Renewable and Sustainable Energy Reviews 199 (2024) 114497

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review article

Heat loss analysis review: Parabolic trough and linear Fresnel collectors

Pedram Alamdari, Mehdi Khatamifar *, Wenxian Lin

College of Science & Engineering, James Cook University, Townsville, QLD 4811, Australia

ARTICLE INFO

Keywords:
Concentrating solar power plants
Linear concentrating solar power
Parabolic trough collectors
Linear Fresnel collectors
Thermal loss
Total heat loss
Convective heat loss
Radiative heat loss
Efficiency
Thermal performance

ABSTRACT

Linear concentrating solar power systems represent the most commonly installed types of concentrating solar power systems. These systems can be categorized into two types: parabolic trough collectors and linear Fresnel collectors. Due to their widespread use, they have garnered significant attention in different studies aiming to enhance their efficiency. This study conducts a review of studies conducted over the past decade, focusing on the various types of heat losses, a crucial parameter influencing the efficiency of linear concentrating solar power systems. It encompasses analytical, experimental, numerical, and hybrid studies related to heat losses in three subsystem classifications: simple tubular absorbers, compound parabolic collectors, and cavity receivers.

Heat loss literature can be categorized into four parts: three focused on reducing losses through enhancements in geometrical and structural configurations, the use of different heat transfer fluids, and various coating materials. The fourth category involves calculating or measuring heat loss alongside other important parameters in a proposed system. The assessment reveals that most studies (62.23% for parabolic trough collectors and 71.4% for linear Fresnel collectors) have focused on general studies to calculate heat loss. Approximately 14.89% of studies on heat loss mitigation for parabolic trough collectors concern geometry and coating materials, and 7.98% involve using different heat transfer fluids to reduce heat losses. In the case of linear Fresnel collectors, 27.14% of studies focus on geometry, while only 1.46% deal with heat transfer fluids, and no studies have been found regarding the use of materials to decrease heat losses in linear Fresnel collectors.

1. Introduction

Solar energy stands out as one of the most promising alternatives to fossil fuels. It can be harnessed through two primary methods: direct conversion and indirect conversion. In the direct conversion approach, solar energy is transformed into electricity utilizing the photovoltaic (PV) effect. This intricate process entails the utilization of solar panels to capture sunlight and subsequently convert it into electrical power. The indirect conversion method involves the implementation of a fluid or solid medium to facilitate the transfer and storage of solar energy. This accumulated energy can be effectively employed in diverse applications, including chemical, thermal, or electricity generation processes [1–3].

Despite the undeniable advantages offered by solar energy systems, similar to PV electricity generation, users of these systems encounter challenges arising from solar radiation fluctuations, varying solar intensities across different geographical locations [4], and the quest for enhanced system efficiencies. While the viability of deploying such systems in specific climates and locations necessitates thorough evaluation, it is crucial to recognize that solar radiation fluctuation and low solar intensity are environmental variables subject to limited control compared to system efficiency. The pursuit of efficiency enhancement is not only attainable but also imperative.

Thus, concentrating solar power (CSP) systems have received significant attention in studies, power plant constructors, and governments due to their energy generation capability and ability to integrate with other systems [5,6]. In CSP systems, as depicted in Fig. 1, solar flux can be concentrated either along a line (utilizing parabolic trough collectors (PTC) and linear Fresnel collectors (LFC)) or at a focal point (employing methods such as cavity towers, parabolic dish collectors, and external receiver solar towers). The emergence of CSP systems can be attributed to several factors, notably their cost-effectiveness, integrative potential with other systems, operational flexibility, and substantial capacity for storing solar energy [7,8]. The operational capacity of CSP plants worldwide has experienced a noteworthy escalation. As reported by Conroy et al. [9], the operational capacity reached 5.8 GW by the end of 2018, which has since increased. Presently, according to Fig. 2, there are 6.36 GW of operational CSP plants globally, with an additional 2.46 GW under construction. Among various nations, China leads in CSP plant deployment, with 586 MW (Megawatts) of operational capacity and 1710 MW under construction. Following China, Spain, and the

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* Corresponding author.
E-mail address: mehdi.khatamifar2@jcu.edu.au (M. Khatamifar).

https://doi.org/10.1016/j.rser.2024.114497
Received 13 December 2023; Received in revised form 12 April 2024; Accepted 22 April 2024

Nomenclature

Greek Symbols

ϵ	Absorptivity
ρ	Reflectivity
τ	Transitivity
θ	Solar incident angle, °

Parameters

A	Surface area, m^2
a	Accommodation coefficient
d	Diameter, m
E	Emissive power, $\mathrm{W/m}^2$
F	View factor
h	Convective heat transfer coefficient, $\mathrm{W/(m^2 \cdot} K)$
J	Radiosity
q	Heat flux, $\mathrm{W/m}^2$
q_d	Solar irradiance considering cleanliness factor and reflections of the reflector, $\mathrm{W/m}^2$
R	Heat transfer resistance, K/W
T	Temperature, K

Subscripts

ab	Absorber
air	Air
am	Ambient
$cond$	Conductive heat transfer
$conv$	Convective heat transfer
en	Glass envelope
HTF	Heat transfer fluid
rad	Radiative heat transfer
ref	Reflective heat transfer
sky	Sky
sol	Solar

USA are notable for their utilization of CSP plants compared to other countries [10].

Efficient heat management stands out as a controllable determinant within CSP systems, contributing significantly to their effectiveness and cost-efficiency. Notably, different forms of losses constitute a pivotal concern within a CSP system, exerting a pronounced influence on their operational efficiency and overall energy production. These phenomena pertain to the optical and thermal dissipation at various stages of energy transfer, resulting in compromised efficiency, diminished energy yields, and escalated operational expenses [12]. Comprehensive knowledge and effective mitigation of losses assume paramount importance in the endeavor to optimize the efficiency, output, and economic feasibility of CSP systems.

In conventional scenarios, linear concentrated solar power (LCSP) systems commonly function within a single-axis tracking system. Consequently, incident solar rays frequently impinge upon the collector surface at an angle, inevitably leading to the manifestation of the cosine effect [13,14]. This effect culminates in a situation where the reflector can direct only a certain percentage (not 100%) of solar rays onto the designated receiver, thus entailing what is referred to as cosine losses [13–15]. Additionally, a fraction of the solar rays reflected from one extremity of the trough reflector cannot be effectively captured by the absorber tube, resulting in what is known as end loss [14,16]. The impact of end losses in LCSP systems is accentuated by the cosine effect, especially in regions at high latitudes and in situations where the length of such systems is limited. In such cases, the proportion of end losses relative to the overall energy collection becomes prominent [13,17,18].

A certain portion of the solar flux, which is reflected by the parabolic mirrors, is either reflected again by secondary reflections or is emitted due to the high temperature of the absorber. Additionally, another segment of the flux dissipates through direct interaction of the absorber or the receiver's cover with the ambient environment, facilitated by convective and conductive heat transfer mechanisms.

In LFCs, different forms of heat losses can contribute to different portions of solar heat flux depending on different conditions. In these systems, total heat loss can range between 50% and 9% of solar heat flux in non-evacuated and evacuated collectors, respectively [19]. Furthermore, in PTCs, the total heat loss is calculated to be almost 17% [20]. Interestingly, under different conditions, the total heat loss can exceed the heat gain of a PTC collector, reaching around 61% of solar heat flux [21].

Consequently, the significance of heat losses cannot be underestimated, as they exert a substantial adverse influence on the operational effectiveness of LCSP systems. This has led to an array of comprehensive research endeavors to delve into the multifaceted aspects of this phenomenon. This scholarly pursuit involves conducting experiments and numerical analyses on LCSP systems, focusing on the examination of losses [22–35]. It also includes proposing an experimental, analytical, numerical, and mathematical model for losses [36–43], to mitigate these losses and address their associated drawbacks.

Thus, the primary objective of this review is to delve into an examination of studies related to different forms of thermal losses in the context of LCSP systems. It will explore the mechanisms for heat losses across various types of PTCs and LFCs and encompass an analysis of presented models and evaluations pertaining to heat losses, recognizing their pivotal role in the performance of these systems. Additionally, this review will undertake a critical assessment of potential methodologies aimed at mitigating heat loss across various types of LCSP systems.

2. Classification of linear concentrated solar systems

As depicted in Figs. 3 and 4, this review is primarily structured with the systematic classification of research endeavors concerning heat loss phenomena within the context of PTCs and LFCs, which are the main LCSP systems. This categorization comprises a comprehensive analysis of heat loss occurrences across distinct configurations of these systems, encompassing those that employ simple tubular absorbers, compound parabolic collectors, and cavity receivers. In PTCs, tubular absorbers are typically positioned above the parabolic reflector. These absorbers, the most common type in PTCs, come in various structures, including uninsulated bare absorbers and those encapsulated within glazed coverings. These coverings feature a confined space sandwiched between the absorber and the enclosure, which is either filled with air or maintained in a vacuum state. Unlike that in PTCs, the use of simple tubular absorbers is not common in LFCs.

Contrasting this configuration, the compound parabolic collector (CPC) adopts a distinct structural arrangement, as illustrated in Fig. 2(*b*). Comprising two semi-parabolic reflectors, this design accommodates absorbers positioned predominantly at the lowermost region of these reflectors. Although this type of reflector is used as a primary reflector in PTCs, compound parabolic collectors are used as the secondary reflector in LFCs and are installed at the top of the linear Fresnel reflectors to reflect solar incidents that are not absorbed in the first reflection (Fig. 3(*b*)).

In a significant novelty for the tubular receiver concept, the linear cavity receiver introduces a novel approach in PTCs, as illustrated in (Fig. 2(*c*). This method leverages the cavity effect to optimize the separation between the passage through which the HTF flows and the immediate ambient environment. This innovative approach aims to mitigate heat losses more effectively. As indicated in (Fig. 3(*c*)

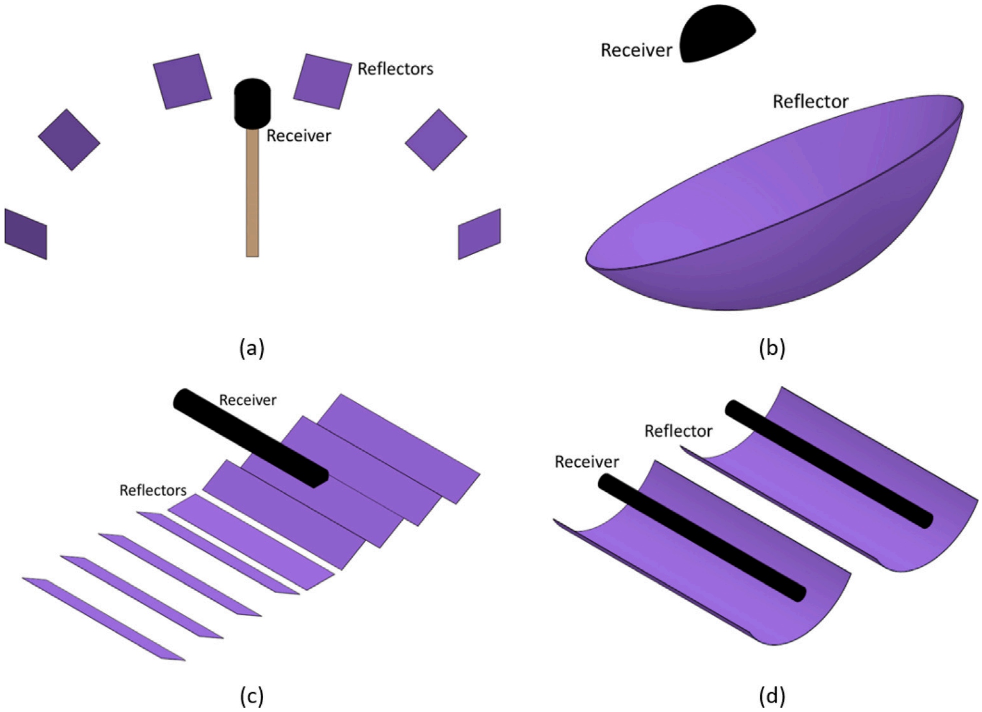

Fig. 1. Different CSP collectors: (a) External Receiver Solar Towers, (b) Cavity Collectors, (c) Linear Fresnel Collector (LFC), and (d) Parabolic Trough Collectors (PTC).
Source: Adapted from [3,7,11]

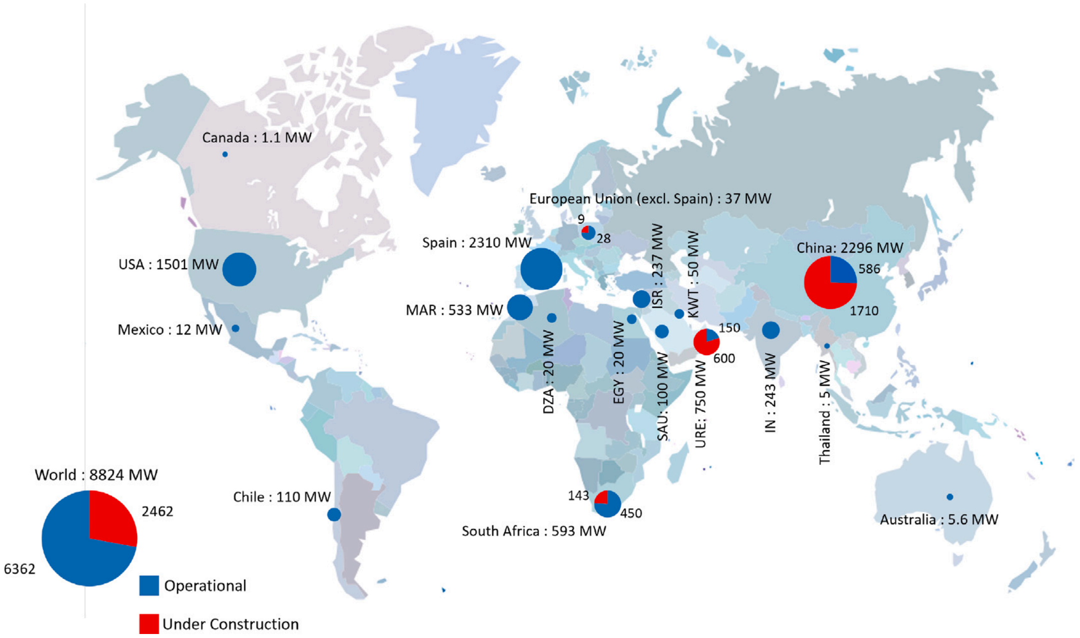

Fig. 2. CSP projects around the world.
Source: Data is collected by [10]

cavity receivers in LFCs differ from those in PTCs. The geometry of cavity receivers in LFCs is usually trapezoidal and used as a secondary reflector, while in PTCs, they typically serve to insulate the central absorbers from the ambient environment and trap the reflected flux.

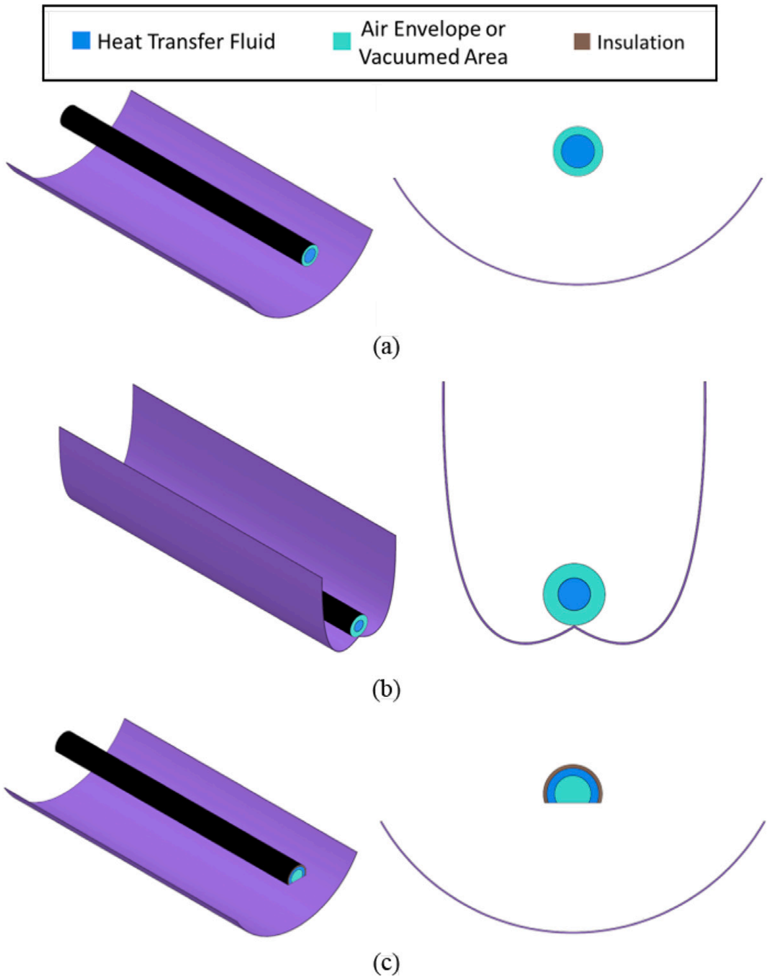

Fig. 3. Different structures of parabolic collectors: (a) Simple Absorber, (b) Compound Parabolic Collector, and (c) Cavity Receiver.

3. Loss mechanisms

3.1. Optical heat losses

In conventional LCSP systems, the utilization of single-axis tracking inherently gives rise to non-zero incident angles. As solar rays must impinge upon the parabolic trough surface perpendicularly, any deviation from the vertical reception of the solar ray results in an inability to absorb 100% of the solar radiation. This phenomenon (termed the ‘cosine effect’) gives rise to cosine losses calculated as follows [44],

$$q_{sol,total} = q_d \cos(\theta), \tag{1}$$

where $q_{sol,total}$ is the received solar flux, θ is the solar incidence angle and q_d is the solar irradiance considering the cleanliness factor and reflectance of the reflector.

