges include job displacement due to automation and the need for workforce retraining, as well as addressing the digital literacy gap among users and maintenance staff [20]. Predictive analysis frameworks in DT systems, as seen in study [158], enable proactive maintenance, reducing downtime, preventing costly repairs, and extending equipment lifespan [158]. Performance optimization frameworks reduce energy waste and operational costs, enhancing economic sustainability by lowering production costs and supporting affordable renewable energy [159]. Risk and fault assessment frameworks, like the proactive approach, enable early issue detection, reducing downtime and minimizing costly reactive maintenance, improving economic resilience in renewable energy plants [160].
- Data Integration and Interoperability Challenges: Effective implementation of Industry 4.0 in renewable energy relies on the seamless integration of diverse data sources, such as sensors, weather forecasts, and historical performance data. Ensuring interoperability across different technologies and standards while transforming legacy systems into digital formats is a significant hurdle [47].
- Workforce and Knowledge Gap: The lack of expertise in both digital technologies and the renewable energy domain creates challenges in adopting Industry 4.0 solutions. There is a high demand for skilled professionals, but many digital experts lack experience with specific energy technologies, further complicating the process of digital transformation [47].
- Cybersecurity Concerns: With increased digital connectivity comes a higher risk of cyber threats to critical infrastructure. Ensuring the security and privacy of vast amounts of data is essential [21].
- Coordinated Defense Strategies: Due to the complexity of distributed energy resources (DERs), it is crucial to move from isolated cybersecurity solutions to coordinated, defense-in-depth strategies across interconnected systems like VPPs, DERMS, and energy trading platforms. These strategies should adapt to the flexible and dynamic nature of DERs, ensuring comprehensive protection against evolving cyber threats [161].
- Advanced Technologies for Resilience: To enhance cybersecurity, DER systems should adopt blockchain and cloud/edge computing for decentralized frameworks, and software-defined networks (SDN) for better visibility and control. Additionally, large language models (LLMs) can be utilized for intelligent, real-time decision-making, strengthening defense mechanisms and ensuring a proactive response to threats [161].

8. Future Prospects for Research

As CSP technologies continue to evolve, nanofluids present significant potential to enhance heat transfer, energy storage, and overall system performance. Despite the promising benefits, challenges such as stability, long-term economic sustainability, and environmental impacts must be carefully addressed. Advancing research into nanofluid technology offers pathways for optimizing CSP systems, address existing challenges, and enhancing solar energy management. This section provides a discussion of key findings from recent research and outlines future research directions for the integration of nanofluids in CSP systems, particularly focusing on nanofluid-based configurations.

- Nanofluid Enhancement: Future research will concentrate on developing nanofluids with smaller nanoparticle sizes and enhanced dispersion properties. These improvements are expected to significantly increase thermal conductivity and heat transfer efficiency, which are crucial for the optimal performance of CSP systems. By focusing on these enhancements, future studies can push the boundaries of nanofluid application in CSP systems, leading to greater energy capture and storage efficiencies.

- Hybrid Systems for Energy Storage: Combining nanofluids with phase change materials (PCMs) for energy storage in CSP systems is a promising avenue for future research. Such hybrid systems could significantly improve energy storage capacity and heat transfer efficiency, enabling CSP systems to operate more sustainably and efficiently. This integration could prove critical for overcoming the intermittent nature of solar energy, providing better heat retention and continuous energy supply.
- Stability and Functionalization of Nanofluids: One of the key challenges in utilizing nanofluids in CSP applications is their stability, especially under extreme operating conditions. Advances in functionalized nanoparticles and the development of advanced surfactants will help improve the stability of nanofluids, making them more viable for long-term use in CSP systems, particularly in parabolic trough collectors (PTC) and solar power tower collectors (SPTC). Overcoming these challenges is essential for the sustained operation of CSP systems in harsh environments.
- Comprehensive Evaluation of Nanofluid Viability: Future research will also need to integrate economic, environmental, and exergy evaluations to assess the long-term viability and sustainability of nanofluids in CSP systems. These assessments are crucial for understanding how nanofluids can be integrated into CSP systems without compromising environmental sustainability or leading to negative social impacts. A balanced approach is necessary to ensure that the advantages of nanofluids outweigh any potential downsides in their application.
- CSP’s Economic Perspective: CSP holds strong potential for large-scale renewable integration due to its dispatchability and storage capabilities. However, its higher levelized cost of electricity (LCoE) compared to PV and wind remains a challenge. Despite a 68% drop in global average LCoE since 2010 and significant reductions in capital and Operations and Maintenance costs, further cost optimization is essential. Innovations in materials, storage, and system design alongside supportive financing and policy frameworks are crucial to enhancing CSP’s economic competitiveness in the global energy transition [162].
- CSP’s Environmental Perspective: Climate change has led to global efforts like the Kyoto Protocol and Clean Development Mechanism (CDM) aimed at reducing emissions. CSP projects have been part of CDM initiatives, offering potential for sustainable energy generation in developing countries. Multi-criteria decision analyses have been used to evaluate the environmental sustainability of these projects, incorporating indicators such as emissions reduction, ecological impact, and long-term viability. This approach provides a structured framework for assessing the environmental performance of CSP systems and supports informed decision-making for future sustainable energy deployments [163].
- CSP’s Social View: Life Cycle Assessment studies on CSP systems reveal gaps in data standardization and impact category coverage, especially regarding decommissioning and subsystem-specific analyses. While climate change remains the most assessed impact, there’s a need for broader social and environmental evaluations, including operational issues and community-level effects, to enhance CSP’s sustainability and public acceptance [164].

The integration of Industry 4.0 technologies holds great promise in transforming CSP systems. The application of AI, ML, and DT technologies can substantially improve the efficiency, monitoring, and optimization of CSP operations. These advancements can facilitate the transition to more sustainable and cost-effective solar energy solutions.

- AI and ML in CSP Optimization: The incorporation of AI and ML into CSP plants can enable data-driven decision-making for optimal energy production. AI-based optimization models have the potential to improve heat transfer in various CSP configurations, including PTC and SPTC, by dynamically adjusting to real-time operational data. This integration can drive higher performance and cost efficiency in CSP systems.
- Digital Twin for Enhanced CSP Operations: DT technology could allow for the virtual simulation and management of CSP plants. This will enable better system control, troubleshooting, and enhanced reliability, ultimately reducing downtime and increasing the operational lifespan of CSP systems. The application of DT could be particularly beneficial for both large-scale and small-scale CSP operations by providing a more accurate representation of the system's behavior under different conditions.
- Role of Industry 4.0 in Global Decarbonization: Emerging evidence from bibliometric evaluations shows that Industry 4.0 technologies have contributed significantly to carbon footprint reduction and environmental sustainability across various sectors, including supply chains [165]. This further reinforces the potential for their integration into CSP systems to enhance sustainable energy management.
- Nanofluid-Industry 4.0 Synergy: Despite limited research into the integration of nanofluids with Industry 4.0 technologies, future studies should focus on leveraging AI and ML to optimize nanofluid performance. This combination could improve heat transfer efficiency, stability, and overall system performance in CSP systems, while addressing key challenges related to nanofluid application. The synergy between nanofluids and Industry 4.0 technologies holds significant potential to unlock new efficiencies and operational capabilities in CSP systems.

9. Conclusions

This review discussed the synergy of CSP technologies, nanofluids, and Industry 4.0 technologies, highlighting the potential to increase energy efficiency, thermal efficiency, and operational sustainability. Each CSP technology, such as PTCs, SPTCs, SDCs, and FRCs, presents specific benefits in the conversion of solar energy, and further optimizable potential using nanofluids and digitization technologies.

