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Review

A Review of the Modeling of Parabolic Trough Solar Collectors Coupled to Solar Receivers with Photovoltaic/Thermal Generation

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Abstract: This paper is a summary of the last ten years of work on the study of parabolic trough collectors (PTCs) and compound parabolic collectors (CPCs) coupled to photovoltaic and thermal solar receiver collectors (SCR-PVTs). While reviewing the state of the art, numerous review papers were found that focused on conventional solar receiver collector (SRC) technology for solar thermal generation. However, there is a lack of review papers summarizing SRC-PVT hybrid technology for solar electric/thermal generation, which would be beneficial for researchers interested in this area of research. This paper provides a review of SRC-PVT hybrid technologies. The theoretical foundations for analyzing and modeling PTC and CPC concentrators coupled to SRC-PVT are described, with an emphasis on modeling through thermal resistances and energy balances. Additionally, this section provides a concise overview of previous studies that have addressed the modeling of PTC and CPC collectors coupled to SCR-PVT, as well as experimental information useful for the validation of new mathematical models of SRC-PVT.

Keywords: concentrated solar thermal; solar electricity; parabolic trough collectors

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1. Introduction

Energy consumption is closely related to the development of civilization and the economy. Electrical and thermal energy power the services that improve society's quality of life. Hence, a diversified and abundant energy supply is considered essential to ensure human progress. Solar photovoltaic thermal concentrator technologies (CPV/T) are potential options to satisfy these needs. These technologies utilize solar radiation as an energy source, making them a form of renewable energy source.

In 2021, worldwide installations of concentrated solar power (CSP) plants were reported to have an energy production capacity of 6 gigawatts. The majority of CSP installations were found in the United States and Spain, whilst countries such as Chile, the United Arab Emirates, China and South Africa are projected to increase their power production through new CSP plant projects. At an industrial level, around 70% of CSP plants currently under construction are based on parabolic trough collectors (PTC), the rest being central tower plants [1]. Despite the efforts made, CSP technology is less advanced than other renewable sources, like conventional solar photovoltaic (PV) or wind energy. Therefore, it is advisable to establish policies that provide financial incentives for CSP plant installation, as well as promoting research and development (R&D) initiatives to decrease installation costs.

In the field of CSP technologies, the parabolic trough collector (PTC) and the compound parabolic collector (CPC) [2,3] are the most investigated solar collectors with linear geometry. Researchers interested in this field can find multiple reviews on the state of the art [4–7]. These review papers provide information on aspects such as modeling, simulation, trends and compilations of recent studies. However, these recent review papers mainly focus on solar receiver collector (SRC) technology for thermal power generation.

There is an increasing tendency to research solar concentrating technologies with photovoltaic and thermal solar receiver collectors (SRC-PVTs) [8]. The purpose of this review paper is to present a summary of the most recent studies focusing on PTCs and CPCs coupled to SRC-PVTs. This review paper includes trends, modeling strategies and simulation.

The document is structured as follows to meet the objectives of this review paper: Firstly, the introduction provides a justification for the development of the review paper. Second, a summary of previous review papers is presented as a background, as well as a summary of recent studies on PTCs and CPCs coupled to SRC-PVTs. The third section discusses the theoretical fundamentals of PTCs and CPCs, through geometrical, optical and thermal analyses, as well as covering a classification and description of the modeling strategies proposed in the summary of recent studies. The fourth section provides the geometrical characteristics of the different SRC-PVTs and the proposed efficiency equations, as well as parameters and values useful for the validation of the simulated mathematical models. Finally, the fifth section discusses the main points to be considered in the analysis of PTCs and CPCs coupled to SRC-PVTs, together with their areas of opportunity and future perspectives.

2. Methodology of the State-of-the-Art Review

2.1. Previous State-of-the-Art Review Papers

Table 1 includes state-of-the-art review papers that focus on the modeling and classification of PTC and CPC collectors. The papers were identified based on a search for papers that provided background for the objectives of this review. This proved to be a useful exercise for the author, who gained a better knowledge of the topic.

Table 1 presents a summary of the review papers by authors [9–13] that classify and describe the fundamentals of modeling and simulation of CSP systems, especially in PTCs. However, these review papers are focused on conventional SRCs. In contrast, the review paper by Herez [8] provides a clearer overview of the classifications and applications of PVT technologies, but does not include modeling and simulation aspects.

Table 1. Summary of state-of-the-art review papers focusing on PTC and CPC.