As illustrated in Fig. 5, a solar ray irradiates a random point on the periphery of the reflector from point ‘W’, represented as point ‘R’ (thus the ‘WR’ ray). This ray is parallel to the Y-Z plane. Subsequently, the reflected light is directed from point ‘R’ to point ‘A’ on the absorber surface. Concurrently, another solar ray, denoted as the ‘SR’ ray, either lies on the ‘WRA’ plane or an arbitrary plane with angle of β respect to the Y-Z plane or the ‘WRA’ plane. The reflected light of this solar ray is designated as the ‘RB’ ray. As Fig. 5 shows, based on the reflectance laws the angle of reflection is equal to the angle of incidence, thus $\varphi_1 = \varphi_2$ and $\alpha_1 = \alpha_2$, indicating $\angle SRW = \angle ARB$. Therefore, the end losses of PTCs and LFCs are calculated as follows:

A) PTCs:

Based on the parabolic equation the height (Y coordinate) of an arbitrary point like ‘R’ is calculated as follows:

$$Y = \frac{Z^2}{4f}, \tag{2}$$

where f is the focal distance of the parabolic trough, and Y and Z are the coordinates of point ‘R’. The cosine effect engenders two distinct outcomes. First, due to this effect, a portion of the absorber, specifically the length denoted as ‘AB’, fails to receive direct solar radiation. Correspondingly, at the opposite end, a fraction of solar rays cannot be fully absorbed and subsequently reflects towards the sky, resulting in an equivalent length corresponding to the Displaced Line of Absorber (ΔL). This phenomenon is referred to as the ‘end loss’ [45] and ΔL is calculated as follows,

$$\Delta L = AB = RB\tan(\beta) = \frac{4f^2 + Z^2}{4f}\tan(\beta). \tag{3}$$

B) LFCs:

$$\Delta L = AB = BN - AN = RN\,(\tan(\varphi_2) - \tan(\alpha_2)) = \sqrt{d^2 + h^2}\,(\tan(\varphi_2) - \tan(\alpha_2)), \tag{4}$$

where d is the distance aligned to the Z-coordinate between point ‘R’ and the absorber, h is the height of the absorber from the reflector aligned to the Y-coordinate [46], and RN represents the normal vector of the tangent plane to the reflector surface at point N.

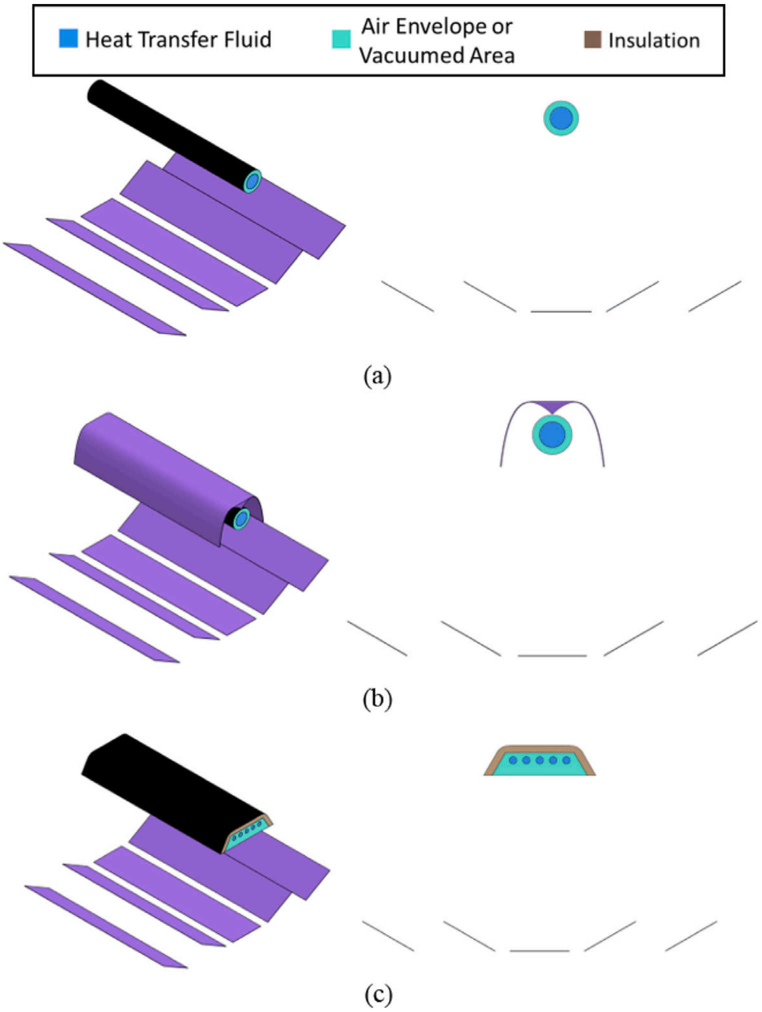

Fig. 4. Different structures of linear Fresnel collectors: (*a*) Simple Absorber, (*b*) Compound Parabolic Collector, and (*c*) Cavity Receiver.

3.2. Thermal losses

A comprehensive assessment reveals that the thermal losses within an absorber of a simple linear concentrated solar system encompass convective, radiative, and conductive heat dissipation. The mathematical modeling of these losses is underpinned by the following assumptions:

- The glass envelope is treated as semitransparent.
- A uniform temperature distribution is presumed for both the glass envelope and the absorber surfaces along the axial direction.
- Solar flux undergoes correction via factors accounting for the end loss, cosine loss, reflectivity of the reflector, and cleanliness.
- The absorber surface is characterized as a gray surface.
- Energy storage within the control volume is disregarded.

The heat transfer model of a tubular absorber of PTC or LFC is illustrated in Fig. 6 and the energy balance on the absorber is as follows,

$$q_{rad,ab-en} + q_{conv,ab-en} + q_{HTF} + q_{cond,bracket} + q_{rad,ab-sky} = q_{sol,ab}, \tag{5}$$

where $q_{rad,ab-en}$ is the radiative heat flux from the absorber to glass envelope, $q_{conv,ab-en}$ is the convective heat flux from the absorber to glass envelope, q_{HTF} is the absorbed heat flux by the HTF, $q_{cond,bracket}$ is the conductive heat flux which passes through the bracket and is lost, $q_{rad,ab-sky}$ is the radiative heat flux from the absorber to the sky, and $q_{sol,ab}$ is the solar flux that is absorbed by the absorber.

For the glass envelope, the energy balances of a linear concentrated solar system are as follows:

$$q_{rad,en-sky} + q_{conv,en-am} = q_{sol,en} + q_{rad,ab-en} + q_{conv,ab-en}, \tag{6}$$

$$q_{rad,ab-en} + q_{conv,ab-en} = q_{radial,cond,en}, \tag{7}$$

$$q_{sol,ab} + q_{sol,en} + q_{sol,en,ref} = q_{sol,total}. \tag{8}$$

where $q_{rad,en-sky}$ represents the radiative heat flux from the glass envelope to the sky, $q_{conv,en-am}$ is the convective heat flux from the glass envelope to the ambient, $q_{sol,en}$ is the absorbed heat flux by the glass envelope, $q_{radial,cond,en}$ is the conductive heat flux passing through the glass envelope wall radially, and $q_{sol,en,ref}$ is reflective heat flux from the glass envelope.

The convective heat transfer between the absorber's outer surface and inner glass envelope is calculated as follows [47]:

$$q_{conv,ab-en} = \pi d_{ab} h_{ab-en} (T_{ab} - T_{en}) \tag{9}$$

where T_{ab} and T_{en} represent the absorber and glass envelope temperatures, respectively, d_{ab} represents the diameter of the absorber, and h_{ab-en} is the overall convective heat transfer coefficient which can be calculated under various conditions, including vacuum, natural convection, and forced convection [47].

Fig. 7 shows the heat transfer resistance network of the absorber and glass envelope of a linear concentrated solar system. This network and its correlations are formulated by Holman [80], in which where

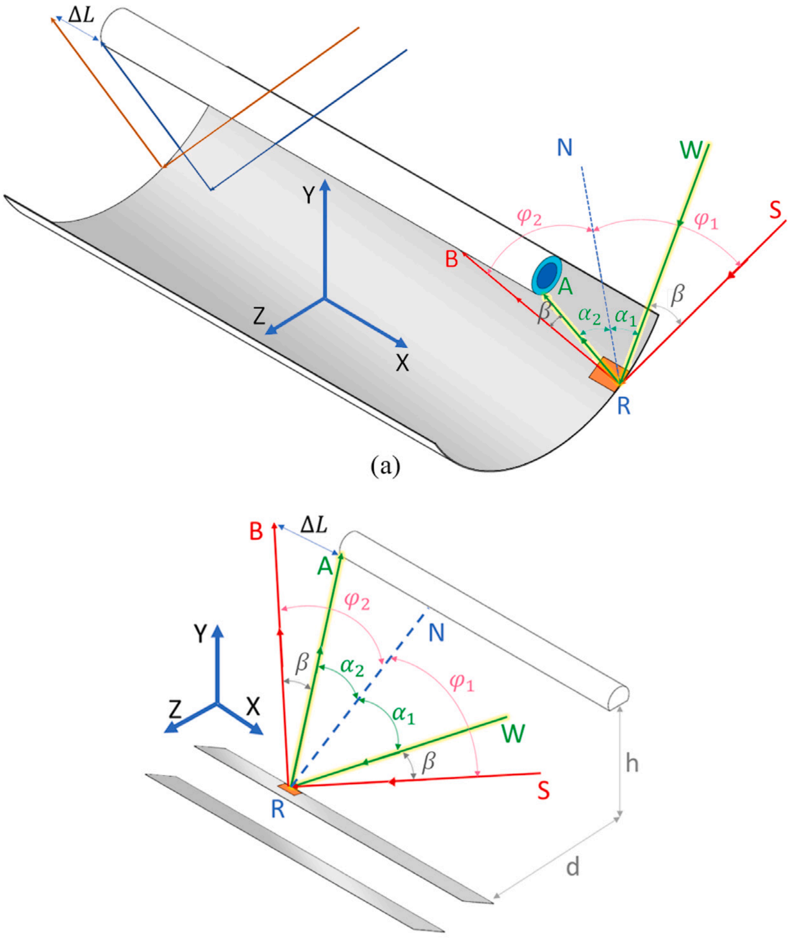

Fig. 5. Schematic of the end loss geometry: (a) PTC, (b) LFC.

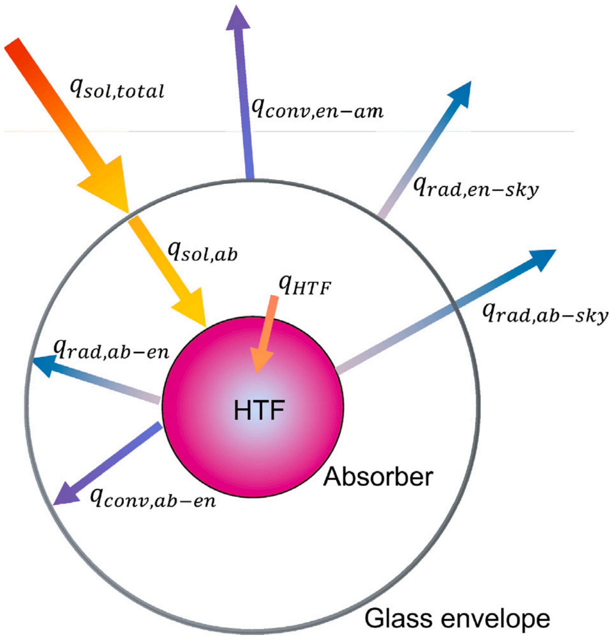

Fig. 6. Heat transfer model of a tubular absorber of linear concentrated system.

Table 1
The definitions of the radiative heat transfer resistances.

Parameter	Definition
$R_{rad,ab}$	$(1-\epsilon_{ab})/(A_{ab}\epsilon_{ab})$
$R_{rad,ab-sky}$	$1/(A_{ab}F_{ab-sky}\tau_{en})$
$R_{rad,ab-en}$	$1/[A_{ab}F_{ab-en}(1-\tau_{en})]$
$R_{rad,en}$	$\rho_{en}/[A_{en}\epsilon_{en}(1-\tau_{en})]$
$R_{rad,en-sky}$	$1/(A_{en}F_{en-sky}\tau_{en})$

$R_{conv,ab-HTF}$ is the convective heat transfer resistance between the absorber and HTF, $R_{cond,ab}$ is the conductive heat transfer resistance of the absorber, $R_{rad,ab}$ is the radiative heat transfer resistance of the absorber, $R_{rad,ab-en}$ is the radiative heat transfer resistance between the absorber and the glass envelope, $R_{conv,ab-en}$ is the convective heat transfer resistance between the absorber and the glass envelope, $R_{rad,ab-sky}$ is the radiative heat transfer resistance between the absorber and the sky, $R_{rad,en}$ is the radiative heat transfer resistance of the glass envelope, $R_{cond,en}$ is the conductive heat transfer resistance of the glass envelope, $R_{rad,en-sky}$ is the radiative heat transfer resistance between the glass envelope and the sky, and $R_{conv,en-sky}$ is the convective heat transfer resistance between the glass envelope and the sky. Furthermore, J is radiosity, τ is transitivity, F is the view factor, ϵ is absorptivity, and ρ is reflectivity, respectively.

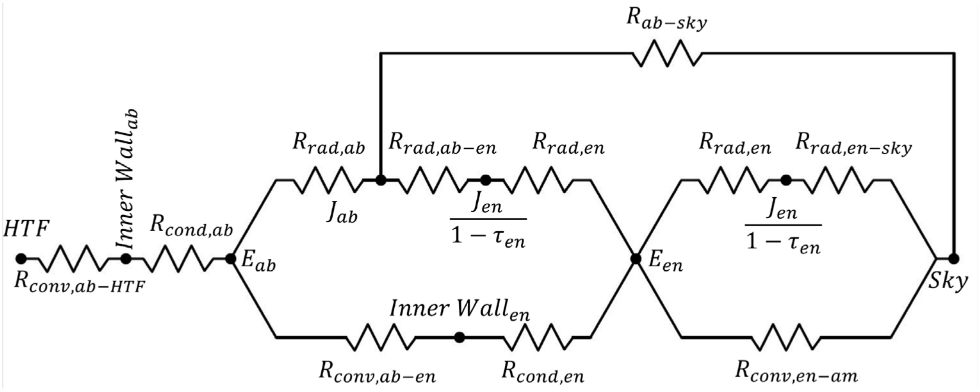

Fig. 7. The heat transfer resistance network of the absorber and glass envelope of a linear concentrated solar system.

Table 2
Comparison with other reviews.

Ref.	Systems		Impacts of factors on the performance			Impacts of factors on the thermal loss		
	PTC	LFC	HTFs	Geometry or structure	Material	HTFs	Geometry or structure	Material
[11,48–56]	✓		✓	✓				
[57]	✓			✓				
[58]	✓							
[59]	✓	✓		✓				
[60]	✓	✓	✓	✓			✓	
[61]	✓			✓	✓			
[62]	✓							
[63–68]	✓		✓	✓	✓			
[69]	✓				✓			
[70]		✓		✓				
[71]	✓	✓	✓					
[72–74]	✓	✓	✓					
[75–77]	✓		✓					
[78]	✓		✓	✓	✓	✓	✓	✓
[79]	✓		✓	✓	✓	✓	✓	✓
Current Study	✓	✓				✓	✓	✓

Resistances are defined in Table 1, in which $A_{ab}F_{ab-en} = A_{en}F_{en-ab} = A_{en}$, $A_{en}F_{en-sky} = A_{en}$, and $A_{ab}F_{ab-sky} = A_{en}$. A_{ab} is the area of the absorber surface, F_{ab-en} is the view factor from the absorber to the surface of the glass envelope, A_{en} is the area of the glass envelope surface, F_{en-ab} is the view factor from the glass envelope to the absorber surface, F_{en-sky} is the view factor from the glass envelope to the sky, and F_{ab-sky} is the view factor from the absorber to the sky. By solving the radiative resistance network and utilizing the radiative properties of the glass envelope and absorber, the radiative heat losses are calculated.

4. Existing reviews involving LCSPs

In the last decade, various reviews have been conducted on LCSP systems to assess the studies in this area from different perspectives [11,48,57,58].

Garcia et al. [81] reviewed the history of launched PTC projects in the past century. Pranesh et al. [79] and Tian et al. [59] studied published literature on various aspects of CPCs and their applications. Kalidasan et al. [60] reviewed the technologies of cavity receivers in PTCs and LFCs. Fredriksson et al. [61] compared different modern PTCs for potential use in large-scale plants. Jebasingh and Herbert [62] investigated the performance and applications of PTCs. Saini et al. [63] reviewed PTCs from technical, economic, and environmental perspectives, including aspects such as geometry and HTFs, and compared these systems with other renewable energy sources. Hafez et al. [64] reviewed different design parameters, mathematical methodologies, and simulations conducted for PTC design. Jamali [69] studied various research on reflectors used in PTC plants. Bellos [70] summarized existing designs of LFCs, enhancement solutions, and their applications.

Numerous reviews have been published addressing solutions for enhancing LCSP systems [49,50,65–67,82]. Ajbar et al. [68] investigated studies that assessed different HTFs and PTC configurations to improve system efficiency. Akbarzadeh and Valipour [51] assessed various numerical and experimental studies focusing on coating materials, geometrical enhancements, and nanofluids to enhance PTC performance. Sharma and Jilte [52] reviewed studies proposing passive solutions, such as geometrical changes, to improve PTC performance. Allam et al. [53] studied different uses of inserts in PTC absorbers as geometric enhancement solutions.