- Nanofluids provide significant improvements in the thermal conductivity, energy absorbance, and exergy efficiency of every type of CSP system. They depend on the type of nanoparticles, concentration, and compatibility of nanofluids with receiver geometries. However, issues including increased viscosity, pressure drop, stability, and environmental concerns must also be addressed.
- To better understand how nanofluids behave inside CSP systems, engineers use simulation tools like CFD. These tools make it easier to optimize designs without the need for costly experiments. Even so, some compromises, such as higher pumping power, must be managed during system design.
- The use of Industry 4.0 technologies such as AI, ML, and DT boosts the performance of CSP further by implementing real-time monitoring and predictive analytics. These technologies enhance system performance by identifying faults early, reducing maintenance, and improving overall reliability. However, there are still technical, regulatory, and financial barriers to overcome.
- Future studies need to work on stabilizing the nanofluids, advancing hybrid TES systems, and specifying optimization and control using Industry 4.0 technologies more precisely. Overcoming the present technological and economic barriers is crucial to ensure the scalable and sustainable use of the technologies in realistic CSP systems.
- While the integrated use of nanofluids and Industry 4.0 technologies in CSP systems is promising, the potential of their integration will create a more favorable opportunity

for next-generation CSP system development. This dual approach also bears an immense ability to enhance the utilization of solar energy, contributing to global sustainability and renewable energy targets.

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Nomenclature

Abbreviations	
AdaBoost	Adaptive Boosting
ACUREX	Adaptive Control for Real-Time Expert Systems
AI	Artificial Intelligence
ANFIS	Adaptive Neuro-Fuzzy Inference Systems
ANN	Artificial Neural Network
CART	Classification and Regression Trees
CDM	Clean Development Mechanism
CFD	Computational Fluid Dynamics
CHF	Constant heat flux
CNN	Convolutional Neural Network
COMSOL	COMSOL Multiphysics
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
DT	Digital Twin
DW	Distilled Water
EES	Engineering Equation Solver
EG	Ethylene Glycol
ELU	Exponential Linear Unit
EO	Earth Mover's Optimization
EOR	Enhanced Oil Recovery
ERTE	Exergetic Efficiency
ETR	Extra Trees Regressor
EXP	Experimental
FDI	False Data Injections
FRC	Fresnel Reflectors Collector
GNP	Graphene Nanoplates
GO	Graphen Oxide
$GtCO_2e$	Gigatonnes of carbon dioxide equivalent
GWO	Grey Wolf Optimizer
HTF	Heat Transfer Fluid
iDLR	Inverse Deep Learning Ray Tracing
IPSO	Improved Particle Swarm Optimization

IPPOA	Improved Prey Predator Optimization Algorithm
KNN	K-Nearest Neighbors
LCOE	Levelized Cost of Energy
LOS	Loss Out
LSTM	Long Short-Term Memory
MAE	Mean Absolute Error
MCRT	Monte Carlo Ray Tracing
MAPE	Mean Absolute Percentage Error
ML	Machine Learning
MLP	Multilayer Perceptron
MWCNT	Multi-Walled Carbon Nanotube
NSGA-II	Non-dominated Sorting Genetic Algorithm II
NUM	Numerical
OpenFOAM	Open-Source Field Operation and Manipulation
OPEX	Operational Expenditure
RVM	Relevance Vector Machine
PCA	Principal Component Analysis
PCM	Phase Change Material
PDE	Partial Differential Equations
PSO	Particle Swarm Optimization
PTC	Parabolic Trough Collector
PV	Photovoltaic
RMSE	Root Mean Squared Error
ROI	Return of Investment
SAA	Simulated Annealing Algorithm
SDC	Solar Dish Collector
SGD	Stochastic Gradient Descent
SPTC	Solar Power Tower Collector
SVM	Support Vector Machine
SVR	Support Vector Regression
TES	Thermal Energy Storage
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WHO	World Health Organization
η_{en}	Energy efficiency
η_{ex}	Exergy efficiency
η_{th}	Thermal efficiency

References

1. Shameer, P.M.; Ramesh, K. Experimental Evaluation on Performance, Combustion Behavior and Influence of in-Cylinder Temperature on NOx Emission in a D.I Diesel Engine Using Thermal Imager for Various Alternate Fuel Blends. *Energy* **2017**, *118*, 1334–1344. [CrossRef]
2. Mohamed Shameer, P.; Ramesh, K.; Sakthivel, R.; Purnachandran, R. Effects of Fuel Injection Parameters on Emission Characteristics of Diesel Engines Operating on Various Biodiesel: A Review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 1267–1281. [CrossRef]
3. Ramasamy, S.; Sivasubramaniyam, V.; Gatto, G.; Kumar, A. DC Link Voltage Control Based Energy Management Strategy for Standalone Solar PV Fed Hybrid System. In Proceedings of the 2023 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Modena, Italy, 17–19 July 2023; pp. 1–6. [CrossRef]
4. Oyekale, J.; Petrollese, M.; Cocco, D.; Cau, G. Annualized Exergoenvironmental Comparison of Solar-Only and Hybrid Solar-Biomass Heat Interactions with an Organic Rankine Cycle Power Plant. *Energy Convers. Manag. X* **2022**, *15*, 100229. [CrossRef]
5. Cascetta, M.; Petrollese, M.; Oyekale, J.; Cau, G. Thermocline vs. Two-Tank Direct Thermal Storage System for Concentrating Solar Power Plants: A Comparative Techno-Economic Assessment. *Int. J. Energy Res.* **2021**, *45*, 17721–17737. [CrossRef]
6. Ramasamy, S.; Ahmad, Z.; Bindu, Y.; Torres, J.R. Simulation Based Analysis of Transformerless Photovoltaic Inverter Topologies for Reactive Power Handling Capability. In Proceedings of the 2020 Second International Conference on Inventive Research in Computing Applications (ICIRCA), Coimbatore, India, 15–17 July 2020; pp. 1028–1034. [CrossRef]