Researcher—Year	Focus	Highlights
Bayareh—2023 [9]	Modeling and simulation of conventional PTC collectors.	• Numerical techniques used for PTC simulation. • Recent advances, challenges and future directions in PTC numerical simulation. • Mathematical models used to simulate PTC performance. • Optimization algorithms to minimize computational costs. • Verification of thermal, optical and thermodynamic performance estimated by simulations.
Singh—2023 [10]	Modeling and simulation of conventional PTC collectors.	• Procedure for geometrical analysis of PTC. • Review of mathematical models related to geometrical parameters, receiver tube thermal losses and PTC performance parameters. • Criteria and description of the thermal resistance model, mathematical equations and thermal losses associated with the receiver. • Performance improvements in PTCs through the use of nanofluids, heat sinks, contact surface adjustment or combinations thereof.

Table 1. *Cont.*

Researcher—Year	Focus	Highlights
Masood—2022 [10]	Characteristics, analysis and improvement strategies for conventional CPC collectors and PVT systems.	• Description of the components of a concentrator photovoltaic system based on CPCs. • Review of the available literature related to the design and evaluation of the optical performance of CPCs for photovoltaic applications. • Compilation of recent CPC research, including studies on the impact of horizontal and vertical fins on heat transfer properties. • Discussion of the challenges facing the research community and appropriate recommendations for future research and development in this field.
Malan—2021 [11]	Mathematical analysis and optical modeling of conventional PTC collectors.	• Optical analysis of the PTC, including measurement techniques and modeling software. • Coupling of optical and thermal analysis to maximize PTC performance. • Discussion of the challenges and limitations of PTC optical and thermal analysis.
Herez—2020 [8]	Overview of solar collectors coupled to SRC-PVTs.	• A novel classification of photovoltaic/thermal collectors. • Description of applications using PVT systems. • Presentation of photovoltaic/thermal (PVT) systems with coupled thermoelectric generators (TEG). • Review of studies on photovoltaic/thermal collectors (PVT) with respect to each classification, application and type of PVT-TEG system.
Yilmaz—2018 [12]	Modeling and simulation of conventional PTC collectors.	• Review of previous studies on PTC modeling. • Description of optical and thermal models and modeling approaches. • Analytical and ray tracing approaches for optical modeling. • Review of stationary and transient heat transfer conditions for thermal modeling. • Description of passive and nanofluid techniques for PTC performance enhancement.

Although many of the fundamentals treated for conventional CSP technologies (such as geometric and optical analysis) are applicable to CPV/Ts, the situation is not the same for the thermal analysis of the SRC-PVT. Previous studies focused on modeling and simulation strategies; however, this topic requires further research. Therefore, this review paper presents an opportunity to expand the scope of the previous reviews.

2.2. Review of Previous Studies

In the review, an initial comprehensive search was carried out for papers reporting on PTCs and CPCs coupled to SRC-PVTs. This search was conducted systematically on various platforms such as Elsevier, MDPI, ASME, Wiley and Google Scholar. The following keywords were utilized:

- PTC—PVT: Parabolic Trough Collector—PhotoVoltaic Thermal;
- CPC—PVT: Compound Parabolic Collector—PhotoVoltaic Thermal;
- CPV/T: Concentrated PhotoVoltaic Thermal;
- LCPV/T: Low Concentrating PhotoVoltaic Thermal;
- HCPV/T: High Concentrating PhotoVoltaic Thermal;
- PTES: Photovoltaic Thermal Electrical System;
- CHAPS: Combined Heat And Power Solar.

Furthermore, a comprehensive search was conducted using the "Research Rabbit 2023" tool in addition to conventional search engines. This particular platform facilitated the identification of articles and researchers linked to a previously provided list of studies by the author (Figure 1) The search was categorized based on factors such as the year, journal, type of collector, and other criteria.