HTFs are another interesting area of research, and many reviews have investigated this subject [54,55,71–73]. Sokhansefat et al. [75] reviewed studies using Al_2O_3 oil nanofluids as HTFs. Panduro et al. [76] examined research on nanofluid usage as HTFs, with a focus on their stability and preparation. Tiwari et al. [74] compared studies introducing various models of nanofluids for use in PTCs, revealing that hybrid nanofluids improve system performance more than mono nanofluids. Krishna et al. [77] conducted a comprehensive study of the latest research pertaining to the utilization of nanofluids as HTFs.

It is worth noting that, while many reviews briefly mention thermal losses as a disadvantage of LCSP systems or cover this parameter in a general sense, it implies that heat losses are often analyzed as a secondary factor in overall thermal performance analysis, and various perspectives on this parameter are not thoroughly explored.

As summarized in Table 2, different review studies on LCSP systems have focused on various solutions to improve the efficiency of these systems. However, these solutions can be revisited from a different perspective, specifically considering the aspect of heat losses. Among numerous reviews, only one study [78,79] delves into heat losses from

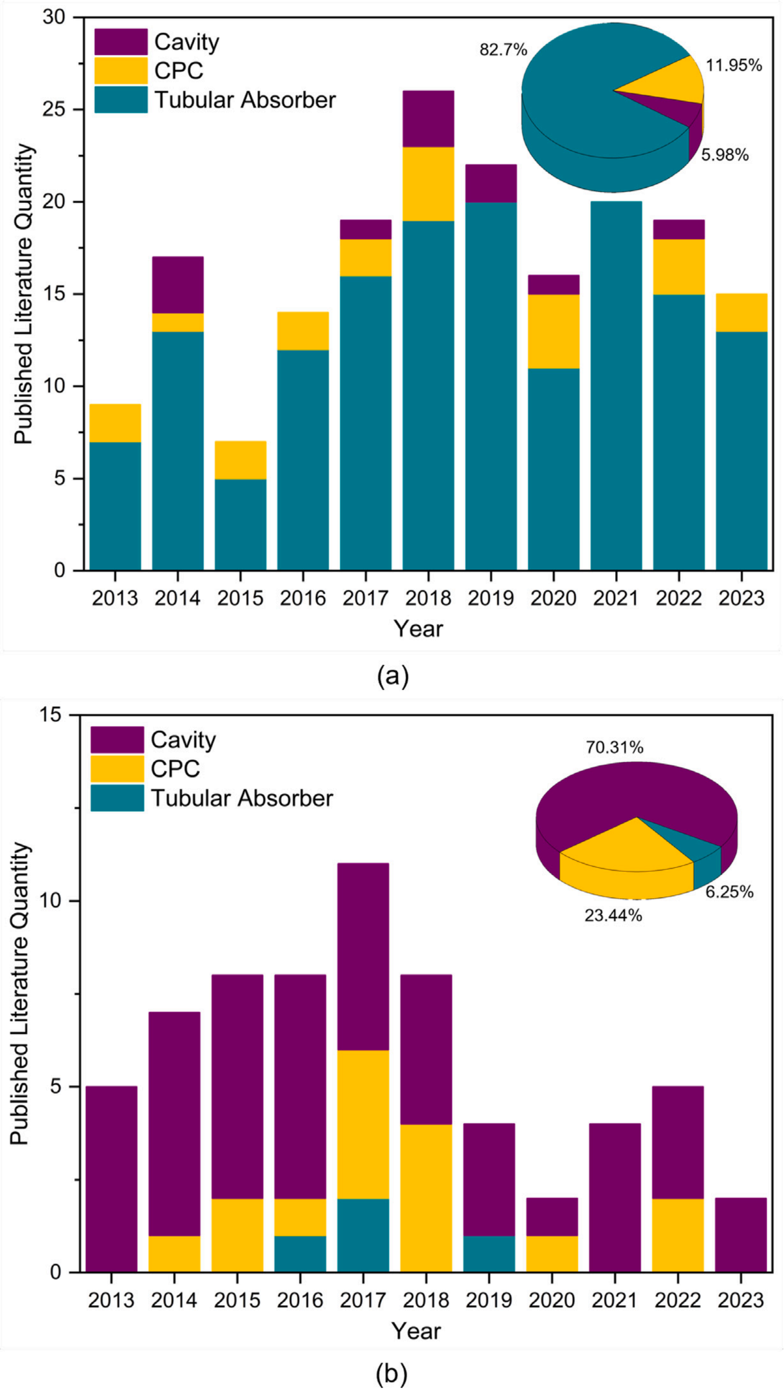

Fig. 8. The quantitative analysis of the published literature in the past ten years: (a) PTC, (b) LFC.

alternative angles by focusing on them beyond the routine approaches of overall thermal performance analysis, particularly for PTCs, briefly.

This observation motivates this study to review past research that concentrates more specifically and in more detail on the thermal losses of LCSP systems.

5. Overtime quantitative analysis of the published literature

Given the significant role of PTCs and LFCs within the solar energy sector, numerous studies have investigated the heat losses of these systems, as highlighted by Fig. 8. In the case of PTCs (Fig. 8(a)), the number of published works has shown two distinct fluctuations during this period. The initial surge, from 2013 to 2018, was followed by a decline in 2015. Since 2015, following the Paris Agreement to tackle climate change and address its associated challenges, research on PTCs has seen a dramatic increase. Subsequently, from 2018 to 2023, although there was a rebound in the number of published research following a dip between 2018 and 2020, the total count of published research did not surpass the 2018 level. Although different studies have explored a diverse range of system types between 2017 and 2020, their primary focus in the study of heat loss has been on tubular absorbers and CPCs.

In contrast, research on LFCs (Fig. 8(b)) has shown different trends. The number of studies related to heat losses of LFCs increased from 2013 to 2017, reaching its peak in 2017. Subsequently, research on

Table 3
Relationships between different parameters and heat losses.

Factor	Ref.	Relationship with heat loss
	PTC	
Absorber temperature	[20,23,35,40,42,83–114]	Direct
Geometrical parameters	Bhuyan et al. [41], Kumar and Kumar [35], Patil et al. [85], Patil et al. [87], Mohamad et al. [88], Guo et al. [115], Patil et al. [111]	Direct
Emissivity of absorber	Bhuyan et al. [41], Xu et al. [36], Kumar and Kumar [35], Maatoug et al. [104], Garg et al. [109], Shinde et al. [112]	Direct
Annulus vacuum pressure	Setien et al. [23], Xu et al. [36], Peng et al. [101], Pierucci et al. [116], Souliotis et al. [110]	Direct
Wind velocity	Xu et al. [36], Manikandan et al. [20], Kumar and Kumar [35], Patil et al. [87], Chandra et al. [92], Peng et al. [101], Agagna et al. [117], Serrano-Aguilera et al. [118], Xu et al. [119], Xu et al. [120], Liang et al. [121]	Direct
Flow rate of heat transfer fluid	Bezaatpour et al. [122], Abed et al. [123], Khandelwal et al. [100], Silva et al. [124], Okonkwo et al. [125], Xu et al. [119]	Indirect
Heat transfer inlet temperature	Zhao et al. [126], Okafor et al. [98], Sivaram et al. [127], Patil and Shekhawat [128], Hassan et al. [103], Thappa et al. [129], Beemkumar et al. [130], Xu et al. [119], Bellos et al. [131]	Direct
	LFC	
Absorber temperature	[19,132,132–162]	Direct
Geometrical parameters	[135,141,144,148,151,154,156,163–169]	Direct
Emissivity of absorber	–	Direct
Annulus vacuum pressure	–	Direct
Wind velocity	[141,149,153,170,171]	Direct
Flow rate of heat transfer fluid	–	Indirect
Heat transfer inlet temperature	Mokhtar et al. [137], Tsekouras et al. [165]	Direct

heat losses for this system declined and reached a minimum in 2023. This could be attributed to the reduced utilization of LFCs compared to PTCs. Similarly to PTCs, the variety of studied systems has become more limited, primarily focusing on cavity receivers, which are the most developed systems in this category.

6. Parametric analysis of heat losses

In the past ten years, a comprehensive understanding of linear concentrated solar technology has been diligently pursued in different research. Their efforts have been aimed at enhancing the overall performance of these systems by presenting innovative solutions. To this end, an array of studies focused on mitigating thermal losses have been conducted, a pivotal factor with undeniable influence on the efficiency and sustainability of LCSP systems. This is evident from Table 3, which highlights various research endeavors dedicated to examining distinct factors that impact heat loss. By establishing a cause-and-effect relationship between each factor and the extent of heat loss, these studies have contributed to a deeper understanding of the performance of such systems.

Besides design parameters such as geometrical aspects, absorber coating materials affecting emissivity, vacuum pressure, HTF flow rate and temperature, and ambient conditions like wind velocity play a crucial role in LCSP systems. These factors must be considered to reduce heat loss and optimize the utilization of solar energy, thereby enhancing system efficiency.

In addition to the parameters mentioned, existing scholarly research has thoroughly investigated various additional variables. These factors encompass the study of alternative HTFs, the use of magnetic fields, the evaluation of surface roughness effects, the optimization of receiver orientation, and the analysis of fluctuations in ambient temperature. Collectively, these efforts contribute to a more comprehensive understanding of the complex interactions among diverse elements within LCSP systems.

Fig. 9 indicates the thematic classification of research on heat losses in LCSP systems. As evident, overall thermal analysis, including the calculation or measurement of heat losses as an effective factor on LCSP systems besides other factors, or modeling of heat loss concerning factors like absorber temperature, and other fundamental and environmental parameters, comprises the largest portion of thematic classification in PTCs and LFCs.

In PTCs (Fig. 9(a)), research focuses on materials aimed at improving absorbance and reducing radiative heat losses, and studies on geometrical and positional features such as absorber dimensions, the use of fins, or novel geometries. In contrast, studies on materials to reduce thermal losses have not been found in LFCs (Fig. 9(b)). Additionally, research on HTFs constitutes the smallest portion for both PTCs and LFCs.

7. Tubular absorber

7.1. Parabolic trough collector

The losses of PTCs with simple tubular absorbers have been studied in three ways. Different research has assessed the overall thermal performance of this type of absorber, including losses, as effective factors, besides other important considerations such as efficiency [99,100,104–106,115,118,129,172–188]. Additionally, various perspectives have been taken into account in these studies, such as location [124,189–191], different times of day and night [127,192–194], use of different HTFs [103,125,128,195–206], structural and geometrical improvements [116,207–215], and utilization of different

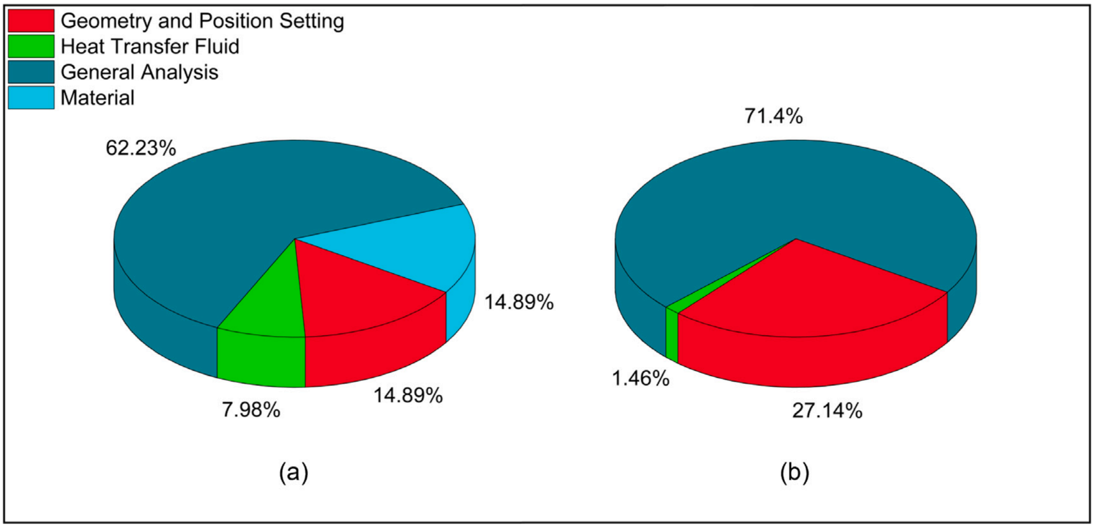

Fig. 9. The thematic analysis of the published literature in the past ten years: (a) PTC and (b) LFC.

materials for coating and absorption [101,216–220]. These investigations have shed light on the substantial influence of these factors on the losses.

Other studies have proposed different solutions to mitigate losses and improve efficiency, consequently enhancing the performance of PTCs with simple tubular absorbers. These solutions include using HTF with better thermal characteristics [221], structural and geometrical improvements [107,130,222–225], coating or manufacturing materials [92,226], and in some studies, the combination of different solutions [123,227–229]. The third approach involves research that specifically studies losses to either know different forms of losses better or propose solutions to reduce them. In this regard, Manikandan et al. [20] conducted a study aimed at quantifying the heat loss in a non-evacuated PTC, considering both uniform and non-uniform flux conditions. Under uniform flux conditions, it was observed that free and forced convection rates were 1.5%–5% and 4%–13% higher, respectively, compared to non-uniform flux scenarios at varying wind velocities. When the receiver length was below 10 m, employing a single glass cover was deemed cost-effective. However, in the case of longer receiver lengths, an increase in the temperature differential between the absorber and the surrounding environment led to elevated rates of heat loss.

In another research, Patil et al. [85] studied the heat loss from a non-evacuated receiver using numerical methods. They investigated the effect of the absorber average temperature, non-uniformity distribution of temperature on the absorber, receiver orientation, and diameter ratio of the glass envelope and absorber. This research revealed that heat loss reduces as the temperature non-uniformity increases. But, by increasing the orientation from zero (parabolic reflector facing to the sky) to 90° (the reflector radius is perpendicular to the sky) heat loss increases. The study also identified an optimum radius ratio (1.375) in the glass envelope diameter at 24 cm, resulting in minimum heat loss. In this ratio, convection heat loss does not occur, and the heat dissipates through conduction only.

HTF, as a reliable solution to reduce heat losses, has also been modified [21,230]. Brahim and Jemni [231] investigated the utilization of CuO and CeO_2 nanoparticles in Syltherm-800 and Therminol-VP1 HTFs. They found that Syltherm-800 with an 8% volume fraction of nanoparticles showed a maximum heat loss reduction of 14.68%, whereas Therminol-VP1 with the same nanoparticle volume fraction achieved a reduction of 5.5%. Heat loss reduction was directly proportional to nanoparticle volume fraction and inversely proportional to the inlet temperature of the nanofluids. Notably, the impact of inlet temperature on heat loss reduction was more significant below 400 °C compared to temperatures above 400 °C.

Bezaatpour et al. [122] assessed the effects of rotational speed and an external magnetic field on heat loss reduction in a solar thermal system incorporating a rotary absorber and nanofluid. Their simulations revealed that an increase in rotation speed led to a marginal rise in heat loss, while the application of an external magnetic field notably decreased heat loss. The optimal conditions for achieving the minimal total heat loss were identified as a magnetic field intensity of 0.1 T (Tesla) and a rotational speed of the rotary absorber set at 0.4 rad/s. Remarkably, under these optimized conditions, a substantial reduction in the total heat loss by 37.42% was observed.

In addition to the previously discussed parameters, the geometrical and structural improvements of receivers also play a crucial role in losses. Both the geometrical properties improvement of receivers and the adoption of novel geometries can help compensate for heat losses [86,232].

Patil et al. [87] optimized the ratio between the absorber and glass envelope diameters to minimize heat loss. Additionally, they examined the influence of wind velocity and temperature uniformity on heat loss. The outcomes indicated that the critical diameter ratio for achieving minimum heat loss, with absorber diameters ranging from 33 mm to 102 mm, lays within the range of 1.5 to 1.25. In contrast, Mohamad et al. [88] evaluated the effects of single- and double-glazed envelopes on heat losses. Their findings demonstrated that an increase in absorber diameter amplified the rate of heat losses.

Zhang et al. [233] explored the incorporation of alternative geometries like U-tube absorbers within a PTC, investigating the impact of natural and forced convection as well as radiation on heat losses. They found convection and radiation accounted for 20.76% and 33.6% of total heat flux losses under calm and windy conditions, respectively.

Fins were employed to enhance heat transfer between the HTF and absorber. Olczak and Olek [234] introduced fins and found heat loss remained below 2.5%, contingent on fin orientation. Wang et al. [89] studied the thermal performance of a single-pass all-glass finned PTC, showing a 15% lower heat loss at 200 °C compared to Sanle-3 [235], but 13% higher than Solel's UVAC3 and 55% higher than Schott's PTR70 [89].

Ahmed et al. [236] introduced an innovative PTC receiver design with toroidal rings of varying sizes integrated into a 38 mm diameter absorber spaced at 76 mm intervals. Their experiments showed significant improvements in heat loss reduction compared to conventional designs. Toroidal rings enhanced heat transfer between the absorber and HTF, leading to lower absorber surface temperatures. Using thicker rings (for instance, 8 mm) reduced radiative heat loss from 19.14 W to 13.69 W and increased convective heat loss from 32.11 W to 43.94 W. Utilizing 2 mm rings resulted in radiative heat loss reductions from 57.37 W to 49.01 W and convective heat loss changes from 33.02 W to 55.10 W, highlighting the impact of ring thickness on heat loss mitigation.

Utilizing radiation shields is another geometrical enhancement that can reduce thermal losses, several studies by Wang et al. [93–96] have introduced innovative radiation shields to mitigate these losses and elevate system efficiency.