7. Ramasamy, S.; Gatto, G.; Kumar, A. Various Non-Isolated Three Phase Grid-Integrated PV Inverter Topologies for Leakage Current Reduction-A Simulation-Based Study. In Proceedings of the 2022 IEEE International Power and Renewable Energy Conference (IPRECON), Kollam, India, 16–18 December 2022; pp. 1–6. [CrossRef]
8. Energy Institute. 2024 Statistical Review of World Energy. Available online: https://www.energyinst.org/statistical-review (accessed on 3 February 2025).
9. Alper, A.; Oguz, O. The Role of Renewable Energy Consumption in Economic Growth: Evidence from Asymmetric Causality. *Renew. Sustain. Energy Rev.* **2016**, *60*, 953–959. [CrossRef]
10. Destek, M.A.; Aslan, A. Renewable and Non-Renewable Energy Consumption and Economic Growth in Emerging Economies: Evidence from Bootstrap Panel Causality. *Renew. Energy* **2017**, *111*, 757–763. [CrossRef]
11. Khan, J.; Arsalan, M.H. Solar Power Technologies for Sustainable Electricity Generation—A Review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 414–425. [CrossRef]
12. Abdullatif Alshuhail, L.; Shaik, F.; Syam Sundar, L. Thermal Efficiency Enhancement of Mono and Hybrid Nanofluids in Solar Thermal Applications—A Review. *Alex. Eng. J.* **2023**, *68*, 365–404. [CrossRef]
13. Choi, S.U.S. Enhancing Thermal Conductivity of Fluids with Nanoparticles. *Am. Soc. Mech. Eng. Fluids Eng. Div. FED* **1995**, *231*, 99–105.
14. Xiong, Q.; Hajjar, A.; Alshuraiaan, B.; Izadi, M.; Altnji, S.; Shehzad, S.A. State-of-the-Art Review of Nanofluids in Solar Collectors: A Review Based on the Type of the Dispersed Nanoparticles. *J. Clean. Prod.* **2021**, *310*, 127528. [CrossRef]
15. Suresh, A.K.; Khurana, S.; Nandan, G.; Dwivedi, G.; Kumar, S. Role on Nanofluids in Cooling Solar Photovoltaic Cell to Enhance Overall Efficiency. *Mater. Today Proc.* **2018**, *5*, 20614–20620. [CrossRef]
16. Peer, M.S.; Casce, M.; Migliari, L.; Petrollese, M. Nanofluids in Thermal Energy Storage Systems: A Comprehensive Review. *Energies* **2025**, *18*, 707. [CrossRef]
17. Sheikholeslami, M.; Farshad, S.A.; Ebrahimpour, Z.; Said, Z. Recent Progress on Flat Plate Solar Collectors and Photovoltaic Systems in the Presence of Nanofluid: A Review. *J. Clean. Prod.* **2021**, *293*, 126119. [CrossRef]
18. Asgharian, H.; Baniasadi, E. A Review on Modeling and Simulation of Solar Energy Storage Systems Based on Phase Change Materials. *J. Energy Storage* **2019**, *21*, 186–201. [CrossRef]
19. Abbas, N.; Awan, M.B.; Amer, M.; Ammar, S.M.; Sajjad, U.; Ali, H.M.; Zahra, N.; Hussain, M.; Badshah, M.A.; Jafry, A.T. Applications of Nanofluids in Photovoltaic Thermal Systems: A Review of Recent Advances. *Phys. A Stat. Mech. Its Appl.* **2019**, *536*, 122513. [CrossRef]
20. Naeem, G.; Asif, M.; Khalid, M. Industry 4.0 Digital Technologies for the Advancement of Renewable Energy: Functions, Applications, Potential and Challenges. *Energy Convers. Manag. X* **2024**, *24*, 100779. [CrossRef]
21. Pandey, V.; Sircar, A.; Bist, N.; Solanki, K.; Yadav, K. Accelerating the Renewable Energy Sector through Industry 4.0: Optimization Opportunities in the Digital Revolution. *Int. J. Innov. Stud.* **2023**, *7*, 171–188. [CrossRef]
22. Kumaresan, T.R.K.; Murugan, S.; Mahima, M.S.P.S. Solar Energy Forecasting Using Machine Learning and Deep Learning Techniques. *Arch. Comput. Methods Eng.* **2023**, *30*, 3059–3079. [CrossRef]
23. Idrissi Kaitouni, S.; Ait Abdelmoula, I.; Es-sakali, N.; Mghazli, M.O.; Er-retby, H.; Zoubir, Z.; El Mansouri, F.; Ahachad, M.; Brigui, J. Implementing a Digital Twin-Based Fault Detection and Diagnosis Approach for Optimal Operation and Maintenance of Urban Distributed Solar Photovoltaics. *Renew. Energy Focus* **2024**, *48*, 100530. [CrossRef]
24. Alawi, O.A.; Kamar, H.M.; Homod, R.Z.; Yaseen, Z.M. Incorporating Artificial Intelligence-Powered Prediction Models for Exergy Efficiency Evaluation in Parabolic Trough Collectors. *Renew. Energy* **2024**, *225*, 120348. [CrossRef]
25. Zayed, M.E.; Zhao, J.; Elsheikh, A.H.; Li, W.; Sadek, S.; Aboelmaaref, M.M. A Comprehensive Review on Dish/Stirling Concentrated Solar Power Systems: Design, Optical and Geometrical Analyses, Thermal Performance Assessment, and Applications. *J. Clean. Prod.* **2021**, *283*, 124664. [CrossRef]
26. Sun, K.; Zhao, T.; Wu, S.; Yang, S. Comprehensive Evaluation of Concentrated Solar Collector and Organic Rankine Cycle Hybrid Energy Process with Considering the Effects of Different Heat Transfer Fluids. *Energy Rep.* **2021**, *7*, 362–384. [CrossRef]
27. Yılmaz, İ.H.; Mwesigye, A. Modeling, Simulation and Performance Analysis of Parabolic Trough Solar Collectors: A Comprehensive Review. *Appl. Energy* **2018**, *225*, 135–174. [CrossRef]
28. Shoeibi, S.; Kargarsharifabad, H.; Mirjalily, S.A.A.; Sadi, M.; Arabkoohsar, A. A Comprehensive Review of Nano-Enhanced Phase Change Materials on Solar Energy Applications. *J. Energy Storage* **2022**, *50*, 104262. [CrossRef]
29. Nawsud, Z.A.; Altouni, A.; Akhijahani, H.S.; Kargarsharifabad, H. A Comprehensive Review on the Use of Nano-Fluids and Nano-PCM in Parabolic Trough Solar Collectors (PTC). *Sustain. Energy Technol. Assess.* **2022**, *51*, 101889. [CrossRef]
30. Bamisile, O.; Cai, D.; Adun, H.; Adedeji, M.; Dagbasi, M.; Dika, F.; Huang, Q. A Brief Review and Comparative Evaluation of Nanofluid Application in Solar Parabolic Trough and Flat Plate Collectors. *Energy Rep.* **2022**, *8*, 156–166. [CrossRef]
31. Sun, L.; Yang, L.; Zhao, N.; Song, J.; Li, X.; Wu, X. A Review of Multifunctional Applications of Nanofluids in Solar Energy. *Powder Technol.* **2022**, *411*, 117932. [CrossRef]