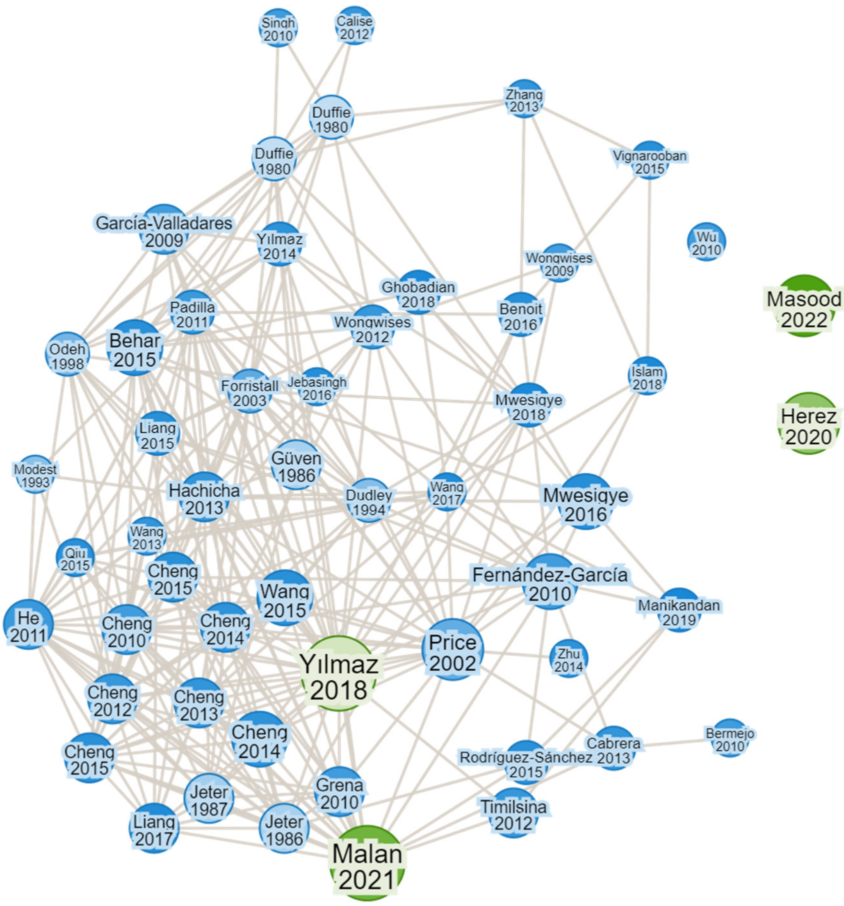


Figure 1. Search for studies of relevance with the Research Rabbit tool.

The search period covered from 2013 to mid-2023, with a focus on selecting the most recent studies with clear numerical data. The objective was to include a minimum of 100 studies for review. Table 2 provides a summary of all the studies focusing on PTCs, while Table 3 provides a summary of all the studies focusing on CPCs.

Table 2. Summary of the review studies focusing on PTCs coupled to SRC-PVTs.

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2023 [14]	Azizi	*Applied Thermal Engineering*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2023 [15]	Hou	*Renewable Energy*	Theoretical	Optical and spectral analysis	N/A
2023 [16]	Renno	*Energies*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2023 [17]	Santana	*Energies*	Theoretical	Evaluation of thermal and/or electrical performance	N/A
2023 [18]	Zheng	*Applied Energy*	Theoretical	Parametric and sensitivity study	Energy balance eq.

Table 2. *Cont.*

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2022 [19]	Acosta	*Renewable Energy*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary
2022 [20]	Dogahe	*Environmental Progress and Sustainable Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	N/A
2022 [21]	Gorouh	*Renewable Energy*	Theoretical and experimental	Simulation and/or validation of a mathematical model	Quasi-stationary, 1D
2022 [22]	Kurşun	*Energy Conversion and Management*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary
2022 [23]	Zhu	*Solar Energy*	Theoretical and experimental	Optical and spectral analysis	N/A
2021 [24]	Cabral	*Solar Energy*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2021 [25]	Herez	*Renewable Energy Focus*	Theoretical	Simulation and/or validation of a mathematical model	Stationary, 1D
2021 [26]	Herez	*Renewable Energy*	Theoretical	Parametric and sensitivity study	Stationary, 1D
2021 [27]	Hu	*Energy Conversion and Management*	Theoretical	Parametric and sensitivity study	Stationary
2021 [28]	Renno	*Energies*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2021 [29]	Zhang	*Energy Conversion and Management*	Theoretical	Evaluation of thermal and/or electrical performance	Energy balance eq.
2021 [30]	Zima	*Energy*	Theoretical and experimental	Simulation and/or validation of a mathematical model	Dynamic, 1D
2020 [31]	Acosta	*Energies*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary
2020 [32]	Alayi	*Environmental Progress and Sustainable Energy*	Theoretical	Parametric and sensitivity study	N/A
2020 [33]	Felsberger	*Energies*	Experimental	Development and experimental testing	N/A
2020 [34]	Gakkhar	*Applied Thermal Engineering*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Stationary, 1D
2020 [35]	Huaxu	*Energy*	Experimental	Optical and spectral analysis	N/A
2020 [36]	Khouya	*Applied Thermal Engineering*	Theoretical	Parametric and sensitivity study	Finite elements
2020 [37]	Otanicar	*Applied Energy*	Theoretical and experimental	Development and experimental testing	Stationary
2020 [38]	Renno	*Energies*	Theoretical	Simulation and/or validation of a mathematical model	Stationary, 1D
2020 [39]	Renno	*Energies*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	N/A
2020 [40]	Riahi	*Energy Conversion and Management*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Dynamic