In their pioneering study, Wang et al. [93] introduced an evacuated receiver design featuring a radiation shield to reduce heat dissipation. This shield, a 120° sector of an 87 mm diameter cylinder, was strategically placed concentrically around the absorber, facing sunlight. The use of an evacuated receiver mitigated the impact of wind velocity on heat loss. Despite the radiation shield's temperature increasing with higher solar irradiances, its effect on absorber heat loss was minimal. Importantly, employing this radiation shield led to a notable 19.1% reduction in heat loss compared to traditional evacuated receivers.

Subsequently, Wang et al. [94] extended their explorations employing an 80 mm diameter radiation shield. This endeavor resulted in a striking 35.9% enhancement in heat loss reduction in comparison to conventional receiver configurations. In a distinct context, Wang et al. [95] directed their focus towards the integration of an 87 mm diameter radiation shield with a 120° sector in a commercial PTC employing molten salt as the HTF. Their findings underscored the considerable potential of the radiation shield, revealing a substantial reduction in heat loss in the PTC equipped with this enhancement. Impressively, this heat loss reduction reached an impressive 24% when the absorber temperature attained 600 °C.

Following their investigations, Wang et al. [96] conducted a numerical and experimental study to further explore the effectiveness of radiation shields. They examined two different PTCs, one with a coated sun-facing outer surface and the other without, each equipped with radiation shields of varying sector angles. Their findings showed that at an absorber temperature of 600 °C, the PTC with the uncoated radiation shield experienced a 24.2% reduction in heat loss, while the coated counterpart demonstrated a slightly lower reduction of 23.4%. The impact of different sector angles on heat loss was more noticeable at higher absorber temperatures. For temperatures below 300 °C, variations in sector angles resulted in negligible differences in heat loss reduction. However, as temperatures exceeded 400 °C, distinct sector angles began to have more significant effects. Notably, at 600 °C, the 60° sector angle led to the highest heat loss reduction, while the 180 °C sector angle had the least impact on heat loss.

The roles of absorber coating, insulation, and radiation shields within solar receivers are pivotal in curtailing heat losses and enhancing overall efficiency. As a result, a multitude of studies have diligently aimed to minimize heat losses and optimize system performance.

Zhao et al. [126] investigated different absorber configurations within a row of PTCs and compared them to using a single material. Multiple absorbers within each PTC significantly reduced total heat loss, achieving up to a 30.5% reduction at 560 °C with an average reduction of 29.3%. Mahendra et al. [114] proposed a half-mirror coating with high reflectivity. This coating selectively absorbed a minimal fraction of solar flux, allowing most solar energy to reach the HTF flow tube while reflecting a substantial portion of emitted radiation. Using a coating with a 180° circumferential heat mirror angle resulted in up to a threefold decrease in total heat loss compared to a non-coated glass envelope. Additionally, this coating improved thermal efficiency by 12%.

In another study, Wang et al. [90] introduced a novel combination of a vanadium dioxide-based thermochromic coating and an aluminum-based radiation shield integrated with a solar absorber component in a PTC setup. They found that the thermochromic layer enabled intrinsic self-regulation of spectral selectivity traits, leading to a significant reduction in heat losses, especially at high absorber temperatures where radiative heat dissipation is critical.

Specifically, at absorber temperatures of 600 °C, the inclusion of the thermochromic coating resulted in an impressive 18.2% reduction in overall heat loss in PTCs with tubular absorbers. Moreover, the synergistic effect of combining the thermochromic coating with the radiation shield led to a substantial 41% reduction in heat loss, highlighting the effectiveness of this dual-pronged approach in enhancing PTC performance.

Similarly, Al-Ansary and Zeitoun [91] presented an innovative methodology involving insulation integration within the solar receiver. The infusion of insulation with thermal conductivity spanning the range of 0.03 W/m^2 K to 0.09 W/m^2 K, strategically positioned within the solar-receiving annular gap, yielded a marked reduction in heat loss ranging from 12% to 15%. This intervention correlated concomitantly with an augmentation of efficiency spanning from 1.8% to 6.4%, underscoring its substantive contribution to thermal enhancement.

As listed in Table 4, there are other studies involving the analysis of impacts of different factors on the overall performance of PTC with a tubular absorber besides different forms of losses.

7.2. Linear Fresnel collector

Although there is some research on LFCs with simple tubular absorbers [144,249,250], using this type of absorber is not common in these collectors. Therefore, only a few studies have evaluated the heat loss of simple tubular absorbers. Hussain and Lee [251] compared the performance of a simple tubular absorber in LFCs and conical solar receivers. Their results showed that the heat losses of the absorber in the conical receiver are higher than in LFCs. Perini et al. [252] investigated the performance of a double-axis tracking LFC. Their results revealed that the low solar absorptance of the absorber and thermal losses represented 33% and 6% of the total heat losses, respectively.

8. Compound parabolic collector

8.1. Parabolic trough collector

CPCs have been extensively analyzed for their thermal performance [110,253–258], heat transfer fluids (HTFs) [259,260], and geometric/structural features [120,131,261–264]. Optimal geometric and structural properties, such as truncation and concentration ratios, are crucial for reducing losses. Higher height-to-width ratios in CPCs require more material for production, but shorter heights do not compromise performance. The truncation ratio compares the actual height to that of a complete CPC [265]. The concentration ratio can be defined as the ratio of aperture to absorber area [266] or the ratio of solar radiation entering the collector to that received by the receiver [267].

In this regard, Francesconi and Antonelli [108] studied a 45° tilted CPC panel with seven concentrators, noting consistent thermal efficiency across most but higher heat loss for the lowest concentrator. They proposed using external double glass to reduce thermal losses by 3 W to 5 W at temperatures below 293 K, with higher truncation values correlating to lower thermal loss for upper concentrators. Antonelli et al. [268] developed a method to estimate thermal losses in CPCs, comparing flat and circular receivers. Tubular receivers had higher specific heat loss due to shorter characteristic length, while flat receivers had greater total heat loss because of larger surface area. Circular receivers had higher convection heat loss, unaffected by tilt angle. Increasing absorber diameter to 30 mm improved convective heat transfer, with minimal additional impact beyond that size.

Garg et al. [109] analyzed CPCs, derived a Nusselt number correlation influenced by parameters like temperatures, wind heat transfer coefficient, and insulation thickness. Zhao et al. [269] proposed integrating an aerogel layer to reduce heat losses. Yuan et al. [270]

Table 4
Previous studies involving heat losses of PTCs with tubular absorbers (Note: Exp = Experimental, Num = Numerical, Anal = Analytical).

Ref.	Method	Absorber insulation	Findings and remarks	Heat loss
Heat transfer fluid				
[237]	Num	Evacuated	Simultaneous employment of dual heat transfer fluids in PTC: • 0.61% to 7.67% overall efficiency improvement.	33.1% to 50.1% heat loss reduction compared with the conventional PTC.
[238]	Num, Anal	Evacuated	Proposing mathematical model for PTC performance and nanofluid heat transfer analysis: • Water+PEO+1%CNT nanofluid exhibits superior performance.	Nanofluids substantially reduce heat loss compared with water (86%, 76%, and 66%) and molten salt (79.15%, 64.34%, and 48.47%).
[228]	Num	Evacuated	Thermal, thermodynamic, and exergoeconomic assessment of a PTC using various nanofluids: • Maximum exergy efficiency attained: oil, Al_2O_3, and Cu - 74.4%; SWCNT - 79.9%.	22% heat loss reduction by using a glass cover at low Reynolds numbers.
[188]	Num	Evacuated and Bare	Modeling direct steam generation in a 12 m length PTC using a two-fluid approach: • 506 K to 525 K absorber surface temperature for 30 bar operating pressure.	95 W/m^2 average heat loss.
[239]	Num	Non-evacuated	Comparing CuO-water nanofluids with pure water as heat transfer fluid in a PTC: • Efficiency increases by 0.444%, 1.26%, and 2% when nanofluid concentration ratios vary at 1%, 3%, and 5%, respectively, compared with pure water.	Heat loss decreases by 4.44%, 12.6%, and 20% as the nanofluid concentration ratios vary at 1%, 3%, and 5%, respectively, compared with pure water.
Structural and geometrical improvement				
[240]	Num	Non-evacuated	Impact of partially metal foam use on PTC: • Nusselt number and collector efficiency improvement.	45% heat loss reduction.
[241]	Exp	Evacuated	Testing a rotatable axis tracking PTC: • Efficiency increment from 41.4% to 49.6%.	10.3% cosine loss diminishing.
[242]	Exp	Evacuated, Non-evacuated	Suggesting the adoption of an elliptical absorber over a traditional circular absorber: • 82.86% Collector's effective heat transfer rate increment.	89.05% thermal loss reduction compared with the circular absorber.
[243]	Exp, Num	Evacuated	Utilizing capillary heat Pipes in PTC applications: • 33% increment in overall efficiency.	46.55% heat loss reduction in the novel system.
[244]	Num	Evacuated	Analyzing PTC with multiple heat transfer tubes: • 0.656% thermal efficiency enhancement and 26.88% heat transfer coefficient in the four heat transfer tube arrangement.	5.63% thermal loss decrement in four heat transfer tubes.
[245]	Num	Evacuated	Analyzing and optimizing ribbed absorber in PTC: • The heat transfer enhancement from 57% to 225%.	The heat loss reduction from 6.4% to 79.3%.
[102]	Num	Evacuated and Non-evacuated	Utilizing the double glass receiver to enhance the performance: • Efficiency improvement especially at high temperatures.	Heat losses decrement from 574.3 W/m to 257.6 W/m.
[246]	Num	Evacuated	Proposing a novel PTC with a 120° angle sector inner transparent radiation shield: 0.93% and 4.42% thermal efficiency enhancement.	15.7% and 14.9% heat loss reduction of the novel receiver in absorber temperature of 400 °C and 600 °C, respectively.
[130]	Exp	Evacuated	Exploring the glass and reflective stainless-steel sheets with thermal storage in a PTC system: • Average PTC efficiency: glass 40.93%, steel 37.41%. • Overall system efficiency: glass 38.35%, steel 35.36%.	• Glass PTC's heat loss coefficient: 2.71 W/m^2 to 1.02 W/m^2. • Stainless steel PTC's heat loss coefficient range: 2.32 W/m^2 to 0.99 W/m^2 K.
[117]	Exp, Num	Evacuated	Utilizing spherical pins in a PTC absorber: • 4.106% overall efficiency enhancement.	• The highest decrease in thermal loss: 9.317% for 5 pins at 0.03 m spacing along the tube. • The lowest decrease in thermal loss: 2.987% for 5 pins at 0.1 m spacing.
Material				
[97]	Exp, Num	Evacuated	Performance of hybrid PTC with photovoltaic panels (PV) and reflective coating: • The exergy efficiency improved by up to 14.3%. • The thermal efficiency improved by up to 13.0%.	• The reflective coating under PV reduced heat loss by more than 5% at 600 °C. • The reflective coating on the upper half cylinder and under PV reduced heat loss by up to 44%.

(*continued on next page*)

Table 4 (*continued*).

Ref.	Method	Absorber insulation	Findings and remarks	Heat loss
[247]	Num	Evacuated	Investigation of using double coating with different properties on the outer surface of the absorber: • Collecting efficiency improvement from 64.7% to 68.1% by double-selective-coated receiver.	31.1% heat loss reduction by the double-selective coated receiver compared with the Schott PTR70 receiver.
[248]	Num	Evacuated	Utilizing heat-reflecting coating film and mirrors on the top half of absorber in different configurations: • The maximum optical efficiency improvement is 0.23% when either the inner or outer glass envelope is coated, and mirrors are used simultaneously in the configuration.	Maximum 2.72% reduction in total thermal loss with inner glass envelope coating.

found a transparent Ethylene tetrafluoroethylene foil reduced heat loss coefficient from 1.561 to 0.907 W/m^2 K, further decreasing by 0.18 W/m^2 K with sealed gaps.

Incorporating evacuated capillary tubes, Xu et al. [119] introduced an innovative CPC incorporating evacuated capillary tubes to target convective heat loss. By isolating capillary tubes within smaller cells, they aimed to minimize airflow space and reduce heat loss compared to flat plate collectors. The system also featured a top glass cover and bottom insulation layer to further optimize performance by shielding the receiver from the environment. Their experiments revealed that despite a 3.3-fold increase in solar irradiation intensity causing a 3 W rise in heat loss, a fourfold increase in air velocity led to only a marginal 0.5 W rise in heat loss. Variations in glass thickness had minimal impact on heat loss, while thicker insulation layers significantly reduced it. Furthermore, increasing the mass flow rate of the HTF resulted in a reduction of 3 W in heat loss, whereas raising the HTF inlet temperature led to an increase of 8.5 W in heat loss. These findings demonstrate the effectiveness of the CPC system in minimizing convective heat loss through strategic design and optimization of operational parameters.

8.2. Linear Fresnel collector

CPCs represent another noteworthy category of receivers utilized in LFCs. Unlike cavity receivers, CPCs typically employ a single absorber tube and often serve the dual purpose of both absorbing solar irradiance and functioning as secondary reflectors to redirect incoming sunlight received from the Fresnel mirrors.

Like PTCs, besides the general analysis that investigated the overall performance of CPCs of LFCs [136,146,153,170,171,271] CPCs are subject to the influence of key parameters, including geometrical and structural characteristics [140,168,272] which significantly impact their losses and overall performance.

Geometrical and structural characteristics can be considered the most focused factors in different research. Montes et al. [19] a hybrid LFC system combining non-evacuated and evacuated absorbers within a CPC. They found that the non-evacuated receiver had nearly double the heat loss compared to the evacuated counterpart. Both types of absorbers experienced increased heat loss with higher absorber-to-ambient temperature differences and wind velocity. Specifically, the non-evacuated absorber showed a more pronounced response to increased wind velocity, with heat loss exceeding 500 W/m at 12 m/s, compared to minimal effects on the evacuated and glazed-shielded receivers. The study recommended a hybrid configuration using non-evacuated absorbers at lower temperatures and transitioning to evacuated absorbers at higher temperatures for optimized performance and cost-effectiveness.

Rungasamy et al. [135] compared four LFC receiver designs and found that the adapted tailored edge ray concentrator monotube receiver had the lowest heat loss, while the adapted tailored edge concentrator multitube receiver experienced the highest. Multitube receivers had significantly higher heat losses, ranging from 1.5 to 2.5 times those of single-tube designs.

Cagnoli et al. [134] studied heat loss in CPC receivers under vacuum and air-filled gap conditions. They found that the evacuated receiver had thermal losses between 30 W/m and 110 W/m due to radiation, whereas the air-filled gap receiver had wider thermal losses ranging from 90 W/m to 250 W/m with convective losses being twice as high as radiative losses. Wind velocity did not affect evacuated receiver heat loss but increased non-evacuated receiver losses by 27%–75%.

Similarly, Reddy et al. [149] conducted a study on a pilot LFC plant, comparing heat losses in non-evacuated and evacuated CPC configurations under varying heat flux conditions. They found that evacuating the absorber can reduce heat loss by approximately 65% to 70%. In non-evacuated absorbers, differences in heat loss were negligible at low DNI levels but increased as DNI rose, reaching up to 30% under certain conditions. In evacuated absorbers, variations in heat loss were primarily associated with different operating conditions, with radiative heat loss dominating (representing 60% to 92% of total heat loss). Additionally, increasing wind velocity from natural to forced convection mode led to higher heat losses, with increases of 13% for non-evacuated and 52% for evacuated configurations. These findings underscore the importance of optimizing absorber design and operational parameters to minimize heat loss in LFC systems.

9. Cavity receivers

9.1. Parabolic trough collector

The merits of linear cavity receivers in mitigating radiative and convective heat losses due to their geometric configuration are acknowledged; however, more studies have been conducted to further diminish these heat losses through innovative approaches mostly with geometrical and structural enhancements [13,112,113,273–276].

Liang et al. [121] investigated the use of a movable wall to reduce heat loss in a cavity receiver. They studied various conditions including HTF temperatures, wind velocities (1 m/s to 5 m/s), and ambient temperatures (−5 °C to 35 °C) with open and closed configurations. Their findings showed that higher wind velocities and HTF temperatures increased heat loss, while lower ambient temperatures reduced heat loss. Using a closed movable wall and cavity cover resulted in heat loss reductions ranging from 6.36% to 13.55%. Comparing horizontal and vertical orientations, they found lower heat loss in the horizontal configuration. This study demonstrates the effectiveness of using a movable wall and cavity cover to mitigate heat loss in cavity receivers under different operating conditions.

Patil et al. [111] compared insulated cavity receivers to conventional air-filled counterparts, exploring half-insulation and full evacuation configurations. They found that modifying the absorber-to-glass envelope diameter ratio in air-filled receivers reduced heat loss by up to 13% at a pressure of 10 Pa. However, heat loss remained higher than that of the Schott PTR70 receiver at pressures below 0.1 Pa. In half-insulated receivers, fiberglass and microtherm insulation led to significant heat loss reductions of 18% and 35%, respectively, compared to air-filled counterparts. Despite this, the microtherm-insulated air cavity receiver still exhibited 24% higher heat loss than the Schott PTR70. Under reduced air pressure conditions (10132.5 Pa), the microtherm-insulated air cavity receiver's heat loss decreased to only 9% above that of the Schott PTR70, highlighting the importance of air pressure in reducing heat loss in cavity receivers.

In a bid to enhance performance, Xiao et al. [277] introduced a V-shaped cavity configuration with finned heat transfer passages, which resulted in a significant 38.7% reduction in heat loss compared to the fin-less counterpart. Arumugam et al. [278] investigated the thermal efficacy of a cavity tube with heat transfer between two evacuated layers, revealing consistently lower heat losses compared to conventional tube counterparts. The reduction in heat losses was attributed to the vacuum enclosure, effectively attenuating convection-based heat losses and enhancing overall thermal efficiency.