32. Kalbande, V.P.; Choudhari, M.S.; Nandanwar, Y.N. Hybrid Nano-Fluid for Solar Collector Based Thermal Energy Storage and Heat Transmission Systems: A Review. *J. Energy Storage* **2024**, *86*, 111243. [CrossRef]
33. Vakili, M.; Akram, S. A Review of Recent Developments in the Application of Machine Learning in Solar Thermal Collector Modelling. *Environ. Sci. Pollut. Res.* **2022**, *30*, 2406–2439. [CrossRef]
34. Alao, K.T.; Gilani, S.I.U.H.; Sopian, K.; Alao, T.O. A Review on Digital Twin Application in Photovoltaic Energy Systems: Challenges and Opportunities. *JMST Adv.* **2024**, *6*, 257–282. [CrossRef]
35. Bennagi, A.; Alhousrya, O.; Cotfas, D.T.; Cotfas, P.A. Comprehensive Study of the Artificial Intelligence Applied in Renewable Energy. *Energy Strateg. Rev.* **2024**, *54*, 101446. [CrossRef]
36. Wang, Q.; Yang, L.; Song, J. Preparation, Thermal Conductivity, and Applications of Nano–Enhanced Phase Change Materials (NEPCMs) in Solar Heat Collection: A Review. *J. Energy Storage* **2023**, *63*, 107047. [CrossRef]
37. Sood, T.; Al Ansari, M.S.; Lakshmana Kishore, T.; Malleswara Rao, L.; Menaria, J.; Mallu, M.R.; Tyagi, D.; Prasad, K.S.; Vasoya, N.H.; Balakrishna Moorthy, C.; et al. A Comprehensive Review of the Influence of Nanomaterials on the Thermal Performance of a Solar Thermal Collectors. *Mater. Today Proc.* **2024**, *in press*. [CrossRef]
38. Hossain, F.; Karim, M.R.; Bhuiyan, A.A. A Review on Recent Advancements of the Usage of Nano Fluid in Hybrid Photovoltaic/Thermal (PV/T) Solar Systems. *Renew. Energy* **2022**, *188*, 114–131. [CrossRef]
39. Raj, P.; Subudhi, S. A Review of Studies Using Nanofluids in Flat-Plate and Direct Absorption Solar Collectors. *Renew. Sustain. Energy Rev.* **2018**, *84*, 54–74. [CrossRef]
40. Fernández, A.G.; Gomez-Vidal, J.; Oró, E.; Kruizenga, A.; Solé, A.; Cabeza, L.F. Mainstreaming Commercial CSP Systems: A Technology Review. *Renew. Energy* **2019**, *140*, 152–176. [CrossRef]
41. Xiong, Q.; Altnji, S.; Tayebi, T.; Izadi, M.; Hajjar, A.; Sundén, B.; Li, L.K.B. A Comprehensive Review on the Application of Hybrid Nanofluids in Solar Energy Collectors. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101341. [CrossRef]
42. Bretado-de los Rios, M.S.; Rivera-Solorio, C.I.; Nigam, K.D.P. An Overview of Sustainability of Heat Exchangers and Solar Thermal Applications with Nanofluids: A Review. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110855. [CrossRef]
43. Hu, G.; Ning, X.; Hussain, M.; Sajjad, U.; Sultan, M.; Ali, H.M.; Shah, T.R.; Ahmad, H. Potential Evaluation of Hybrid Nanofluids for Solar Thermal Energy Harvesting: A Review of Recent Advances. *Sustain. Energy Technol. Assess.* **2021**, *48*, 101651. [CrossRef]
44. Rashid, F.L.; Aljibori, H.S.; Mohammed, H.I.; Ameen, A.; Ahmad, S.; Ben Hamida, M.B.; Al-Rubaye, A.H. Recent Advances and Developments of the Application of Hybrid Nanofluids in Parabolic Solar Collector Energy Systems and Guidelines for Future Prospects. *J. Eng. Res.* **2024**, *in press*. [CrossRef]
45. Omara, Z.M.; Ahmed, M.M.Z.; Alawee, W.H.; Shanmugan, S.; Elashmawy, M. A Comprehensive Review of Nano-Enhanced Phase Change Materials on Solar Stills with Scientometric Analysis. *Results Eng.* **2024**, *22*, 102088. [CrossRef]
46. Kavousi-Fard, A.; Dabbaghjamanesh, M.; Jafari, M.; Fotuhi-Firuzabad, M.; Dong, Z.Y.; Jin, T. Digital Twin for Mitigating Solar Energy Resources Challenges: A Perspective Review. *Sol. Energy* **2024**, *274*, 112561. [CrossRef]
47. Aghaei, M.; Kolahi, M.; Esmailifar, S.M.; Sizkouhi, A.M.; Nedaei, A.; Manni, M.; Eskandari, A.; Lobaccaro, G. Digital Twin Technology in Solar Energy. In *Digital Twin Technology for the Energy Sector*; Elsevier: Amsterdam, The Netherlands, 2025; pp. 191–212. ISBN 9780443140709.
48. Milidonis, K.; Blanco, M.J.; Grigoriev, V.; Panagiotou, C.F.; Bonanos, A.M.; Constantinou, M.; Pye, J.; Asselineau, C.A. Review of Application of AI Techniques to Solar Tower Systems. *Sol. Energy* **2021**, *224*, 500–515. [CrossRef]
49. Padilla, R.V.; Demirkaya, G.; Goswami, D.Y.; Stefanakos, E.; Rahman, M.M. Heat Transfer Analysis of Parabolic Trough Solar Receiver. *Appl. Energy* **2011**, *88*, 5097–5110. [CrossRef]
50. De Oliveira Siqueira, A.M.; Gomes, P.E.N.; Torrezani, L.; Lucas, E.O.; Da Cruz Pereira, G.M. Heat Transfer Analysis and Modeling of a Parabolic Trough Solar Collector: An Analysis. *Energy Procedia* **2014**, *57*, 401–410. [CrossRef]
51. Wang, Y.; Liu, Q.; Lei, J.; Jin, H. Performance Analysis of a Parabolic Trough Solar Collector with Non-Uniform Solar Flux Conditions. *Int. J. Heat Mass Transf.* **2015**, *82*, 236–249. [CrossRef]
52. Li, Q.; Erqi, E.; Qiu, Y. Triple-Objective Optimization of He Brayton Cycles for Ultra-High-Temperature Solar Power Tower. *Energy Convers. Manag.* **2022**, *270*, 116210. [CrossRef]
53. Merchán, R.P.; Santos, M.J.; Medina, A.; Calvo Hernández, A. High Temperature Central Tower Plants for Concentrated Solar Power: 2021 Overview. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111828. [CrossRef]
54. Bellos, E. Progress in Beam-down Solar Concentrating Systems. *Prog. Energy Combust. Sci.* **2023**, *97*, 101085. [CrossRef]
55. Ho, C.K.; Iverson, B.D. Review of High-Temperature Central Receiver Designs for Concentrating Solar Power. *Renew. Sustain. Energy Rev.* **2014**, *29*, 835–846. [CrossRef]
56. Aseri, T.K.; Sharma, C.; Kandpal, T.C. A Techno-Economic Appraisal of Parabolic Trough Collector and Central Tower Receiver Based Solar Thermal Power Plants in India: Effect of Nominal Capacity and Hours of Thermal Energy Storage. *J. Energy Storage* **2022**, *48*, 103976. [CrossRef]
57. Xiao, G.; Nie, J.; Xu, H.; Zhang, C.; Zhu, P. Performance Analysis of a Solar Power Tower Plant Integrated with Trough Collectors. *Appl. Therm. Eng.* **2022**, *214*, 118853. [CrossRef]