Table 2. *Cont.*

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2020 [41]	Wang	*Renewable Energy*	Theoretical	Optical and spectral analysis	N/A
2020 [42]	Wingert	*Solar Energy*	Experimental	Optical and spectral analysis	N/A
2019 [43]	Adam	*Energy*	Theoretical	Optical and spectral analysis	Stationary, 2D
2019 [44]	Alves	*Solar Energy*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary, 3D, Finite elements 3D
2019 [45]	Karathanassis	*Renewable Energy*	Theoretical	Simulation and/or validation of a mathematical model	Dynamic
2019 [46]	Liew	*Renewable Energy*	Theoretical	Evaluation of thermal and/or electrical performance	1D, Energy balance eq.
2019 [47]	Maatallah	*Solar Energy*	Theoretical	Simulation and/or validation of a mathematical model	Dynamic, 3D
2019 [48]	Renno	*Applied Thermal Engineering*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary
2019 [49]	Renno	*Energy Conversion and Management*	Theoretical and experimental	Simulation and/or validation of a mathematical model	Stationary, 1D
2019 [50]	Valizadeh	*Renewable Energy*	Theoretical	Energy and exergy analysis	Stationary, 1D
2019 [51]	Wang	*Energy*	Theoretical	Optical and spectral analysis	Finite elements
2019 [52]	Widyolar	*Applied Energy*	Theoretical and experimental	Optical and spectral analysis	N/A
2018 [53]	Ben Youssef	*Solar Energy*	Theoretical and experimental	Parametric and sensitivity study	2D, Finite elements
2018 [54]	Ben Youssef	*Solar Energy*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary
2018 [55]	Otanicar	*Applied Energy*	Experimental	Optical and spectral analysis	N/A
2018 [56]	Renno	*Energies*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Stationary, 1D, Finite elements
2018 [57]	Widyolar	*Solar Energy*	Theoretical	Optical and spectral analysis	N/A
2018 [58]	Widyolar	*Applied Energy*	Theoretical	Optical and spectral analysis	N/A
2017 [59]	An	*Energy Conversion and Management*	Theoretical and experimental	Parametric and sensitivity study	Stationary
2017 [60]	Karathanassis	*Renewable Energy*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2017 [61]	Mohsenzadeh	*Renewable Energy*	Experimental	Development and experimental testing	N/A
2017 [62]	Srivastava	*Solar Energy*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary, 3D, Finite elements
2017 [63]	Wang	*Applied Thermal Engineering*	Theoretical and experimental	Optical and spectral analysis	N/A

Table 2. *Cont.*

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2017 [64]	Widyolar	*Renewable Energy*	Theoretical and experimental	Optical and spectral analysis	Finite elements
2017 [65]	Yazdanifard	*Energy Conversion and Management*	Theoretical	Parametric and sensitivity study	Quasi-stationary, 1D
2016 [66]	Brekke	*Journal of Solar Energy Engineering*	Theoretical	Simulation and/or validation of a mathematical model	2D
2016 [67]	Stanley	*Applied Energy*	Experimental	Optical and spectral analysis	N/A
2015 [68]	Al-Nimr	*Solar Energy*	Theoretical	Parametric and sensitivity study	Stationary
2014 [69]	Barrau	*Solar Energy*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2014 [70]	Xu	*Journal of Thermal Science and Engineering Applications*	Theoretical	Simulation and/or validation of a mathematical model	Stationary, 2D, Finite elements
2013 [71]	Calise	*Energy*	Theoretical	Simulation and/or validation of a mathematical model	Stationary
2013 [72]	Karathanassis	*Applied Thermal Engineering*	Theoretical	Study of geometries and/or solar tracking	N/A

Table 3. Summary of the review studies focusing on CPCs coupled to SRC-PVTs.