9.2. Linear Fresnel collector

Cavity receivers, a conventional type of receivers in LFCs, typically feature absorber tubes embedded in their top walls to mitigate the influence of ambient environmental conditions on the absorbers. A review of pertinent literature, as presented in Table 5, underscores the extensive body of research dedicated to analyzing heat losses in this receiver configuration. Besides general analysis that studied the overall performance of these systems [137,142,143,151,159,163,164,279–283], the literature collectively identifies several key parameters that significantly influence heat loss within cavity receivers, which can be broadly categorized into three main areas: geometrical and structural characteristics [141,148,167], HTFs [155,166,284], and coating and insulating. These parameters have emerged as focal points for understanding and optimizing heat loss mechanisms. Various methodologies have been employed to explore the interplay of these factors in the heat losses and performance of LFCs.

Sousa et al. [150] studied a multi-tube trapezoidal cavity absorber in an LFC, using selective paint on absorber tubes to reduce heat losses. Unpainted tubes had the lowest heat loss coefficient, despite the paint's higher emissivity. Selective painting led to a modest reduction in heat loss (0.5% to 3.1%) due to reduced radiation from upper surfaces compared to fully painted tubes.

Qiu et al. [133] developed a numerical model for an LFC with a trapezoidal cavity receiver. They found that heat loss increased with higher fluid temperatures, solar irradiance, and wind velocity. Introducing a glass shield reduced heat loss by 1.9% to 6.6% by minimizing temperature differences. Radiative heat loss was dominant (81% to 87%), but convective loss in the receiver became significant (76% to 81%) under high wind. The study highlighted that increasing the coating emissivity substantially raised total heat loss (160% to 180% for the system, 100% to 134% for the receiver).

In addition to investigating various geometrical parameters, proposing new geometries and configurations is another intriguing aspect of this type of receiver research.

Manikumar and Arasu [132,160] explored new designs for an LFC with a trapezoidal cavity receiver. They investigated the impact of using an absorber copper plate and positioning the absorber tube between the cavity's top wall and the plate on heat loss. The study found that employing a coated plate reduced the heat loss coefficient significantly. Specifically, black chrome-coated absorber surfaces reduced the heat loss coefficient by 18.5% to 25.8% for cavity absorbers with a plate and by 15.6% to 16.5% for cavity absorbers without a plate, compared to uncoated surfaces.

In a distinct context, Manikumar et al. [145] studied the impact of an absorber plate and selective coating on trapezoidal cavity receiver performance, finding that coatings significantly reduced heat loss coefficients by 56% to 58% in plated tube setups and 36% to 38% in ordinary tube configurations. Incorporating an absorber plate also reduced heat loss by 21% to 25%. Ebrahimpour et al. [158] introduced a novel receiver design featuring a central hot circular wall surrounded by inclined adiabatic wings. They observed that higher angles of adiabatic walls and increased wind velocity increased heat loss, while a higher ratio of ambient to absorber temperature reduced heat loss. Additionally, a higher heat transfer coefficient between the glass cover and ambient environment intensified total heat loss by approximately 19.63%.

10. Opportunities, major issues, challenges, and recommended future work

CSP systems like LCSP offer distinct advantages over other solar systems, such as photovoltaic cells. Research indicates that the capacity utilization factor, which measures the ratio of the actual output from a solar plant over the year to the maximum possible output under ideal conditions, is 15% higher in the best-case scenario for PTC plants compared to photovoltaic plants [286]. Despite this, CSP systems, including LCSP, generate more electricity without storage compared to PVs [287].

However, the most significant advantage of CSP systems over photovoltaics lies in their capability for heat storage, allowing them to generate electricity even when the sun is not shining [288]. This is particularly crucial given the intermittent nature of renewable energy resources, the challenges associated with photovoltaic battery intermittency management, and the shortage of raw materials for battery production.

In this context, research focused on mitigating heat loss in LCSP systems plays a crucial role in advancing renewable and sustainable energy solutions, especially in addressing the intermittency issues prevalent in the energy landscape.

A thorough review of the existing literature in this field reveals that the majority of published studies concerning LCSP systems are either laboratory experiments or numerical simulations employing various methods. Nonetheless, despite the widespread application of these systems in solar plants and even domestic settings, there is a noticeable lack of practical and in-situ studies.

It is noteworthy that despite the substantial body of experiential literature on LCSP systems, many of these studies utilize electrical heaters for heat flux application or have not been conducted in a full-scale LCSP plant [83,112,116,218,243]. This distinction between experimental conditions and real-world scenarios underscores the need for more comprehensive field-based research. Such an approach would provide scientists and designers with a comprehensive understanding of how simplifying assumptions made during design and calculations differ from real-world outcomes. Consequently, there is a clear imperative for more focused research into the intricate dynamics of heat losses in LCSP systems to enhance the comprehension of these systems and their potential for improved performance.

However, conducting in-situ research poses challenges, including elevated costs and the requirement for specialized measurement systems. Furthermore, despite their global prevalence, finding suitable sites for such research can be a challenging endeavor.

While there has been extensive research on the analysis of heat losses and system performance, there has been relatively less specific focus on directly reducing these losses, which have a direct impact on performance. This could be attributed to the fact that many efforts to enhance LCSP systems performance, such as using HTFs with superior thermal properties or incorporating fins and porous materials into the absorber, indirectly contribute to reducing heat losses. Consequently, the isolated examination of heat losses as a distinct factor influencing the efficiency of LCSP systems has received comparatively less attention in studies.

Directly focusing on the critical factors that impact heat loss mitigation is more crucial than merely calculating or measuring heat loss in LCSP systems. Within the domain of PTCs (Fig. 9(a)), several critical factors influence heat loss and system performance. Geometrical and positional features, as well as material properties, are among these

Table 5
Published literature about heat losses of LFCs with cavity receivers (Note: Exp = Experimental, Num = Numerical, Anal = Analytical).

Ref.	Method	Receiver condition	Findings and remarks	Heat loss
			Overall thermal analysis	
[169]	Num	Top and side walls insulated. Glass shield in aperture.	Multi-objective optimization aims to minimize the insulation area and heat loss while considering geometry characteristics.	• Heat loss for 51.9 mm insulation: 460.5 W • Heat loss for 48.6 mm insulation: 462.6 W • Heat loss for 42.531 mm insulation: 469.4 W
[138]	Num	Not Specified	Numerical investigation of a LFC in superheated steam production: • Thermal efficiency: 37.5%	• Minimum overall heat loss coefficient: 4.83 W/m^2 C • Maximum overall heat loss coefficient: 6.3505 W/m^2 C
[139]	Anal, Exp	Top and side walls insulated. Glass shield in aperture.	Investigating the thermal performance of an LFC with a V-shaped cavity:	The predicted overall heat loss coefficient for the LFC system ranges from 6.25 W/m^2 K to 7.52 W/m^2 K.
[285]	Num	Top and side walls insulated. Glass shield in aperture.	Modeling the thermal performance of an LFC with a triangular cavity receiver: • System efficiency: 45.2% at 90 °C 36.6% at 150 °C	The overall heat loss coefficient is calculated to be 110 W/m^2 at a temperature of 150 °C.
			Geometrical and structural analysis	
[152]	Num, Exp	Top and side walls insulated. Glass shield in aperture.	Comparing the performance of different cavity receiver shapes in an LFC: • Triangular receiver thermal efficiency: 61.8% Rectangular receiver thermal efficiency: 69.8%	• Semicircular receiver had heat loss values between 43.0 W/m^2 K and 99.0 W/m^2. • Triangular receiver exhibited heat loss ranging from 41.9 W/m^2 K to 105.7 W/m^2. • Rectangular receiver showed heat loss in the range of 50.5 W/m^2 K to 115.0 W/m^2.
[156]	Num	Top and side walls insulated. Glass shield in aperture.	Geometrical analysis of an LFC with a trapezoidal cavity receiver: • The cavity with a depth of 100mm exhibits the highest thermal performance.	The heat loss coefficient decreases with a higher inclination of side walls, leading to a 9% reduction at a 60° inclination compared to 30°.

factors that have received relatively less attention. Proposing novel geometries of PTCs can help reduce convective and radiative heat losses while optimizing solar energy absorption, thereby increasing overall efficiency.

The thermal and radiative properties of materials used in the manufacturing of PTCs are equally important, as heat losses depend on these properties. Exploring the effects of material properties, such as inner and outer coatings, can significantly reduce heat losses. Additionally, the utilization of HTFs with superior thermal properties, such as nanofluids and phase change materials (PCMs), is another crucial but relatively less explored factor in mitigating heat losses. These fluids not only impact convective heat loss through higher heat transfer rates from the absorbers but also influence heat storage losses due to their enhanced heat capacity.

Furthermore, the integration of radiation shields or additional reflectors has received limited attention in different research. These aspects present potential methods for reducing heat losses, particularly in situations where radiative heat losses are unavoidable. By delving into these aspects, blackconducting studies can uncover innovative strategies to enhance the performance and efficiency of PTC systems.

Concerning LFCs (Fig. 9(b)), while emissivity and thermal conductivity impact the heat loss of LFC absorbers, there has been no specific study on the effect of materials used in absorbers and receivers on heat loss reduction. Cavity receivers play a major role in LFCs (Fig. 7(b)). Their inherent geometrical characteristics can reduce convective heat loss, but since radiative heat loss comprises the major portion of heat loss in these systems [279], it is essential to investigate the feasibility of using different coatings. Additionally, the use of HTFs with superior thermal properties is the least researched aspect of heat loss mitigation. These fluids have the potential to extract more heat flux from the absorber and reduce heat losses due to a decrease in absorber temperature.

Exploring enhanced materials with superior thermal properties, novel geometries, integrating radiation shields, and utilizing supplementary reflectors are all interesting areas for scholarly research. Nevertheless, it is essential to acknowledge that each of these avenues comes with its unique set of challenges, including financial considerations, installation constraints, and practical utility limitations. Addressing these challenges in the implementation of novel solutions for mitigating heat losses presents an intellectually stimulating field of inquiry in itself, complementing the initial research endeavors.

In summary, the major suggested future works concerning heat losses in LCSP systems can be listed as follows:

- Conduct in-situ investigations of heat losses.
- Explore the use of novel geometries to mitigate heat losses.
- Improve sun-tracking systems for enhanced efficiency.
- Investigate various nanofluids as primary HTFs.
- Explore the potential of various PCMs as heat transfer or storage fluids.
- Study the feasibility of filling the glass envelope with semi-transparent fluids to reduce radiative heat loss.
- Investigation of using different coating and insulator materials.
- Consider the integration of radiation shields and supplementary reflectors.

11. Conclusion

This study presents a comprehensive review of research concerning various modes of thermal losses, encompassing radiative and convective losses, which play a pivotal role in the performance of linear concentrated solar systems i.e., Parabolic Trough Collectors and Linear Fresnel Collectors. Studies on heat losses in these systems can be classified into three main categories.

The first category comprises general analyses, with overall thermal performance evaluation being the primary focus, while heat losses are considered a secondary factor. These studies assess heat losses affected by parameters such as location, time, geometry, structure, and different coatings. Although heat losses are not the primary focus of these studies, they significantly contribute to understanding how various factors affect them.

The second category includes studies proposing solutions to improve efficiency as the primary objective and mitigate heat losses as secondary parameters. Building upon the effective factors identified in the first category, proposed solutions for efficiency improvement and heat loss mitigation include using HTFs with better thermal characteristics, geometrical and structural enhancements, or implementing coatings to enhance convective and radiative performance.

The third category views heat losses as the primary factor in LCSP systems and explores various solutions, including structural and geometrical modifications, alternative HTFs, radiation shields to reduce radiative heat loss, different insulations, and modified coatings to decrease both convective and radiative heat losses.

Reviewing studies across these three categories reveals numerous parameters, independently and interactively, influencing heat loss. Parameters such as absorber surface temperature, geometrical characteristics, optical and radiative properties, environmental conditions, and HTF flow rate and temperature are among the most influential factors. The diverse range of influential factors and their complex interactive effects on heat loss have prompted numerous numerical, analytical, and experimental studies to be conducted in this field.

However, the research focusing on heat losses as a primary parameter which significantly impact the performance of LCSP remains relatively limited compared to the research that treats heat losses as secondary factors. Given the profound impact of heat losses, there is a growing need to explore strategies for their reduction. This area warrants further exploration through various means, including in-situ studies, proposing new geometries and materials, and developing integrated systems.

This review provides valuable insights for stakeholders in regions with high solar irradiance, like the Middle East, North Africa, and parts of Asia. Understanding heat losses in linear concentrated solar systems is crucial for optimizing performance in electricity generation and water desalination. Industries from mining to food processing can benefit by minimizing heat losses, enhancing efficiency in process heating and steam generation, leading to cost savings and reduced carbon emissions. This actionable knowledge can drive sustainable energy adoption and industrial innovation regionally.

While our review thoroughly examines heat losses in linear concentrated solar systems, it is crucial to note some limitations. Firstly, we may not have fully explored their sensitivity to environmental conditions like temperature, humidity, and wind speed due to data constraints or experimental limitations. Also, challenges with data availability and quality may have affected the depth of our analysis, as reliable data on heat losses can be scarce and inconsistent. However, despite these limitations, our review offers valuable insights into understanding heat loss mechanisms in these systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Solar Energy Industries Association. Solar technologies. 2023, https://www.seia.org/initiatives/solar-technologies. [Accessed: 16 September 2023].

[2] Duffie JA, Beckman WA. Solar engineering of thermal processes. 4th Ed.. John Wiley & Sons; 2013.

[3] Hachicha AA, Yousef BAA, Said Z, Rodríguez I. A review study on the modeling of high-temperature solar thermal collector systems. Renew Sustain Energy Rev 2019;112:280–98.

[4] Poddar S, Kay M, Prasad A, Evans JP, Bremner S. Changes in solar resource intermittency and reliability under Australia's future warmer climate. Sol Energy 2023;266:112039.

[5] Powell KM, Rashid K, Ellingwood K, Tuttle J, Iverson BD. Hybrid concentrated solar thermal power systems: A review. Renew Sustain Energy Rev 2017;80:215–37.

[6] Islam MT, Huda N, Abdullah A, Saidur R. A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends. Renew Sustain Energy Rev 2018;91:987–1018.

[7] Blanco MJ, Miller S. Introduction to concentrating solar thermal (CST) technologies. In: Blanco MJ, Santigosa LR, editors. Advances in concentrating solar thermal research and technology. Woodhead Publishing; 2017, p. 3–25.

[8] Caccia M, Tabandeh-Khorshid M, Itskos G, Strayer AR, Caldwell AS, Pidaparti S, et al. Ceramic–metal composites for heat exchangers in concentrated solar power plants. Nature 2018;562:406–9.

[9] Conroy T, Collins MN, Grimes R. A review of steady-state thermal and mechanical modelling on tubular solar receivers. Renew Sustain Energy Rev 2020;119:109591.

[10] National Renewable Energy Laboratory. Concentrating solar power projects. 2023, https://solarpaces.nrel.gov/projects. [Accessed: 1 September 2023].

[11] Wang F, Cheng Z, Tan J, Yuan Y, Shuai Y, Liu L. Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review. Renew Sustain Energy Rev 2017;79:1314–28.

[12] Kim J, Kim JS, Stein W. Simplified heat loss model for central tower solar receiver. Sol Energy 2015;116:314–22.

[13] Xu C, Chen Z, Li M, Zhang P, Ji X, Luo X, et al. Research on the compensation of the end loss effect for parabolic trough solar collectors. Appl Energy 2014;115:128–39.

[14] Bellos E, Tzivanidis C, Moghimi MA. Reducing the optical end losses of a linear Fresnel reflector using novel techniques. Sol Energy 2019;186:247–56.

[15] Gong G, Huang X, Wang J, Hao M. An optimized model and test of the China's first high temperature parabolic trough solar receiver. Sol Energy 2010;84:2230–45.

[16] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renew Sustain Energy Rev 2010;14:1695–721.

[17] Li M, Xu C, Ji X, Zhang P, Yu Q. A new study on the end loss effect for parabolic trough solar collectors. Energy 2015;82:382–94.

[18] Mishra P, Pandey M, Tamaura Y, Tiwari S. Numerical analysis of cavity receiver with parallel tubes for cross-linear concentrated solar system. Energy 2021;220:119609.

[19] Montes MJ, Abbas R, Muñoz M, Muñoz-Antón J, Martínez-Val JM. Advances in the linear Fresnel single-tube receivers: Hybrid loops with non-evacuated and evacuated receivers. Energy Convers Manage 2017;149:318–33.

[20] Manikandan GK, Iniyan S, Goic R. Experimental analysis of heat loss of a non–evacuated parabolic trough collector receiver subjected to uniform and non-uniform wall heat flux condition. Energy Sources Part A: Recov Util Environ Eff 2021;43:2807–19.

[21] Ouagued M, Khellaf A, Loukarfi L. Estimation of the temperature, heat gain and heat loss by solar parabolic trough collector under Algerian climate using different thermal oils. Energy Convers Manage 2013;75:191–201.

[22] Oufadel A, Ydrissi ME, Hassani AA, Ghennioui H, Ghennioui A, Bennouna EG, et al. In-situ heat losses measurements of parabolic trough receiver tubes based on infrared camera and artificial intelligence. Environ Chall 2023;10:100679.

[23] Setien E, López-Martín R, Valenzuela L. Methodology for partial vacuum pressure and heat losses analysis of parabolic troughs receivers by infrared radiometry. Infrared Phys Technol 2019;98:341–53.

[24] Filho VCP, Sá ABD, Passos JC, Colle S. Experimental and numerical analysis of thermal losses of a parabolic trough solar collector. Energy Procedia 2014;57:381–90.

[25] Saifaoui D, Aittaleb A, Mouden ME, Saifaoui D, Aittaleb A, Kebch AE, et al. Numerical simulation of thermal losses on the parabolic trough collector under TRANSYS. J Optoelectron Adv Mater 2013;15:1335–8.