58. He, Y.L.; Qiu, Y.; Wang, K.; Yuan, F.; Wang, W.Q.; Li, M.J.; Guo, J.Q. Perspective of Concentrating Solar Power. *Energy* **2020**, *198*, 117373. [CrossRef]
59. Kumar, V.; Shrivastava, R.L.; Untawale, S.P. Fresnel Lens: A Promising Alternative of Reflectors in Concentrated Solar Power. *Renew. Sustain. Energy Rev.* **2015**, *44*, 376–390. [CrossRef]
60. Malik, M.Z.; Shaikh, P.H.; Zhang, S.; Lashari, A.A.; Leghari, Z.H.; Baloch, M.H.; Memon, Z.A.; Caiming, C. A Review on Design Parameters and Specifications of Parabolic Solar Dish Stirling Systems and Their Applications. *Energy Rep.* **2022**, *8*, 4128–4154. [CrossRef]
61. Bellos, E.; Tzivanidis, C. Solar Concentrating Systems and Applications in Greece—A Critical Review. *J. Clean. Prod.* **2020**, *272*, 122855. [CrossRef]
62. Olawuyi, D.S. Renewable Energy Sources. *Environ. Policy Law* **2013**, *43*, 233–238. [CrossRef]
63. Benyakhlef, S.; Al Mers, A.; Merroun, O.; Bouatem, A.; Boutammachte, N.; El Alj, S.; Ajdad, H.; Erregueragui, Z.; Zemmouri, E. Impact of Heliostat Curvature on Optical Performance of Linear Fresnel Solar Concentrators. *Renew. Energy* **2016**, *89*, 463–474. [CrossRef]
64. Bellos, E.; Tzivanidis, C. Assessment of Linear Solar Concentrating Technologies for Greek Climate. *Energy Convers. Manag.* **2018**, *171*, 1502–1513. [CrossRef]
65. Baharoon, D.A.; Rahman, H.A.; Omar, W.Z.W.; Fadhl, S.O. Historical Development of Concentrating Solar Power Technologies to Generate Clean Electricity Efficiently—A Review. *Renew. Sustain. Energy Rev.* **2015**, *41*, 996–1027. [CrossRef]
66. Zhu, G.; Wendelin, T.; Wagner, M.J.; Kutscher, C. History, Current State, and Future of Linear Fresnel Concentrating Solar Collectors. *Sol. Energy* **2014**, *103*, 639–652. [CrossRef]
67. Benrezkallah, A.; Marif, Y.; Soudani, M.E.; Belhadj, M.M.; Hamidatou, T.; Mekhloufi, N.; Aouachir, A. Thermal Performance Evaluation of the Parabolic Trough Solar Collector Using Nanofluids: A Case Study in the Desert of Algeria. *Case Stud. Therm. Eng.* **2024**, *60*, 104797. [CrossRef]
68. AbdEl-Rady Abu-Zeid, M.; Elhenawy, Y.; Bassyouni, M.; Majozi, T.; Toderas, M.; Al-Qabandi, O.A.; Kishk, S.S. Performance Enhancement of Flat-Plate and Parabolic Trough Solar Collector Using Nanofluid for Water Heating Application. *Results Eng.* **2024**, *21*, 101673. [CrossRef]
69. Bellos, E.; Tzivanidis, C. Thermal Analysis of Parabolic Trough Collector Operating with Mono and Hybrid Nanofluids. *Sustain. Energy Technol. Assess.* **2018**, *26*, 105–115. [CrossRef]
70. Alhamayani, A. Performance Analysis and Machine Learning Algorithms of Parabolic Trough Solar Collectors Using Al_2O_3-MWCNT as a Hybrid Nanofluid. *Case Stud. Therm. Eng.* **2024**, *57*, 104321. [CrossRef]
71. Ram, S.; Ganesan, H.; Saini, V.; Kumar, A. Performance Assessment of a Parabolic Trough Solar Collector Using Nanofluid and Water Based on Direct Absorption. *Renew. Energy* **2023**, *214*, 11–22. [CrossRef]
72. Dou, L.; Ding, B.; Zhang, Q.; Kou, G.; Mu, M. Numerical Investigation on the Thermal Performance of Parabolic Trough Solar Collector with Synthetic Oil/Cu Nanofluids. *Appl. Therm. Eng.* **2023**, *227*, 120376. [CrossRef]
73. Raza, S.H.; Qamar, A.; Noor, F.; Riaz, F.; Usman, M.; Farooq, M.; Sultan, M.; Rehman, A.U.; Shahzadi, A.; Andresen, J.M. Experimental Analysis of Thermal Performance of Direct Absorption Parabolic Trough Collector Integrating Water Based Nanofluids for Sustainable Environment Applications. *Case Stud. Therm. Eng.* **2023**, *49*, 103366. [CrossRef]
74. Alhamayani, A.; Al-lehaibi, M. The Effect of Adding Hybrid Nanoparticles (Al_2O_3–TiO_2) on the Performance of Parabolic Trough Solar Collectors Using Different Thermal Oils and Molten Salts. *Case Stud. Therm. Eng.* **2024**, *59*, 104593. [CrossRef]
75. Bellos, E.; Tzivanidis, C. A Review of Concentrating Solar Thermal Collectors with and without Nanofluids. *J. Therm. Anal. Calorim.* **2019**, *135*, 763–786. [CrossRef]
76. Babita; Sharma, S.K.; Gupta, S.M. Preparation and Evaluation of Stable Nanofluids for Heat Transfer Application: A Review. *Exp. Therm. Fluid Sci.* **2016**, *79*, 202–212. [CrossRef]
77. Siva Reddy, E.; Meenakshi Reddy, R.; Krishna Reddy, K. Experimental Study on Thermal Efficiency of Parabolic Trough Collector (PTC) Using Al_2O_3/H_2O Nanofluid. *Appl. Mech. Mater.* **2015**, *787*, 192–196. [CrossRef]
78. Qin, C.; Kim, J.B.; Lee, B.J. Performance Analysis of a Direct-Absorption Parabolic-Trough Solar Collector Using Plasmonic Nanofluids. *Renew. Energy* **2019**, *143*, 24–33. [CrossRef]
79. Kasaeian, A.; Daneshazarian, R.; Rezaei, R.; Pourfayaz, F.; Kasaeian, G. Experimental Investigation on the Thermal Behavior of Nanofluid Direct Absorption in a Trough Collector. *J. Clean. Prod.* **2017**, *158*, 276–284. [CrossRef]
80. Bretado de los Rios, M.S.; Rivera-Solorio, C.I.; García-Cuéllar, A.J. Thermal Performance of a Parabolic Trough Linear Collector Using Al_2O_3/H_2O Nanofluids. *Renew. Energy* **2018**, *122*, 665–673. [CrossRef]
81. Bilal, F.R.; Arunachala, U.C.; Sandeep, H.M. Experimental Validation of Energy Parameters in Parabolic Trough Collector with Plain Absorber and Analysis of Heat Transfer Enhancement Techniques. *J. Phys. Conf. Ser.* **2018**, *953*, 012030. [CrossRef]
82. Kasaeian, A.; Daviran, S.; Azarian, R.D.; Rashidi, A. Performance Evaluation and Nanofluid Using Capability Study of a Solar Parabolic Trough Collector. *Energy Convers. Manag.* **2015**, *89*, 368–375. [CrossRef]

83. Okonkwo, E.C.; Abid, M.; Ratlamwala, T.A.H. Numerical Analysis of Heat Transfer Enhancement in a Parabolic Trough Collector Based on Geometry Modifications and Working Fluid Usage. *J. Sol. Energy Eng. Trans. ASME* **2018**, *140*, 051009. [CrossRef]
84. Bellos, E.; Tzivanidis, C. Optimization of a Solar-Driven Trigeneration System with Nanofluid-Based Parabolic Trough Collectors. *Energies* **2017**, *10*, 848. [CrossRef]
85. Rehan, M.A.; Ali, M.; Sheikh, N.A.; Khalil, M.S.; Chaudhary, G.Q.; Rashid, T.u.; Shehryar, M. Experimental Performance Analysis of Low Concentration Ratio Solar Parabolic Trough Collectors with Nanofluids in Winter Conditions. *Renew. Energy* **2018**, *118*, 742–751. [CrossRef]
86. Heyhat, M.M.; Valizade, M.; Abdolahzade, S.; Maerefat, M. Thermal Efficiency Enhancement of Direct Absorption Parabolic Trough Solar Collector (DAPTSC) by Using Nanofluid and Metal Foam. *Energy* **2020**, *192*, 116662. [CrossRef]
87. Abu-Hamdeh, N.H.; Salilih, E.M.; Alsulami, R.A.; Rawa, M.J.H.; Aljinaidi, A.A.; Alazwari, M.A.; Eltaher, M.A.; Almitani, K.H.; Abulkhair, H.A.; Alnefaie, K.A.; et al. The Effects of Incident Solar Radiation on the Collector Efficiency Using Coolant Hybrid Nanofluid via Simulation of Solar Tower System with the Parallel Heat Exchangers. *J. Taiwan Inst. Chem. Eng.* **2021**, *124*, 106–115. [CrossRef]
88. Shatnawi, H.; Lim, C.W.; Ismail, F.B.; Aldossary, A. An Optimisation Study of a Solar Tower Receiver: The Influence of Geometry and Material, Heat Flux, and Heat Transfer Fluid on Thermal and Mechanical Performance. *Heliyon* **2021**, *7*, e07489. [CrossRef]
89. Taylor, R.A.; Phelan, P.E.; Otanicar, T.P.; Walker, C.A.; Nguyen, M.; Trimble, S.; Prasher, R. Applicability of Nanofluids in High Flux Solar Collectors. *J. Renew. Sustain. Energy* **2011**, *3*, 023104. [CrossRef]
90. Loni, R.; Asli-Ardeh, E.A.; Ghobadian, B.; Kasaeian, A. Experimental Study of Carbon Nano Tube/Oil Nanofluid in Dish Concentrator Using a Cylindrical Cavity Receiver: Outdoor Tests. *Energy Convers. Manag.* **2018**, *165*, 593–601. [CrossRef]
91. Khan, M.S.; Abid, M.; Ali, H.M.; Amber, K.P.; Bashir, M.A.; Javed, S. Comparative Performance Assessment of Solar Dish Assisted S-CO_2 Brayton Cycle Using Nanofluids. *Appl. Therm. Eng.* **2019**, *148*, 295–306. [CrossRef]
92. Loni, R.; Askari Asli-Ardeh, E.; Ghobadian, B.; Najafi, G.; Bellos, E. Effects of Size and Volume Fraction of Alumina Nanoparticles on the Performance of a Solar Organic Rankine Cycle. *Energy Convers. Manag.* **2019**, *182*, 398–411. [CrossRef]
93. Loni, R.; Askari Asli-Ardeh, E.; Ghobadian, B.; Kasaeian, A.B.; Bellos, E. Thermal Performance Comparison between Al_2O_3/Oil and SiO_2/Oil Nanofluids in Cylindrical Cavity Receiver Based on Experimental Study. *Renew. Energy* **2018**, *129*, 652–665. [CrossRef]
94. Goudarzi, K.; Shojaeizadeh, E.; Nejati, F. An Experimental Investigation on the Simultaneous Effect of CuO-H_2O Nanofluid and Receiver Helical Pipe on the Thermal Efficiency of a Cylindrical Solar Collector. *Appl. Therm. Eng.* **2014**, *73*, 1236–1243. [CrossRef]
95. Loni, R.; Asli-Ardeh, E.A.; Ghobadian, B.; Ahmadi, M.H.; Bellos, E. GMDH Modeling and Experimental Investigation of Thermal Performance Enhancement of Hemispherical Cavity Receiver Using MWCNT/Oil Nanofluid. *Sol. Energy* **2018**, *171*, 790–803. [CrossRef]
96. Loni, R.; Asli-Ardeh, E.A.; Ghobadian, B.; Kasaeian, A.B.; Bellos, E. Energy and Exergy Investigation of Alumina/Oil and Silica/Oil Nanofluids in Hemispherical Cavity Receiver: Experimental Study. *Energy* **2018**, *164*, 275–287. [CrossRef]
97. Aslfattahi, N.; Loni, R.; Bellos, E.; Najafi, G.; Kadirgama, K.; Harun, W.S.W.; Saidur, R. Efficiency Enhancement of a Solar Dish Collector Operating with a Novel Soybean Oil-Based-MXene Nanofluid and Different Cavity Receivers. *J. Clean. Prod.* **2021**, *317*, 128430. [CrossRef]
98. Barghi Jahromi, M.S.; Kalantar, V.; Samimi-Akhijahani, H. Evaluation of Performance, Energy, and Exergy Analysis of a Solar Parabolic Dish Collector Connected to a Dryer with Nanofluid and PCM. *J. Energy Storage* **2024**, *98*, 112969. [CrossRef]
99. Kant, R.; Kumar, A.; Dubey, M.K. Energetic, Exergetic, Exergoeconomic, and Enviroeconomic Analysis of Solar Dish-Integrated Water Desalination System with Various Nanofluids. *Groundw. Sustain. Dev.* **2024**, *26*, 101207. [CrossRef]
100. Loni, R.; Askari Asli-Areh, E.; Ghobadian, B.; Kasaeian, A.B.; Gorjian, S.; Najafi, G.; Bellos, E. Research and Review Study of Solar Dish Concentrators with Different Nanofluids and Different Shapes of Cavity Receiver: Experimental Tests. *Renew. Energy* **2020**, *145*, 783–804. [CrossRef]
101. Rajendran, D.R.; Sundaram, E.G.; Jawahar, P. Experimental Studies on the Effect of Enhanced Thermal Conductivity of SiC+Water Nanofluid in the Performance of Small Scale Solar Parabolic Dish Receiver. *Int. J. Nanosci.* **2018**, *17*, 1760025. [CrossRef]
102. Ghodbane, M.; Said, Z.; Hachicha, A.A.; Boumeddane, B. Performance Assessment of Linear Fresnel Solar Reflector Using MWCNTs/DW Nanofluids. *Renew. Energy* **2020**, *151*, 43–56. [CrossRef]
103. Huang, W.; Marefati, M. Energy, Exergy, Environmental and Economic Comparison of Various Solar Thermal Systems Using Water and Thermia Oil B Base Fluids, and CuO and Al_2O_3 Nanofluids. *Energy Rep.* **2020**, *6*, 2919–2947. [CrossRef]
104. Bellos, E.; Tzivanidis, C.; Papadopoulos, A. Enhancing the Performance of a Linear Fresnel Reflector Using Nanofluids and Internal Finned Absorber. *J. Therm. Anal. Calorim.* **2019**, *135*, 237–255. [CrossRef]
105. Salehi, N.; Lavasani, A.M.; Mehdipour, R.; Yazdi, M.E. Effect of Nano Fluids on the Thermal Performance and Efficiency of Linear Fresnel Collector in Hot Summer Months. *J. Renew. Energy Environ.* **2021**, *8*, 42–51. [CrossRef]
106. Ghodbane, M.; Said, Z.; Tiwari, A.K.; Syam Sundar, L.; Li, C.; Boumeddane, B. 4E (Energy, Exergy, Economic and Environmental) Investigation of LFR Using MXene Based Silicone Oil Nanofluids. *Sustain. Energy Technol. Assess.* **2022**, *49*, 101715. [CrossRef]