[26] AlZahrani AA, Dincer I. Energy and exergy analyses of a parabolic trough solar power plant using carbon dioxide power cycle. Energy Convers Manage 2018;158:476–88.

[27] AlZahrani AA, Dincer I. Thermodynamic analysis of an integrated transcritical carbon dioxide power cycle for concentrated solar power systems. Sol Energy 2018;170:557–67.

[28] Habib L, Hassan MI, Shatilla Y. A realistic numerical model of lengthy solar thermal receivers used in parabolic trough CSP plants. Energy Procedia 2015;75:473–8.

[29] Alshqirate AA, Alblawi A, Asfer M. Potential of a parabolic trough solar concentrator for electric energy production. Heat Transf 2020;49:693–708.

[30] Yang B, Wang W, Wang L. Experimental study on parabolic trough solar heating system. In: Engineering and technological solutions for sustainable development. Applied mechanics and materials, vol. 694, Trans Tech Publications Ltd; 2014, p. 155–8.

[31] Islam M, Saha SC, Karim MA, Yarlagadda PKDV. A method of three-dimensional thermo-fluid simulation of the receiver of a standard parabolic trough collector. In: Khan MMK, Chowdhury AA, Hassan NMS, editors. Application of thermo-fluid processes in energy systems: key issues and recent developments for a sustainable future. Singapore: Springer; 2018, p. 203–30.

[32] Roostaee A, Ameri M. Effect of linear Fresnel concentrators field key parameters on reflectors configuration, trapezoidal cavity receiver dimension, and heat loss. Renew Energy 2019;134:1447–64.

[33] Roostaee A, Ameri M. A comparative study of different optimised mirrors layouts of linear Fresnel concentrators on annual energy and exergy efficiencies. Int J Ambient Energy 2022;43:2627–44.

[34] Rawani A, Kumar A, Singh P, Ansu AK. Performance analysis of cylindrical parabolic solar collector with twisted tape on solar radiation. Mater Today: Proc 2021;47:3064–7.

[35] Kumar D, Kumar S. Simulation analysis of overall heat loss coefficient of parabolic trough solar collector at computed optimal air gap. Energy Procedia 2017;109:86–93.

[36] Xu L, Stein W, Kim JS, Too YCS, Guo M, Wang Z. Transient numerical model for the thermal performance of the solar receiver. Appl Therm Eng 2018;141:1035–47.

[37] Yilmaz IH, Soylemez MS, Hayta H, Yumrutas R. Model-based performance analysis of a concentrating parabolic trough collector array. In: Dincer I, Midilli A, Kucuk H, editors. Progress in exergy, energy, and the environment. Cham: Springer International Publishing; 2014, p. 815–27.

[38] Siqueira AMDO, Gomes PEN, Torrezani L, Lucas EO, Pereira GMDC. Heat transfer analysis and modeling of a parabolic trough solar collector: An analysis. Energy Procedia 2014;57:401–10.

[39] Islam M, Saha SC, Yarlagadda PKDV, Karim A. A tool to minimize the need of Monte Carlo ray tracing code for 3D finite volume modelling of a standard parabolic trough collector receiver under a realistic solar flux profile. Energy Sci Eng 2020;8:3087–102.

[40] Sallaberry F, Valenzuela L, López-Martín R, Jalón AGD, Perez D. Heat losses model for standardized testing of receiver tubes for parabolic-troughs. AIP Conf Proc 2018;2033.

[41] Bhuyan U, Sahoo SS, Satapathy PK, Parida PK. Heat loss modelling and analysis of parabolic trough solar collector using computational approach. Aust J Mech Eng 2019;17:24–37.

[42] Wang R, Sun J, Hong H, Liu Q. An on-site test method for thermal and optical performances of parabolic-trough loop for utility-scale concentrating solar power plant. Sol Energy 2017;153:142–52.

[43] Ghodbane M, Boumeddane B. Optical modeling and thermal behavior of a parabolic trough solar collector in the Algerian Sahara. Model Meas Control B 2017;86:406–26.

[44] Zou B, Jiang Y, Yao Y, Yang H. Optical performance of parabolic trough solar collectors under condition of multiple optical factors. Appl Therm Eng 2019;160:114070.

[45] Zou B, Jiang Y, Yao Y, Yang H. Impacts of non-ideal optical factors on the performance of parabolic trough solar collectors. Energy 2019;183:1150–65.

[46] Ma J, Chang Z. Understanding the effects of end-loss on linear Fresnelcollectors. IOP Conf Ser: Earth Environ Sci 2018;121:052052.

[47] Forristall R. Heat transfer analysis and modeling of a parabolic trough solar receiver implemented in engineering equation solver. National Renewable Energy Laboratory; 2003, https://www.nrel.gov/docs/fy04osti/34169.pdf. [Accessed: 1 September 2023].

[48] Yılmaz IH, Mwesigye A. Modeling, simulation and performance analysis of parabolic trough solar collectors: A comprehensive review. Appl Energy 2018;225:135–74.

[49] Upadhyay BH, Patel AJ, Ramana PV. A detailed review on solar parabolic trough collector. Int J Ambient Energy 2022;43:176–96.

[50] Abed N, Afgan I. An extensive review of various technologies for enhancing the thermal and optical performances of parabolic trough collectors. Int J Energy Res 2020;44:5117–64.

[51] Akbarzadeh S, Valipour MS. Heat transfer enhancement in parabolic trough collectors: A comprehensive review. Renew Sustain Energy Rev 2018;92:198–218.

[52] Sharma M, Jilte R. A review on passive methods for thermal performance enhancement in parabolic trough solar collectors. Int J Energy Res 2021;45:4932–66.

[53] Allam M, Tawfik M, Bekheit M, El-Negiry E. Heat transfer enhancement in parabolic trough receivers using inserts: A review. Sustain Energy Technol Assess 2021;48:101671.

[54] Bellos E, Said Z, Tzivanidis C. The use of nanofluids in solar concentrating technologies: A comprehensive review. J Clean Prod 2018;196:84–99.

[55] Bellos E, Tzivanidis C, Tsimpoukis D. Enhancing the performance of parabolic trough collectors using nanofluids and turbulators. Renew Sustain Energy Rev 2018;91:358–75.

[56] Bellos E, Tzivanidis C. Alternative designs of parabolic trough solar collectors. Prog Energy Combust Sci 2019;71:81–117.

[57] Abdulhamed AJ, Adam NM, Ab-Kadir MZA, Hairuddin AA. Review of solar parabolic-trough collector geometrical and thermal analyses, performance, and applications. Renew Sustain Energy Rev 2018;91:822–31.

[58] Salgado Conrado L, Rodriguez-Pulido A, Calderón G. Thermal performance of parabolic trough solar collectors. Renew Sustain Energy Rev 2017;67:1345–59.

[59] Tian M, Su Y, Zheng H, Pei G, Li G, Riffat S. A review on the recent research progress in the compound parabolic concentrator (CPC) for solar energy applications. Renew Sustain Energy Rev 2018;82:1272–96.

[60] Kalidasan B, Hassan MA, Pandey AK, Chinnasamy S. Linear cavity solar receivers: A review. Appl Therm Eng 2023;221:119815.

[61] Fredriksson J, Eickhoff M, Giese L, Herzog M. A comparison and evaluation of innovative parabolic trough collector concepts for large-scale application. Sol Energy 2021;215:266–310.

[62] Jebasingh VK, Herbert GMJ. A review of solar parabolic trough collector. Renew Sustain Energy Rev 2016;54:1085–91.

[63] Saini P, Singh S, Kajal P, Dhar A, Khot N, Mohamed ME, et al. A review of the techno-economic potential and environmental impact analysis through life cycle assessment of parabolic trough collector towards the contribution of sustainable energy. Heliyon 2023;9:e17626.

[64] Hafez AZ, Attia AM, Eltwab HS, ElKousy AO, Afifi AA, AbdElhamid AG, et al. Design analysis of solar parabolic trough thermal collectors. Renew Sustain Energy Rev 2018;82:1215–60.

[65] Manikandan GK, Iniyan S, Goic R. Enhancing the optical and thermal efficiency of a parabolic trough collector – a review. Appl Energy 2019;235:1524–40.

[66] Kumaresan G, Sudhakar P, Santosh R, Velraj R. Experimental and numerical studies of thermal performance enhancement in the receiver part of solar parabolic trough collectors. Renew Sustain Energy Rev 2017;77:1363–74.

[67] Nakul S, Arunachala UC. Status, trends and significance of parabolic trough technology in the changing heat transportation scenario. Sol Energy 2019;187:57–81.

[68] Ajbar W, Parrales A, Huicochea A, Hernández JA. Different ways to improve parabolic trough solar collectors' performance over the last four decades and their applications: A comprehensive review. Renew Sustain Energy Rev 2022;156:111947.

[69] Jamali H. Investigation and review of mirrors reflectance in parabolic trough solar collectors (PTSCs). Energy Rep 2019;5:145–58.

[70] Bellos E. Progress in the design and the applications of linear Fresnel reflectors – a critical review. Therm Sci Eng Prog 2019;10:112–37.

[71] Rubbi F, Das L, Habib K, Aslfattahi N, Saidur R, Alam SU. A comprehensive review on advances of oil-based nanofluids for concentrating solar thermal collector application. J Mol Liq 2021;338:116771.

[72] Bonk A, Sau S, Uranga N, Hernaiz M, Bauer T. Advanced heat transfer fluids for direct molten salt line-focusing CSP plants. Prog Energy Combust Sci 2018;67:69–87.

[73] Farhana K, Kadirgama K, Rahman M, Ramasamy D, Noor M, Najafi G, et al. Improvement in the performance of solar collectors with nanofluids — a state-of-the-art review. Nano-Struct Nano-Objects 2019;18:100276.

[74] Tiwari AK, Kumar V, Said Z, Paliwal HK. A review on the application of hybrid nanofluids for parabolic trough collector: Recent progress and outlook. J Clean Prod 2021;292:126031.

[75] Sokhansefat T, Kasaeian AB, Kowsary F. Heat transfer enhancement in parabolic trough collector tube using Al2O3/synthetic oil nanofluid. Renew Sustain Energy Rev 2014;33:636–44.

[76] Panduro EAC, Finotti F, Largiller G, Lervåg KY. A review of the use of nanofluids as heat-transfer fluids in parabolic-trough collectors. Appl Therm Eng 2022;211:118346.

[77] Krishna Y, Faizal M, Saidur R, Ng KC, Aslfattahi N. State-of-the-art heat transfer fluids for parabolic trough collector. Int J Heat Mass Transfer 2020;152:119541.

[78] Kumaresan G, Sudhakar P, Santosh R, Velraj R. Experimental and numerical studies of thermal performance enhancement in the receiver part of solar parabolic trough collectors. Renew Sustain Energy Rev 2017;77:1363–74.

[79] Pranesh V, Velraj R, Christopher S, Kumaresan V. A 50 year review of basic and applied research in compound parabolic concentrating solar thermal collector for domestic and industrial applications. Sol Energy 2019;187:293–340.

[80] Holman JP. Heat transfer. 10th Ed.. McGraw-Hill Education; 2010.

[81] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renew Sustain Energy Rev 2010;14(7):1695–721.

[82] Sandeep HM, Arunachala UC. Solar parabolic trough collectors: A review on heat transfer augmentation techniques. Renew Sustain Energy Rev 2017;69:1218–31.

[83] Wang Q, Yang H, Hu M, Cao J, Pei G, Yang H. Optimization strategies and verifications of negative thermal-flux region occurring in parabolic trough solar receiver. J Clean Prod 2021;278:123407.

[84] Wang R, Qu W, Sun J, Hong H. An on-site test method for optical efficiency of large-size parabolic trough collectors. Energy Procedia 2017;105:486–91.

[85] Patil RG, Kale DM, Panse SV, Joshi JB. Numerical study of heat loss from a non-evacuated receiver of a solar collector. Energy Convers Manage 2014;78:617–26.

[86] Okonkwo EC, Ratlamwala TAH, Abid M. Energy, exergy, exergoeconomic, and exergoenvironmental study of a parabolic trough collector using a converging-diverging receiver tube. Int J Exergy 2019;29:131–54.
[87] Patil RG, Panse SV, Joshi JB. Optimization of non-evacuated receiver of solar collector having non-uniform temperature distribution for minimum heat loss. Energy Convers Manage 2014;85:70–84.
[88] Mohamad A, Orfi J, Alansary H. Heat losses from parabolic trough solar collectors. Int J Energy Res 2014;38:20–8.
[89] Wang Y, Zhu Y, Chen H, Yang L, Yang M. Thermal performance of a single-pass all-glass parabolic trough receiver. J Energy Eng 2017;143:04016029.
[90] Wang Q, Shen B, Huang J, Yang H, Pei G, Yang H. A spectral self-regulating parabolic trough solar receiver integrated with vanadium dioxide-based thermochromic coating. Appl Energy 2021;285:116453.
[91] Al-Ansary H, Zeitoun O. Heat loss experiments on a non-evacuated parabolic trough receiver employing a thermally insulating layer in the annular gap. In: Proceedings of the ASME 2013 7th international conference on energy sustainability. Minneapolis, Minnesota; 2013, p. ES2013–18078, V001T03A003.
[92] Chandra YP, Singh A, Mohapatra SK, Kesari JP, Rana L. Numerical optimization and convective thermal loss analysis of improved solar parabolic trough collector receiver system with one sided thermal insulation. Sol Energy 2017;148:36–48.
[93] Wang Q, Li J, Yang H, Su K, Hu M, Pei G. Performance analysis on a high-temperature solar evacuated receiver with an inner radiation shield. Energy 2017;139:447–58.
[94] Wang Q, Yang H, Zhong S, Huang Y, Hu M, Cao J, et al. Quantitative analyses and a novel optimization strategy on negative energy-flow region in parabolic trough solar receivers. Sol Energy 2020;196:663–72.
[95] Wang Q, Hu M, Yang H, Cao J, Li J, Su Y, et al. Energetic and exergetic analyses on structural optimized parabolic trough solar receivers in a concentrated solar–thermal collector system. Energy 2019;171:611–23.
[96] Wang Q, Yang H, Huang X, Li J, Pei G. Numerical investigation and experimental validation of the impacts of an inner radiation shield on parabolic trough solar receivers. Appl Therm Eng 2018;132:381–92.
[97] Wang Q, Yao Y, Shen Z, Yang H. A hybrid parabolic trough solar collector system integrated with photovoltaics. Appl Energy 2023;329:120336.
[98] Okafor IF, Dirker J, Meyer JP. Influence of non-uniform heat flux distributions on the secondary flow, convective heat transfer and friction factors for a parabolic trough solar collector type absorber tube. Renew Energy 2017;108:287–302.
[99] Agagna B, Smaili A, Behar O. An improved model for predicting the performance of parabolic trough solar collectors. Int J Energy Res 2018;42:4512–21.
[100] Khandelwal DK, Kumar KR, Kaushik SC. Heat transfer analysis of receiver for large aperture parabolic trough solar collector. Int J Energy Res 2019;43:4295–311.
[101] Peng Y, Ren T, Xia B, Wang Y, Zhu Y. Numerical investigation of a novel single-pass all-glass receiver for parabolic trough collector. Energy Sources Part A: Recov Util Environ Eff 2021;43:1838–52.
[102] Osorio JD, Rivera-Alvarez A. Performance analysis of parabolic trough collectors with double glass envelope. Renew Energy 2019;130:1092–107.
[103] Hassan MA, Fouad A, Dessoki K, Al-Ghussain L, Hamed A. Performance analyses of supercritical carbon dioxide-based parabolic trough collectors with double-glazed receivers. Renew Energy 2023;215:118884.
[104] Maatoug MA, Boukhriss M, Timoumi M, Jammali A, Bacha HB. Theoretical study of a mathematical approach of a modeling of the solar collector with a parabolic cylindrical type concentration effect. Euro-Mediter J Environ Integr 2023;8:353–64.
[105] Moloodpoor M, Mortazavi A, Ozbalta N. Thermal analysis of parabolic trough collectors via a swarm intelligence optimizer. Sol Energy 2019;181:264–75.
[106] Hoste G, Schuknecht N. Thermal efficiency analysis of SkyFuel's advanced, large-aperture, parabolic trough collector. Energy Procedia 2015;69:96–105.
[107] Hu T, Kwan TH, Zhang H, Wang Q, Pei G. Thermal performance investigation of the newly shaped vacuum tubes of parabolic trough collector system. Energy 2023;278:127802.
[108] Francesconi M, Antonelli M. A CFD analysis to investigate thermal losses in a panel composed of several CPC concentrators. Therm Sci Eng Prog 2018;5:278–88.
[109] Garg A, Ray B, Jain S. Development of Nusselt number correlation for solar CPC with a tubular receiver. Therm Sci Eng Prog 2023;37:101553.
[110] Souliotis M, Papaefthimiou S, Caouris YG, Zacharopoulos A, Quinlan P, Smyth M. Integrated collector storage solar water heater under partial vacuum. Energy 2017;139:991–1002.
[111] Patil RG, Panse SV, Joshi JB, Dalvi VH. Alternative designs of evacuated receiver for parabolic trough collector. Energy 2018;155:66–76.
[112] Shinde TU, Dalvi VH, Patil RG, Mathpati CS, Panse SV, Joshi JB. Thermal performance analysis of novel receiver for parabolic trough solar collector. Energy 2022;254:124343.
[113] Gharbia Y, Grami S, Wazwaz A. Vacuum cavity parabolic trough collector. In: Proceedings of the ASME 2014 international mechanical engineering congress & exposition. Montreal, Quebec; 2014, p. IMECE2014–37103.
[114] Khullar V, Mahendra P, Mittal M. Applicability of heat mirrors in reducing thermal losses in concentrating solar collectors. J Therm Sci Eng Appl 2018;10:061004.
[115] Guo J, Huai X, Liu Z. Performance investigation of parabolic trough solar receiver. Appl Therm Eng 2016;95:357–64.
[116] Pierucci G, Hosouli S, Salvestroni M, Messeri M, Fagioli F, Taddei F, et al. Experimental methodology and thermal loss tests on small size absorber tubes for solar applications. Energies 2018;11:2552.
[117] Agagna B, Behar O, Smaili A. Thermal performance enhancement in parabolic trough solar collectors by using an absorber tube with spherical pins. Energy Sources Part A: Recov Util Environ Eff 2022;44:8161–83.
[118] Serrano-Aguilera JJ, Valenzuela L, Parras L. Thermal hydraulic RELAP5 model for a solar direct steam generation system based on parabolic trough collectors operating in once-through mode. Energy 2017;133:796–807.
[119] Xu RJ, Zhao YQ, Chen H, Wu QP, Yang LW, Wang HS. Numerical and experimental investigation of a compound parabolic concentrator-capillary tube solar collector. Energy Convers Manage 2020;204:112218.
[120] Xu R, Chen J, Zhang X, Wang R, Xu S. Heat leakage numerical investigation of a compound parabolic concentrator-pulsating heat pipe solar collector. J Therm Sci 2022;31:1318–26.
[121] Liang H, Fan M, You S, Xia J, Zhang H, Wang Y. An analysis of the heat loss and overheating protection of a cavity receiver with a novel movable cover for parabolic trough solar collectors. Energy 2018;158:719–29.
[122] Bezaatpour M, Rostamzadeh H, Bezaatpour J. Hybridization of rotary absorber tube and magnetic field inducer with nanofluid for performance enhancement of parabolic trough solar collector. J Clean Prod 2021;283:124565.
[123] Abed N, Afgan I, Cioncolini A, Iacovides H, Nasser A. Effect of various multiple strip inserts and nanofluids on the thermal–hydraulic performances of parabolic trough collectors. Appl Therm Eng 2022;201:117798.
[124] Silva R, Pérez M, Fernández-Garcia A. Modeling and co-simulation of a parabolic trough solar plant for industrial process heat. Appl Energy 2013;106:287–300.
[125] Okonkwo EC, Essien EA, Kavaz D, Abid M, Ratlamwala TAH. Olive leaf-synthesized nanofluids for solar parabolic trough collector-thermal performance evaluation. J Therm Sci Eng Appl 2019;11:041009.
[126] Zhao K, Jin H, Gai Z, Hong H. A thermal efficiency-enhancing strategy of parabolic trough collector systems by cascadingly applying multiple solar selective-absorbing coatings. Appl Energy 2022;309:118508.
[127] Sivaram PM, Nallusamy N, Suresh M. Experimental and numerical investigation on solar parabolic trough collector integrated with thermal energy storage unit. Int J Energy Res 2016;40:1564–75.
[128] Patil MS, Shekhawat SP. Performance assessment of parabolic trough collector receiver with Al2 O3 nanofluid. J Water Environ Nanotechnol 2022;7:332–43.
[129] Thappa S, Chauhan A, Anand Y, Anand S. Thermal and geometrical assessment of parabolic trough collector-mounted double-evacuated receiver tube system. Clean Technol Environ Policy 2021;23:2861–81.
[130] Beemkumar N, Yuvarajan D, Karthikeyan A, Ganesan S. Comparative experimental study on parabolic trough collector integrated with thermal energy storage system by using different reflective materials. J Therm Anal Calorim 2019;137:941–8.
[131] Bellos E, Korres DN, Tzivanidis C. Investigation of a compound parabolic collector with a flat glazing. Sustainability 2023;15:4347.
[132] Manikumar R, Arasu AV. Heat loss characteristics study of a trapezoidal cavity absorber with and without plate for a linear Fresnel reflector solar concentrator system. Renew Energy 2014;63:98–108.
[133] Qiu Y, He YL, Wu M, Zheng ZJ. A comprehensive model for optical and thermal characterization of a linear Fresnel solar reflector with a trapezoidal cavity receiver. Renew Energy 2016;97:129–44.
[134] Cagnoli M, Mazzei D, Procopio M, Russo V, Savoldi L, Zanino R. Analysis of the performance of linear Fresnel collectors: Encapsulated vs. evacuated tubes. Sol Energy 2018;164:119–38.
[135] Rungasamy AE, Craig KJ, Meyer JP. Comparative performance evaluation of candidate receivers for an etendue-conserving compact linear Fresnel mirror field. Sol Energy 2022;231:646–63.
[136] Nixon JD, Davies PA. Construction and experimental study of an elevation linear Fresnel reflector. J Solar Energy Eng Trans ASME 2016;138.
[137] Mokhtar G, Boussad B, Noureddine S. A linear Fresnel reflector as a solar system for heating water: Theoretical and experimental study. Case Stud Therm Eng 2016;8:176–86.
[138] Ghodbane M, Boumeddane B, Said Z, Bellos E. A numerical simulation of a linear Fresnel solar reflector directed to produce steam for the power plant. J Clean Prod 2019;231:494–508.
[139] Lin M, Sumathy K, Dai YJ, Wang RZ, Chen Y. Experimental and theoretical analysis on a linear Fresnel reflector solar collector prototype with V-shaped cavity receiver. Appl Therm Eng 2013;51:963–72.
[140] Reddy KS, Balaji S, Sundararajan T. Estimation of heat losses due to wind effects from linear parabolic secondary reflector –receiver of solar LFR module. Energy 2018;150:410–33.
[141] Reddy KS, Kumar KR. Estimation of convective and radiative heat losses from an inverted trapezoidal cavity receiver of solar linear Fresnel reflector system. Int J Therm Sci 2014;80:48–57.