107. Yang, M.; Wang, S.; Zhu, Y.; Taylor, R.A.; Moghimi, M.A.; Wang, Y. Thermal Stability and Performance Testing of Thermal Applications. *Energies* **2020**, *13*, 876. [CrossRef]
108. Salehi, N.; Mehdipour, R.; Lavasani, A.M.; Eftekhari Yazdi, M. Investigating the Increased Heat Performance of Direct Steam Generation of Fresnel Power Plant Using Nanoparticles. *Environ. Prog. Sustain. Energy* **2021**, *40*, e13480. [CrossRef]
109. Bellos, E.; Tzivanidis, C.; Tsimpoukis, D. Enhancing the Performance of Parabolic Trough Collectors Using Nanofluids and Turbulators. *Renew. Sustain. Energy Rev.* **2018**, *91*, 358–375. [CrossRef]
110. Alnaqi, A.A.; Alsarraf, J.; Al-Rashed, A.A.A.A. Numerical Investigation of Hydrothermal Efficiency of a Parabolic Dish Solar Collector Filled with Oil Based Hybrid Nanofluid. *J. Taiwan Inst. Chem. Eng.* **2021**, *124*, 238–257. [CrossRef]
111. Arun, M.; Barik, D.; Ahmad, H.; Alraddadi, I.; Shenashen, M.A.; Khan, Z.A. Parabolic Trough Solar Collector Technology Using TiO_2 Nanofluids with Dimpled Tubes. *Case Stud. Therm. Eng.* **2024**, *61*, 104840. [CrossRef]
112. Samiezadeh, S.; Khodaverdian, R.; Doranehgard, M.H.; Chehrmonavari, H.; Xiong, Q. CFD Simulation of Thermal Performance of Hybrid Oil-Cu-Al_2O_3 Nanofluid Flowing through the Porous Receiver Tube inside a Finned Parabolic Trough Solar Collector. *Sustain. Energy Technol. Assess.* **2022**, *50*, 101888. [CrossRef]
113. Hou, G.; Yadav, A.; Ali, E.; Naeem, Y.A.; Ahmed, F.F.; Muzammil, K.; Falih, K.T.; Abdulridui, H.A.; Kadhum, E.H.; Omran, A.A.; et al. Thermal Performance Improvement for Parabolic Trough Solar Collectors Integrated with Twisted Fin and Nanofluid: Modeling and Validation. *Case Stud. Therm. Eng.* **2024**, *60*, 104763. [CrossRef]
114. Byiringiro, J.; Chaanaoui, M.; Halimi, M. Heat Transfer Enhancement of a Parabolic Trough Solar Collector Using Innovative Receiver Configurations Combined with a Hybrid Nanofluid: CFD Analysis. *Renew. Energy* **2024**, *233*, 121169. [CrossRef]
115. Al-Rabeeah, A.Y.; Seres, I.; Farkas, I. Experimental and Numerical Investigation of Parabolic Trough Solar Collector Thermal Efficiency Enhanced by Graphene–Fe_3O_4/Water Hybrid Nanofluid. *Results Eng.* **2024**, *21*, 101887. [CrossRef]
116. Ghasemi, S.E.; Ranjbar, A.A. Effect of Using Nanofluids on Efficiency of Parabolic Trough Collectors in Solar Thermal Electric Power Plants. *Int. J. Hydrogen Energy* **2017**, *42*, 21626–21634. [CrossRef]
117. Mwesigye, A.; Meyer, J.P. Optimal Thermal and Thermodynamic Performance of a Solar Parabolic Trough Receiver with Different Nanofluids and at Different Concentration Ratios. *Appl. Energy* **2017**, *193*, 393–413. [CrossRef]
118. Brahim, T.; Jemni, A. Comparative Study of Parabolic Trough Solar Collector Using Sysltherm-800 and Therminol-VP1 Non-Metallic Nanofluids. *Therm. Sci. Eng. Prog.* **2023**, *43*, 101951. [CrossRef]
119. Esmaeili, Z.; Akbarzadeh, S.; Rashidi, S.; Valipour, M.S. Effects of Hybrid Nanofluids and Turbulator on Efficiency Improvement of Parabolic Trough Solar Collectors. *Eng. Anal. Bound. Elem.* **2023**, *148*, 114–125. [CrossRef]
120. Hatami, M.; Geng, J.; Jing, D. Enhanced Efficiency in Concentrated Parabolic Solar Collector (CPSC) with a Porous Absorber Tube Filled with Metal Nanoparticle Suspension. *Green Energy Environ.* **2018**, *3*, 129–137. [CrossRef]
121. Safari Chukami, B.; Heyhat, M.M. Numerical Investigation on the Effect of Al_2O_3-Water Nanofluid on Direct Steam Generation in Parabolic Trough Collectors. *Appl. Therm. Eng.* **2024**, *241*, 122300. [CrossRef]
122. Bellos, E.; Tzivanidis, C.; Tsimpoukis, D. Thermal, Hydraulic and Exergetic Evaluation of a Parabolic Trough Collector Operating with Thermal Oil and Molten Salt Based Nanofluids. *Energy Convers. Manag.* **2018**, *156*, 388–402. [CrossRef]
123. Salilih, E.M.; Abu-Hamdeh, N.H.; Alsulami, R.A.; Rawa, M.J.H.; Aljinaidi, A.A.; Alazwari, M.A.; Eltaher, M.A.; Almitani, K.H.; Alnefaie, K.A.; Abusorrah, A.M.; et al. Annual Performance Analysis of Small Scale Industrial Waste Heat Assisted Solar Tower Power Plant and Application of Nanofluid. *J. Taiwan Inst. Chem. Eng.* **2021**, *124*, 216–227. [CrossRef]
124. Hai, T.; Alazzawi, A.k.; Ju, Y.; Wang, D.; Wang, S. Integration of Vanadium-Chlorine Thermochemical Cycle with a Nano-Particle Aided Solar Power Tower for Power and Hydrogen Cogeneration. *Int. J. Hydrogen Energy* **2024**, *52*, 580–593. [CrossRef]
125. Askari, I.B.; Shahsavar, A.; Jamei, M.; Calise, F.; Karbasi, M. A Parametric Assessing and Intelligent Forecasting of the Energy and Exergy Performances of a Dish Concentrating Photovoltaic/Thermal Collector Considering Six Different Nanofluids and Applying Two Meticulous Soft Computing Paradigms. *Renew. Energy* **2022**, *193*, 149–166. [CrossRef]
126. Ouyang, P.; Xu, Y.P.; Qi, L.Y.; Xing, S.M.; Fooladi, H. Comprehensive Evaluation of Flat Plate and Parabolic Dish Solar Collectors' Performance Using Different Operating Fluids and MWCNT Nanofluid in Different Climatic Conditions. *Energy Rep.* **2021**, *7*, 2436–2451. [CrossRef]
127. Bellos, E.; Tzivanidis, C. Multi-Criteria Evaluation of a Nanofluid-Based Linear Fresnel Solar Collector. *Sol. Energy* **2018**, *163*, 200–214. [CrossRef]
128. Said, Z.; Ghodbane, M.; Sundar, L.S.; Tiwari, A.K.; Sheikholeslami, M.; Boumeddane, B. Heat Transfer, Entropy Generation, Economic and Environmental Analyses of Linear Fresnel Reflector Using Novel RGO-Co_3O_4 Hybrid Nanofluids. *Renew. Energy* **2021**, *165*, 420–437. [CrossRef]
129. Ordóñez, F.; Valverde, D.; Arias, R.; Rojas, R. Numerical Study of a Nanofluid-Based Receiver for Linear Fresnel Collectors. *Appl. Therm. Eng.* **2023**, *230*, 120746. [CrossRef]
130. Wang, G.; Ge, Z.; Lin, J. Design and Performance Analysis of a Novel Solar Photovoltaic/Thermal System Using Compact Linear Fresnel Reflector and Nanofluids Beam Splitting Device. *Case Stud. Therm. Eng.* **2022**, *35*, 102167. [CrossRef]

131. Tao, H.; Alawi, O.A.; Homod, R.Z.; Mohammed, M.K.; Goliatt, L.; Togun, H.; Shafik, S.S.; Heddam, S.; Yaseen, Z.M. Data Driven Insights for Parabolic Trough Solar Collectors: Artificial Intelligence-Based Energy and Exergy Performance Analysis. *J. Clean. Prod.* **2024**, *443*, 141069. [CrossRef]
132. Ruiz-Moreno, S.; Gallego, A.J.; Camacho, E.F. Artificial Neural Network-Based Fault Detection and Isolation in a Parabolic-Trough Solar Plant with Defocusing Strategy. *Sol. Energy* **2023**, *262*, 111909. [CrossRef]
133. Oufadel, A.; El Ydrissi, M.; Hassani, A.A.; Ghennioui, H.; Ghennioui, A.; Ghali bennouna, E.; Amri, A.E.; Abdi, F. In-Situ Heat Losses Measurements of Parabolic Trough Receiver Tubes Based on Infrared Camera and Artificial Intelligence. *Environ. Chall.* **2023**, *10*, 100679. [CrossRef]
134. Kumar, A.; Sharma, B.K.; Almohsen, B.; Pérez, L.M. Artificial Neural Network Analysis of Jeffrey Hybrid Nanofluid with Gyrotactic Microorganisms for Optimizing Solar Thermal Collector Efficiency. *Sci. Rep.* **2025**, *15*, 4729. [CrossRef]
135. Zaaoumi, A.; Bah, A.; Ciocan, M.; Sebastian, P.; Balan, M.C.; Mechaqrane, A.; Alaoui, M. Estimation of the Energy Production of a Parabolic Trough Solar Thermal Power Plant Using Analytical and Artificial Neural Networks Models. *Renew. Energy* **2021**, *170*, 620–638. [CrossRef]
136. Ruiz-Moreno, S.; Sanchez, A.J.; Gallego, A.J.; Camacho, E.F. A Deep Learning-Based Strategy for Fault Detection and Isolation in Parabolic-Trough Collectors. *Renew. Energy* **2022**, *186*, 691–703. [CrossRef]
137. Mustafa, J.; Alqaed, S.; Sharifpur, M. Numerical Study on Performance of Double-Fluid Parabolic Trough Solar Collector Occupied with Hybrid Non-Newtonian Nanofluids: Investigation of Effects of Helical Absorber Tube Using Deep Learning. *Eng. Anal. Bound. Elem.* **2022**, *140*, 562–580. [CrossRef]
138. Cetina-Quiñones, A.J.; Bassam, A.; Carrillo, J.G.; Ricalde, L.J.; Pérez-Quintana, I.; de Paz, P.L. *Toward a Sustainable Dairy Industry in Mexico: Optimization of a Parabolic Trough Solar Collector System with Passive Heat-Transfer Enhancement Techniques and a Machine Learning Approach*; Springer: Cham, The Netherlands, 2024; ISBN 0123456789.
139. Suwa, T. Transient Heat Transfer Performance Prediction Using a Machine Learning Approach for Sensible Heat Storage in Parabolic Trough Solar Thermal Power Generation Cycles. *J. Energy Storage* **2022**, *56*, 105965. [CrossRef]
140. Venkatesaperumal, R.; Jafar, K.S. Machine Learning Predictions for Enhancing Solar Parabolic Trough Collector Efficiency with Corrugated Tube Receivers. *Sadhana-Acad. Proc. Eng. Sci.* **2024**, *49*, 130. [CrossRef]
141. Pargmann, M.; Maldonado Quinto, D.; Schwarzbözl, P.; Pitz-Paal, R. High Accuracy Data-Driven Heliostat Calibration and State Prediction with Pretrained Deep Neural Networks. *Sol. Energy* **2021**, *218*, 48–56. [CrossRef]
142. Sievers, L.T.E.; Pargmann, M.; Maldonado Quinto, D.; Hoffschmidt, B. End-to-End Sensitivity Analysis of a Hybrid Heliostat Calibration Process Involving Artificial Neural Networks. *Sol. Energy* **2025**, *287*, 113219. [CrossRef]
143. Lewen, J.; Pargmann, M.; Cherti, M.; Jitsev, J.; Pitz-paal, R.; Quinto, M. Inverse Deep Learning Ray Tracing for Heliostat Surface Prediction. *Sol. Energy* **2024**, *289*, 113312. [CrossRef]
144. Salari, A.; Shakibi, H.; Alimohammadi, M.; Naghdbishi, A.; Goodarzi, S. A Machine Learning Approach to Optimize the Performance of a Combined Solar Chimney-Photovoltaic Thermal Power Plant. *Renew. Energy* **2023**, *212*, 717–737. [CrossRef]
145. Hosseinifard, F.; Hosseinpour, M.; Salimi, M.; Amidpour, M. Greening Enhanced Oil Recovery: A Solar Tower and PV-Assisted Approach to Post-Combustion Carbon Capture with Machine Learning Insights. *Energy Nexus* **2025**, *17*, 100381. [CrossRef]
146. Tariq, R.; Torres-Aguilar, C.E.; Xamán, J.; Zavala-Guillén, I.; Bassam, A.; Ricalde, L.J.; Carvente, O. Digital Twin Models for Optimization and Global Projection of Building-Integrated Solar Chimney. *Build. Environ.* **2022**, *213*, 108807. [CrossRef]
147. Khosravi, A.; Syri, S.; Pabon, J.J.G.; Sandoval, O.R.; Caetano, B.C.; Barrientos, M.H. Energy Modeling of a Solar Dish/Stirling by Artificial Intelligence Approach. *Energy Convers. Manag.* **2019**, *199*, 112021. [CrossRef]
148. Li, N.; Jiang, Y.; Aksoy, M.; Zain, J.M.; Kumar Nutakki, T.U.; Abdalla, A.N.; Hai, T. Exergo-Economic Analyzes of a Combined CPVT Solar Dish/Kalina Cycle/HDH Desalination System; Intelligent Forecasting Using Artificial Neural Network (ANN) and Improved Particle Swarm Optimization (IPSO). *Renew. Energy* **2024**, *235*, 121254. [CrossRef]
149. Mohite, S.J.; Reddy, K.S. Optical and Thermal Analysis of Solar Parabolic Dish Cavity Receiver System for Hydrogen Production Using Deep Learning. *Energy Convers. Manag.* **2023**, *292*, 117415. [CrossRef]
150. Zayed, M.E.; Zhao, J.; Li, W.; Elsheikh, A.H.; Elaziz, M.A. A Hybrid Adaptive Neuro-Fuzzy Inference System Integrated with Equilibrium Optimizer Algorithm for Predicting the Energetic Performance of Solar Dish Collector. *Energy* **2021**, *235*, 121289. [CrossRef]
151. Bamasag, A.; Essa, F.A.; Omara, Z.M.; Bahgat, E.; Alsaiari, A.O.; Abulkhair, H.; Alsulami, R.A.; Elsheikh, A.H. Machine Learning-Based Prediction and Augmentation of Dish Solar Distiller Performance Using an Innovative Convex Stepped Absorber and Phase Change Material with Nanoadditives. *Process Saf. Environ. Prot.* **2022**, *162*, 112–123. [CrossRef]
152. Zayed, M.E.; Zhao, J.; Li, W.; Elsheikh, A.H.; Elaziz, M.A.; Yousri, D.; Zhong, S.; Mingxi, Z. Predicting the Performance of Solar Dish Stirling Power Plant Using a Hybrid Random Vector Functional Link/Chimp Optimization Model. *Sol. Energy* **2021**, *222*, 1–17. [CrossRef]
153. Ahmadpour, A.; Dejamkhooy, A.; Shayeghi, H. Optimization and Modelling of Linear Fresnel Reflector Solar Concentrator Using Various Methods Based on Monte Carlo Ray–Trace. *Sol. Energy* **2022**, *245*, 67–79. [CrossRef]

154. Rehman, S.; Zayed, M.E.; Irshad, K.; Menesy, A.S.; Kotb, K.M.; Saeed Alzahrani, A.; Alhems, L.M. Design, Commissioning and Operation of a Large-Scale Solar Linear Fresnel System Integrated with Evacuated Compound Receiver: Field Testing, Thermodynamic Analysis, and Enhanced Machine Learning-Based Optimization. *Sol. Energy* **2024**, *278*, 112785. [CrossRef]
155. Meligy, R.; Montenon, A.; Hassan, H.A. Comparative Analysis of Machine Learning Models of Linear Fresnel Solar Collector. *Renew. Energy* **2024**, *230*, 120865. [CrossRef]
156. Chicaiza, W.D.; Machado, D.O.; Sánchez, A.J.; Escaño, J.M.; Normey-Rico, J.E. Fault Data Injection Detection on a Digital-Twin: Fresnel Solar Concentrator. *IFAC-PapersOnLine* **2024**, *58*, 37–42. [CrossRef]
157. Machado, D.O.; Chicaiza, W.D.; Escaño, J.M.; Gallego, A.J.; de Andrade, G.A.; Normey-Rico, J.E.; Bordons, C.; Camacho, E.F. Digital Twin of a Fresnel Solar Collector for Solar Cooling. *Appl. Energy* **2023**, *339*, 120944. [CrossRef]
158. Yang, X.; Ran, Y.; Zhang, G.; Wang, H.; Mu, Z.; Zhi, S. A Digital Twin-Driven Hybrid Approach for the Prediction of Performance Degradation in Transmission Unit of CNC Machine Tool. *Robot. Comput. Integr. Manuf.* **2022**, *73*, 102230. [CrossRef]
159. Wang, P.; Luo, M. A Digital Twin-Based Big Data Virtual and Real Fusion Learning Reference Framework Supported by Industrial Internet towards Smart Manufacturing. *J. Manuf. Syst.* **2021**, *58*, 16–32. [CrossRef]
160. Wei, Y.; Hu, T.; Zhou, T.; Ye, Y.; Luo, W. Consistency Retention Method for CNC Machine Tool Digital Twin Model. *J. Manuf. Syst.* **2021**, *58*, 313–322. [CrossRef]
161. Chen, J.; Yan, J.; Kemmeugne, A.; Kassouf, M.; Debbabi, M. Cybersecurity of Distributed Energy Resource Systems in the Smart Grid: A Survey. *Appl. Energy* **2025**, *383*, 125364. [CrossRef]
162. Khan, M.I.; Gutiérrez-Alvarez, R.; Asfand, F.; Bicer, Y.; Sgouridis, S.; Al-Ghamdi, S.G.; Jouhara, H.; Asif, M.; Kurniawan, T.A.; Abid, M.; et al. The Economics of Concentrating Solar Power (CSP): Assessing Cost Competitiveness and Deployment Potential. *Renew. Sustain. Energy Rev.* **2024**, *200*, 114551. [CrossRef]
163. Simsek, Y.; Watts, D.; Escobar, R. Sustainability Evaluation of Concentrated Solar Power (CSP) Projects under Clean Development Mechanism (CDM) by Using Multi Criteria Decision Method (MCDM). *Renew. Sustain. Energy Rev.* **2018**, *93*, 421–438. [CrossRef]
164. Palmero-González, M.A.; Batuecas, E.; Marugán-Cruz, C.; Santana, D. Life Cycle Assessment Studies of Concentrated Solar Power Technology: A Literature Review. *Sustain. Energy Technol. Assess.* **2025**, *75*, 104257. [CrossRef]
165. Briatore, F.; Vanni, F.; Mosca, M.T.; Mosca, R.N.; Fruggiero, F.; Mancusi, F. Exploring Industry 4.0's Role in Sustainable Supply Chains: Perspectives from a Bibliometric Review. *Logistics* **2025**, *9*, 26. [CrossRef]