[142] de Sá AB, Filho VCP, Tadrist L, Passos JC. Experimental study of a linear Fresnel concentrator: A new procedure for optical and heat losses characterization. Energy 2021;232:121019.

[143] Saxena A, Jhamaria N, Singh S, Sahoo SS. Numerical analysis of convective and radiative heat losses from trapezoidal cavity receiver in LFR systems. Sol Energy 2016;137:308–16.

[144] Singhal AK, Sharma MS, Negi BS, Mathur SS. Performance testing of a linear Fresnel reflector. Int J Energy Res 1986;10(1):39–46.

[145] Manikumar RR, Arasu AV, Jayaraj S. Numerical simulation of a trapezoidal cavity absorber in the linear Fresnel reflector solar concentrator system. Int J Green Energy 2014;11:344–63.

[146] Baba YF, Mers AA, ur Rehman T, Ajdad H, Bouatem A, Faik A, et al. No-vacuum mono-tube compound parabolic collector receiver for linear Fresnel concentrator: Numerical and experimental approach for dynamic behavior assessment. Energy Convers Manage 2022;268:115986.

[147] Heimsath A, Bern G, Rooyen DV, Nitz P. Quantifying optical loss factors of small linear concentrating collectors for process heat application. Energy Procedia 2014;48:77–86.

[148] Manikumar R, Palanichamy R, Arasu AV. Heat transfer analysis of an elevated linear absorber with trapezoidal cavity in the linear Fresnel reflector solar concentrator system. J Therm Sci 2015;24:90–8.

[149] Reddy KS, Balaji S, Sundararajan T. Heat loss investigation of 125kWth solar LFR pilot plant with parabolic secondary evacuated receiver for performance improvement. Int J Therm Sci 2018;125:324–41.

[150] Sousa S, Sá A, Pigozzo V, Passos JC. Experimental evaluation of heat loss from a LFC's multi-tube trapezoidal cavity absorber considering strategic painting of the tubes. AIP Conf Proc 2018;2033:050004.

[151] Moghimi MA, Craig KJ, Meyer JP. Optimization of a trapezoidal cavity absorber for the linear Fresnel reflector. Sol Energy 2015;119:343–61.

[152] Lin M, Sumathy K, Dai YJ, Zhao XK. Performance investigation on a linear Fresnel lens solar collector using cavity receiver. Sol Energy 2014;107:50–62.

[153] Shanmugapriya B, Reddy KS, Sundarajan T. Performance investigation of linear evacuated absorber of 2-stage solar linear Fresnel reflector module under non-uniform flux distribution. Int J Low-Carbon Technol 2018;13:92–101.

[154] Moghimi MA, Craig KJ, Meyer JP. Simulation-based optimisation of a linear Fresnel collector mirror field and receiver for optical, thermal and economic performance. Sol Energy 2017;153:655–78.

[155] Sahoo SS, Singh S, Banerjee R. Steady state hydrothermal analysis of the absorber tubes used in linear Fresnel reflector solar thermal system. Sol Energy 2013;87:84–95.

[156] Lai Y, Wu T, Che S, Dong Z, Lyu M. Thermal performance prediction of a trapezoidal cavity absorber for a linear Fresnel reflector. Adv Mech Eng 2013;2013:615742.

[157] Sahoo SS, Singh S, Banerjee R. Thermal hydraulic simulation of absorber tubes in linear Fresnel reflector solar thermal system using RELAP. Renew Energy 2016;86:507–16.

[158] Ebrahimpour Z, Farshad SA, Sheikholeslami M. Solar LFR system with new cavity reflector employing DO model. ZAMM - J Appl Math Mech / Zeitschrift für Angew Math Mech 2021;101:e202000226.

[159] Sultana T, Morrison GL, Taylor R, Rosengarten G. TRNSYS modeling of a linear Fresnel concentrating collector for solar cooling and hot water applications. J Solar Energy Eng 2015;137:021014.

[160] Manikumar R, Arasu AV. An analytical and experimental study of the linear Fresnel reflector solar concentrator system. Distrib Gener Alternat Energy J 2014;29:52–80.

[161] Alcalde-Morales S, Valenzuela L, Serrano-Aguilera JJ. Heat losses in a trapezoidal cavity receiver of a linear Fresnel collector: A CFD approach. Heliyon 2023;9(8):e18692.

[162] Zhou L, Li X, Zhao Y, Dai Y. Performance assessment of a single/double hybrid effect absorption cooling system driven by linear Fresnel solar collectors with latent thermal storage. Sol Energy 2017;151:82–94.

[163] Montes MJ, Abbas R, Barbero R, Rovira A. A new design of multi-tube receiver for Fresnel technology to increase the thermal performance. Appl Therm Eng 2022;204:117970.

[164] Dabiri S, Khodabandeh E, Poorfar AK, Mashayekhi R, Toghraie D, Zade SAA. Parametric investigation of thermal characteristic in trapezoidal cavity receiver for a linear Fresnel solar collector concentrator. Energy 2018;153:17–26.

[165] Tsekouras P, Tzivanidis C, Antonopoulos K. Optical and thermal investigation of a linear Fresnel collector with trapezoidal cavity receiver. Appl Therm Eng 2018;135:379–88.

[166] Famiglietti A, Lecuona A. Small-scale linear Fresnel collector using air as heat transfer fluid: Experimental characterization. Renew Energy 2021;176:459–74.

[167] Sahoo SS, Varghese SM, Kumar CS, Viswanathan SP, Singh S, Banerjee R. Experimental investigation and computational validation of heat losses from the cavity receiver used in linear Fresnel reflector solar thermal system. Renew Energy 2013;55:18–23.

[168] Reddy KS, Balaji S, Sundararajan T. Heat loss prediction from solar LFR linear evacuated surface receiver with variable 2-stage concentrated flux. In: Proceedings of the ISES solar world congress 2017 - IEA sHC international conference on solar heating and cooling for buildings and industry 2017. 2017, p. 2109–16.

[169] Ardekani MM, Craig KJ, Meyer JP. Optimization of insulation of a linear Fresnel collector. AIP Conf Proc 2017;1850:040005.

[170] Barbón A, López-Smeetz C, Bayón L, Pardellas A. Wind effects on heat loss from a receiver with longitudinal tilt angle of small-scale linear Fresnel reflectors for urban applications. Renew Energy 2020;162:2166–81.

[171] Hofer A, Cuevas F, Heimsath A, Nitz P, Platzer WJ, Scholl S. Extended heat loss and temperature analysis of three linear Fresnel receiver designs. Energy Procedia 2015;69:424–33.

[172] Janotte N, Lüpfert E, Pottler K, Schmitz M. Full parabolic trough qualification from prototype to demonstration loop. AIP Conf Proc 2017;1850:020010.

[173] Zhu S, Yu G, Ma Y, Cheng Y, Wang Y, Yu S, et al. A free-piston stirling generator integrated with a parabolic trough collector for thermal-to-electric conversion of solar energy. Appl Energy 2019;242:1248–58.

[174] Liu T, Liu Q, Lei J, Sui J. A new solar hybrid clean fuel-fired distributed energy system with solar thermochemical conversion. J Clean Prod 2019;213:1011–23.

[175] Basha SK, Behura AK. Investigation of thermal performance of a parabolic trough solar collector using different heat transfer fluids. Energy Sources Part A: Recov Util Environ Eff 2023;45:7198–221.

[176] Sun J, Liu Q, Hong H. Numerical study of parabolic-trough direct steam generation loop in recirculation mode: Characteristics, performance and general operation strategy. Energy Convers Manage 2015;96:287–302.

[177] Balghouthi M, Ali ABH, Trabelsi SE, Guizani A. Optical and thermal evaluations of a medium temperature parabolic trough solar collector used in a cooling installation. Energy Convers Manage 2014;86:1134–46.

[178] Agagna B, Smaili A, Falcoz Q. Optical and thermal analysis of a parabolic trough solar collector through coupling MCRT and FVM techniques. In: 2017 international renewable and sustainable energy conference. IRSEC, 2017, p. 1–6.

[179] Valenzuela L, López-Martín R, Zarza E. Optical and thermal performance of large-size parabolic-trough solar collectors from outdoor experiments: A test method and a case study. Energy 2014;70:456–64.

[180] Sallaberry F, Valenzuela L, Palacin LG. On-site parabolic-trough collector testing in solar thermal power plants: Experimental validation of a new approach developed for the IEC 62862-3-2 standard. Sol Energy 2017;155:398–409.

[181] Mansour K, Boudries R, Dizene R. Optical, 2D thermal modeling and exergy analysis applied for performance prediction of a solar PTC. Sol Energy 2018;174:1169–84.

[182] Bilal FR, Arunachala UC, Sandeep HM. 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.

[183] Mouaky A, Merrouni AA, Laadel NE, Bennouna EG. Simulation and experimental validation of a parabolic trough plant for solar thermal applications under the semi-arid climate conditions. Sol Energy 2019;194:969–85.

[184] Balasubramanian KR, Jinshah BS, Ravikumar K, Divakar S. Thermal and hydraulic characteristics of a parabolic trough collector based on an open natural circulation loop: The effect of fluctuations in solar irradiance. Sustain Energy Technol Assess 2022;52:102290.

[185] Ahmed MH. Two dimension numerical modeling of receiver tube performance for concentrated solar power plant. Energy Procedia 2014;57:551–60.

[186] Good P, Ambrosetti G, Pedretti A, Steinfeld A. A 1.2 MWth solar parabolic trough system based on air as heat transfer fluid at 500 °C — Engineering design, modelling, construction, and testing. Sol Energy 2016;139:398–411.

[187] Reddy KS, Ananthsornaraj C. Design, development and performance investigation of solar parabolic trough collector for large-scale solar power plants. Renew Energy 2020;146:1943–57.

[188] Pal RK, Kumar KR. Two-fluid modeling of direct steam generation in the receiver of parabolic trough solar collector with non-uniform heat flux. Energy 2021;226.

[189] Ghoneim AA, Mohammedein AM. Parabolic trough collector performance in a hot climate. J Energy Eng 2016;142.

[190] Nguimdo LA, Teka J, Fopossie FD. Thermal analysis of parabolic trough solar collector and assessment of steam power potential at two locations in Cameroon. Int J Renew Energy Res 2021;11:1136–48.

[191] Fiamonzini LA, Rivas GA, Junior OHA. Workbench for a parabolic trough solar collector with a tracking system. Sci World J 2022;2022.

[192] Sagar V, Kumar R. Thermal performance steady of a parabolic trough collector with K-type coaxial thermocouple. AIP Conf Proc 2018;2018:020023.

[193] Zhang S, Liu M, Zhao Y, Liu J, Yan J. Energy and exergy analyses of a parabolic trough concentrated solar power plant using molten salt during the start-up process. Energy 2022;254:124480.

[194] Gharehdaghi S, Moujaes SF, Nejad AM. Thermal-fluid analysis of a parabolic trough solar collector of a direct supercritical carbon dioxide Brayton cycle: A numerical study. Sol Energy 2021;220:766–87.

[195] Chaabane M, Mhiri H, Bournot P. Effect of phase change materials integration on the thermal performance of a parabolic trough collector. J Energy Eng 2021;147:04021024.

[196] Muruganantham P, Dhanapal B. Optimal forecasting of thermal conductivity and storage in parabolic trough collector using phase change materials. J Eng Res 2021;9:249–68.

[197] Borzuei D, Moosavian SF, Ahmadi A, Ahmadi R, Bagherzadeh K. An experimental and analytical study of influential parameters of parabolic trough solar collector. J Renew Energy Environ 2021;8:52–66.
[198] Abed N, Afgan I, Cioncolini A, Iacovides H, Nasser A. Assessment and evaluation of the thermal performance of various working fluids in parabolic trough collectors of solar thermal power plants under non-uniform heat flux distribution conditions. Energies 2020;13(15):3776.
[199] Eslami S, Gholami A, Bakhtiari A, Zandi M, Noorollahi Y. Experimental investigation of a multi-generation energy system for a nearly zero-energy park: A solution toward sustainable future. Energy Convers Manage 2019;200:112107.
[200] Wu YT, Liu SW, Xiong YX, Ma CF, Ding YL. Experimental study on the heat transfer characteristics of a low melting point salt in a parabolic trough solar collector system. Appl Therm Eng 2015;89:748–54.
[201] Ji GJ, Gu JM, Chen Z, Lu BB, Gao Y. Experimental research on heat transfer characteristic of HITEC molten salt in evacuated tube solar collector. Front Energy Res 2023;11:1150326.
[202] Ekiciler R, Arslan K, Turgut O. Application of nanofluid flow in entropy generation and thermal performance analysis of parabolic trough solar collector: Experimental and numerical study. J Therm Anal Calorim 2023;148:7299–318.
[203] Abu-Hamdeh NH, Abusorrah AM, Bayoumi MM, Oztop HF, Sun C. Numerical study on heat loss from the surface of solar collector tube filled by oil-NE-PCM/Al2O3 in the presence of the magnetic field. J Therm Anal Calorim 2021;144:2627–39.
[204] Heyhat MM, 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.
[205] Basbous N, Taqi M, Janan MA. Thermal performances analysis of a parabolic trough solar collector using different nanofluids. In: Proceedings of the 2016 international renewable and sustainable energy conference. Marrakech, Morocco; 2016, p. 322–6.
[206] Kasaiean A, Sameti M, Daneshazarian R, Noori Z, Adamian A, Ming T. Heat transfer network for a parabolic trough collector as a heat collecting element using nanofluid. Renew Energy 2018;123:439–49.
[207] Paetzold J, Cochard S, Fletcher DF, Vassallo A. Wind engineering analysis of parabolic trough collectors to optimise wind loads and heat loss. Energy Procedia 2015;69:168–77.
[208] Paetzold J, Cochard S, Fletcher DF, Vassallo A. Wind effects in solar fields with various collector designs. AIP Conf Proc 2016;1734:020018.
[209] Chater H, Asbik M, Mouaky A, Koukouch A, Belandria V, Sarh B. Experimental and CFD investigation of a helical coil heat exchanger coupled with a parabolic trough solar collector for heating a batch reactor: An exergy approach. Renew Energy 2023;202:1507–19.
[210] Halimi M, Outana I, Diouri J, Amrani AE, Messaoudi C. Experimental investigation of absorbed flux circumferential distribution of an absorber with U-pipe tube exchanger for parabolic trough collectors. Appl Therm Eng 2018;129:1230–9.
[211] Reddy KS, Kumar KR, Ajay CS. Experimental investigation of porous disc enhanced receiver for solar parabolic trough collector. Renew Energy 2015;77:308–19.
[212] Vengadesan E, Rumaney ARI, Mitra R, Harichandan S, Senthil R. Heat transfer enhancement of a parabolic trough solar collector using a semicircular multitube absorber. Renew Energy 2022;196:111–24.
[213] Vengadesan E, Thameenansari S, Manikandan EJ, Senthil R. Experimental study on heat transfer enhancement of parabolic trough solar collector using a rectangular channel receiver. J Taiwan Inst Chem Eng 2022;135:104361.
[214] Li L, Li H, Xu Q, Huang W. Performance analysis of Azimuth tracking fixed mirror solar concentrator. Renew Energy 2015;75:722–32.
[215] Peng S, Hong H, Jin H, Zhang Z. A new rotatable-axis tracking solar parabolic-trough collector for solar-hybrid coal-fired power plants. Sol Energy 2013;98:492–502.
[216] Fernández-García A, Rojas E, Pérez M, Silva R, Hernández-Escobedo Q, Manzano-Agugliaro F. A parabolic-trough collector for cleaner industrial process heat. J Clean Prod 2015;89:272–85.
[217] Geete A, Sharma R. Experimental exergy analyses on fabricated parabolic solar collector with/without preheater and different collector materials. Int J Ambient Energy 2019;40:577–89.
[218] Kaluba VS, Mohamad K, Ferrer P. Experimental and simulated performance of hot mirror coatings in a parabolic trough receiver. Appl Energy 2020;257:114020.
[219] Nagaraj A. Experimental study of epoxy based graphite coating on parabolic trough solar collector. J Phys Conf Ser 2022;2180:012001.
[220] Al-Rabeeah AY, Seres I, Farkas I. Experimental investigation and performance evaluation of parabolic trough solar collector for hot water generation. J Eng Thermophys 2021;30:420–32.
[221] Barbosa EG, Martins MA, de Araujo MEV, Renato NdS, Zolnier S, Pereira EG, et al. Experimental evaluation of a stationary parabolic trough solar collector: Influence of the concentrator and heat transfer fluid. J Clean Prod 2020;276:124174.
[222] Motwani K, Chotai N, Patel J, Hadiya R. Design and experimental investigation on cut tube absorber for solar parabolic trough collector. Energy Sources Part A: Recov Util Environ Eff 2020;1–12.
[223] Wang Q, Hu M, Yang H, Cao J, Li J, Su Y, et al. Performance evaluation and analyses of novel parabolic trough evacuated collector tubes with spectrum-selective glass envelope. Renew Energy 2019;138:793–804.
[224] Rashid K, Safdarnejad SM, Powell KM. Process intensification of solar thermal power using hybridization, flexible heat integration, and real-time optimization. Chem Eng Process - Process Intensif 2019;139:155–71.
[225] Patil MS, Shekhawat SP. Performance analysis and ANN modeling of solar parabolic trough collector. Appl Solar Energy (Engl Transl Geliotekhnika) 2022;58:538–50.
[226] Alhassan T, Tijani M, Jaafar B, Universiti T, Mara S, Alam S, et al. Numerical investigation of thermal losses from air filled annulus of a parabolic trough solar collector. J Mech Eng 2016;13:1–15.
[227] Abed N, Afgan I, Iacovides H, Cioncolini A, Khurshid I, Nasser A. Thermal-hydraulic analysis of parabolic trough collectors using straight conical strip inserts with nanofluids. Nanomaterials 2021;11:853.
[228] Vahedi B, Golab E, Sadr AN, Vafai K. Thermal, thermodynamic and exergoeconomic investigation of a parabolic trough collector utilizing nanofluids. Appl Therm Eng 2022;206:118117.
[229] Nakar D, Feuermann D. Surface roughness impact on the heat loss of solar vacuum heat collector elements (HCE). Renew Energy 2016;96:148–56.
[230] Okonkwo EC, Abid M, Ratlamwala TA, Abbasoglu S, Dagbasi M. Optimal analysis of entropy generation and heat transfer in parabolic trough collector using green-synthesized TiO_2/water nanofluids. J Solar Energy Eng 2019;141:031011.
[231] Brahim T, Jemni A. Comparative study of parabolic trough solar collector using syltherm-800 and therminol-VP1 non-metallic nanofluids. Therm Sci Eng Prog 2023;43:101951.
[232] Yehia MH, Hassan MA, Abed N, Khalil A, Bailek N. Combined thermal performance enhancement of parabolic trough collectors using alumina nanoparticles and internal fins. Int J Eng Res Afr 2022;62:107–32.
[233] Zhang L, Yu Z, Fan L, Wang W, Chen H, Hu Y, et al. An experimental investigation of the heat losses of a U-type solar heat pipe receiver of a parabolic trough collector-based natural circulation steam generation system. Renew Energy 2013;57:262–8.
[234] Olczak P, Olek M. The influence of evacuated-tube collector assembly on heat loss in tracking solar system with parabolic mirror reflectors. Procedia Eng 2016;157:317–24.
[235] Gong G, Huang X, Wang J, Hao M. An optimized model and test of the China's first high temperature parabolic trough solar receiver. Sol Energy 2010;84:2230–45.
[236] Ahmed KRA, Kumar JPN, Shyam A, Natarajan E, Iniyan S, Goic R. Experimental investigation on a solar parabolic trough receiver tube enhanced by toroidal rings. Int J Energy Res 2022;46:6637–53.
[237] Liu P, Dong Z, Xiao H, Liu Z, Liu W. A novel parabolic trough receiver by inserting an inner tube with a wing-like fringe for solar cascade heat collection. Renew Energy 2021;170:327–40.
[238] Hadi AI, Jamel MS. Using nanofluid technology. Int J Mech Eng and Technol 2019;10:571–93.
[239] Fayadh SB, Khalil WH, Dawood HK. Numerical study on the effect of using CuO-water nanofluid as a heat transfer fluid on the performance of the parabolic trough solar collector. CFD Lett 2023;15(5):120–33.
[240] Jamal-Abad MT, Saedodin S, Aminy M. Experimental investigation on a solar parabolic trough collector for absorber tube filled with porous media. Renew Energy 2017;107:156–63.
[241] Qu W, Wang R, Hong H, Sun J, Jin H. Test of a solar parabolic trough collector with rotatable axis tracking. Appl Energy 2017;207:7–17.
[242] Jebasingh VK, Johns JD, Arunkumar T. Assessment of circular and elliptical absorber tube in solar parabolic trough collector. Int J Ambient Energy 2022;43:873–8.
[243] Boukhalfa M, Merzouk M, Merzouk NK, Feidt M, Blet N. Performance analysis of a parabolic trough collector using a heat pipe exchanger. Environ Progr Sustain Energy 2022;41:e13897.
[244] Bellos E, Daniil I, Tzivanidis C. Multiple cylindrical inserts for parabolic trough solar collector. Appl Therm Eng 2018;143:80–9.
[245] Liu P, Wu J, Chen L, Liu Z, Liu W. Numerical analysis and multi-objective optimization design of parabolic trough receiver with ribbed absorber tube. Energy Rep 2021;7:7488–503.
[246] Wang Q, Yang H, Hu M, Huang X, Li J, Pei G. Preliminary performance study of a high-temperature parabolic trough solar evacuated receiver with an inner transparent radiation shield. Sol Energy 2018;173:640–50.
[247] Yang H, Wang Q, Huang X, Li J, Pei G. Performance study and comparative analysis of traditional and double-selective-coated parabolic trough receivers. Energy 2018;145:206–16.
[248] Qiu Y, Xu M, Li Q, Xu Y, Wang J. A novel evacuated receiver improved by a spectral-selective glass cover and rabbit-ear mirrors for parabolic trough collector. Energy Convers Manage 2021;227:113589.
[249] Zhu Y, Shi J, Li Y, Wang L, Huang Q, Xu G. Design and thermal performances of a scalable linear Fresnel reflector solar system. Energy Convers Manage 2017;146:174–81.
[250] Pulido-Iparraguirre D, Valenzuela L, Serrano-Aguilera J, Fernández-García A. Optimized design of a linear Fresnel reflector for solar process heat applications. Renew Energy 2019;131:1089–106.

[251] Hussain MI, Lee GH. Performance Comparison and Model Validation of a Conical Solar Reflector and a Linear Fresnel Concentrator. J Solar Energy Eng 2016;138(6):061014.
[252] Perini S, Tonnellier X, King P, Sansom C. Theoretical and experimental analysis of an innovative dual-axis tracking linear Fresnel lenses concentrated solar thermal collector. Sol Energy 2017;153:679–90.
[253] Gu X, Taylor RA, Rosengarten G. Analysis of a new compound parabolic concentrator-based solar collector designed for methanol reforming. J Solar Energy Eng 2014;136:041012.
[254] Yang M, Pei G, Li G, Wang J, Ji J. Experimental comparison of compound parabolic concentrator with three low concentration ratio. Taiyangneng Xuebao/Acta Energiae Solaris Sinica 2017;38:431–7.
[255] Varghese J, Samsher, Manjunath K. Collector characterisation and heat loss tests on a novel batch solar water heater with CPC reflector for households. Int J Ambient Energy 2020;41:759–66.
[256] Wang P, Liu DY, Xu C, Zhou L, Xia L. Conjugate heat transfer modeling and asymmetric characteristic analysis of the heat collecting element for a parabolic trough collector. Int J Therm Sci 2016;101:68–84.
[257] Imam MFIA, Beg RA, Rahman MS, Khan MZH. Performance of PVT solar collector with compound parabolic concentrator and phase change materials. Energy Build 2016;113:139–44.
[258] Reddy KS, Parthiban A, Mallick TK. Numerical modeling of heat losses in a line focusing solar compound parabolic concentrator with planar absorber. Appl Therm Eng 2020;181:115938.
[259] Christopher SS, Ahmed KRA, Shyam A, Iniyan S. Experimental study in a compound parabolic solar concentrator with different configurations of thermal energy storage system. Int J Green Energy 2023;21:54–63.
[260] Christopher SS, Kumaresan V. 2E (energy and exergy) analysis of solar evacuated tube-compound parabolic concentrator with different configurations of thermal energy storage system. Environ Sci Pollut Res 2022;29:61135–47.
[261] Messaouda A, Hamdi M, Hazami M, Guizani AA. Analysis of an integrated collector storage system with vacuum glazing and compound parabolic concentrator. Appl Therm Eng 2020;169:114958.
[262] Li X, Dai YJ, Li Y, Wang RZ. Comparative study on two novel intermediate temperature CPC solar collectors with the U-shape evacuated tubular absorber. Sol Energy 2013;93:220–34.
[263] Aguilar-Jiménez JA, Velázquez N, Acuña A, López-Zavala R, González-Uribe LA. Effect of orientation of a CPC with concentric tube on efficiency. Appl Therm Eng 2018;130:221–9.
[264] Karwa N, Jiang L, Winston R, Rosengarten G. Receiver shape optimization for maximizing medium temperature CPC collector efficiency. Sol Energy 2015;122:529–46.
[265] Jiang C, Yu L, Yang S, Li K, Wang J, Lund PD, et al. A review of the compound parabolic concentrator (CPC) with a tubular absorber. Energies 2020;13:695.
[266] Sakthivadivel D, Balaji K, Rufuss DDW, Iniyan S, Suganthi L. Chapter 1 - solar energy technologies: Principles and applications. In: Ren J, editor. Renewable-energy-driven future. Academic Press; 2021, p. 3–42.
[267] Zheng H. Chapter 2 - solar energy utilization and its collection devices. In: Zheng H, editor. Solar energy desalination technology. Amsterdam: Elsevier; 2017, p. 47–171.
[268] Antonelli M, Francesconi M, Di Marco P, Desideri U. Analysis of heat transfer in different CPC solar collectors: A CFD approach. Appl Therm Eng 2016;101:479–89.
[269] Zhao L, Bhatia B, Cooper T, Strobach E, Yang S, Weinstein LA, et al. Intermediate temperature solar thermal collector enabled by non-evacuated transparent aerogel and non-tracking compound parabolic concentrator. In: Proceedings of the international heat transfer conference 16. Beijing, China; 2018, p. 7559–66.
[270] Yuan G, Fan J, Kong W, Furbo S, Perers B, Sallaberry F. Experimental and computational fluid dynamics investigations of tracking CPC solar collectors. Sol Energy 2020;199:26–38.
[271] Sharma V, Nayak JK, Kedare SB. Effects of shading and blocking in linear Fresnel reflector field. Sol Energy 2015;113:114–38.
[272] Zhu G. New adaptive method to optimize the secondary reflector of linear Fresnel collectors. Sol Energy 2017;144:117–26.
[273] Wang W, Li M, Hassanien RHE, Ji ME, Feng Z. Optimization of thermal performance of the parabolic trough solar collector systems based on GA-BP neural network model. Int J Green Energy 2017;14:819–30.
[274] Mohamad K, Ferrer P. Parabolic trough efficiency gain through use of a cavity absorber with a hot mirror. Appl Energy 2019;238:1250–7.
[275] Korres DN, Tzivanidis C. Investigation of a novel small-sized bifacial cavity PTC and comparison with conventional configurations. Therm Sci Eng Prog 2020;17:100355.
[276] Li X, Chang H, Duan C, Zheng Y, Shu S. Thermal performance analysis of a novel linear cavity receiver for parabolic trough solar collectors. Appl Energy 2019;237:431–9.
[277] Xiao X, Zhang P, Shao DD, Li M. Experimental and numerical heat transfer analysis of a V-cavity absorber for linear parabolic trough solar collector. Energy Convers Manage 2014;86:49–59.
[278] Arumugam S, Ramakrishna P, Sangavi S. A comparative thermal analysis of conventional parabolic receiver tube and cavity model tube in a solar parabolic concentrator. IOP Conf Ser: Mater Sci Eng 2018;310.
[279] Mohan S, Saxena A, Singh S. Heat loss analysis from a trapezoidal cavity receiver in LFR system using conduction-radiation model. Sol Energy 2018;159:37–43.
[280] Mahmood H, Hossin K. Daily, monthly and annual thermal performance of a linear Fresnel reflector to drive an organic rankine-cycle system. Clean Energy 2021;5:673–89.
[281] Said Z, Ghodbane M, Tiwari AK, Ali HM, Boumeddane B, Ali ZM. 4E (energy, exergy, economic, and environment) examination of a small LFR solar water heater: An experimental and numerical study. Case Stud Therm Eng 2021;27:101277.
[282] Lai Y, Che S, Lu M, Dong Z, Song G, Ma C. Numerical simulation of a trapezoidal cavity absorber for a linear Fresnel reflector. In: Proceedings of the 2013 international conference on materials for renewable energy and environment. Chengdu, China; 2013, p. 89–93.
[283] Cocco D, Migliari L, Serra F. Influence of thermal energy losses on the yearly performance of medium size CSP plants. In: Proceedings of the 28th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems. Pau, France; 2015.
[284] 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.
[285] Ghafoor QJA, Jaber MWK, Mahmoud MS, Khudheyer AF. Absorber with triangular cavity for a linear Fresnel collector investigated numerically. Int J Mech Eng 2022;7:616–9.
[286] Awan AB, Zubair M, Praveen R, Bhatti AR. Design and comparative analysis of photovoltaic and parabolic trough based CSP plants. Sol Energy 2019;183:551–65.
[287] Boretti A. Cost and production of solar thermal and solar photovoltaics power plants in the United States. Renew Energy Focus 2018;26:93–9.
[288] Shahabuddin M, Alim M, Alam T, Mofijur M, Ahmed S, Perkins G. A critical review on the development and challenges of concentrated solar power technologies. Sustain Energy Technol Assess 2021;47:101434.