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2023 [73]	Cabral	*Energies*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	N/A
2023 [74]	Korres	*Sustainability*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary, Finite elements
2023 [75]	Saberi	*Case Studies in Thermal Engineering*	Theoretical and experimental	Simulation and/or validation of a mathematical model	Stationary
2020 [76]	Li	*Solar Energy*	Experimental	Study of geometries and/or solar tracking	Differential eq.
2020 [77]	Li	*Solar Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Continuity eq.
2020 [78]	Li	*Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Dynamic, Continuity eq.
2020 [79]	Nasseriyan	*Energies*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Stationary, Finite elements, Differential eq.
2019 [80]	Cabral	*Solar Energy*	Theoretical	Optical and spectral analysis	Quasi-dynamic
2019 [81]	Haiping	*Applied Thermal Engineering*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2019 [82]	Haiping	*Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Quasi-stationary
2019 [83]	Haiping	*Journal of Cleaner Production*	Theoretical and experimental	Simulation and/or validation of a mathematical model	Stationary, 1D

Table 3. *Cont.*

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2019 [84]	Wang	*Solar Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Dynamic and Stationary
2019 [85]	Xinxin	*Desalination*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Stationary, 1D
2019 [86]	Yang	*Energy Conversion and Management*	Theoretical and experimental	Simulation and/or validation of a mathematical model	Dynamic
2018 [87]	Cabral	*Solar Energy*	Theoretical	Study of geometries and/or solar tracking	Stationary, 1D
2018 [88]	Gupta	*Desalination*	Theoretical	Simulation and/or validation of a mathematical model	Quasi-stationary
2018 [89]	Jaaz	*Results in Physics*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2018 [90]	Tiwari	*Solar Energy*	Theoretical	Energy and exergy analysis	Quasi-stationary, 1D
2018 [91]	Torres	*Energies*	Theoretical	Study of geometries and/or solar tracking	N/A
2018 [92]	Zhang	*Solar Energy*	Theoretical and experimental	Optical and spectral analysis	Energy balance eq.
2017 [93]	Haiping	*International Journal of Energy Research*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	N/A
2017 [94]	Heng	*Journal of Solar Energy Engineering*	Theoretical and experimental	Simulation and/or validation of a mathematical model	3D, Finite elements, Differential eq.
2017 [95]	Jaaz	*Materials*	Experimental	Evaluation of thermal and/or electrical performance	N/A
2017 [96]	Liu	*Energy Conversion and Management*	Theoretical	Evaluation of thermal and/or electrical performance	Stationary, 3D, Finite elements
2017 [97]	Probell	*Solar Energy*	Experimental	Development and experimental testing	N/A
2017 [98]	Singh	*Solar Energy*	Theoretical	Evaluation of thermal and/or electrical performance	Quasi-stationary, Energy balance eq.
2017 [99]	Tripathi	*Solar Energy*	Theoretical and experimental	Study of geometries and/or solar tracking	Quasi-stationary, Energy balance eq.
2017 [100]	Tripathi	*Energy Conversion and Management*	Theoretical	Evaluation of thermal and/or electrical performance	Quasi-stationary
2017 [101]	Zhang	*Renewable Energy*	Theoretical and experimental	Optical and spectral analysis	Non uniformity eq.
2016 [102]	Atheaya	*Solar Energy*	Theoretical	Energy and exergy analysis	Quasi-stationary
2016 [103]	Probell	*Solar Energy*	Theoretical and experimental	Optical and spectral analysis	Finite elements
2016 [104]	Tripathi	*Solar Energy*	Theoretical	Parametric and sensitivity study	Quasi-stationary, Energy balance eq.
2016 [105]	Tripathi	*Solar Energy*	Theoretical	Energy and exergy analysis	Quasi-stationary, 1D, Energy balance eq.
2016 [106]	Vance	*Journal of Solar Energy Engineering*	Theoretical	Study of geometries and/or solar tracking	N/A

Table 3. *Cont.*

Year	Researcher	Journal	Study	Main Focus of Work	Modeling Considerations
2016 [107]	Yousef	*Energy Conversion and Management*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Quasi-stationary, Governing Eq.
2015 [108]	Li	*Solar Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Dynamic
2015 [109]	Li	*Applied Energy*	Theoretical and experimental	Development and experimental testing	N/A
2015 [110]	Zhou	*Energies*	Theoretical	Optical and spectral analysis	Stationary, Finite elements
2014 [111]	Bahaidarah	*Applied Energy*	Theoretical and experimental	Evaluation of thermal and/or electrical performance	Stationary, 1D, Energy balance eq.
2014 [112]	Guiqiang	*Applied Energy*	Theoretical and experimental	Optical and spectral analysis	N/A
2014 [113]	Li	*Energy Conversion and Management*	Theoretical and experimental	Optical and spectral analysis	N/A

Within Tables 2 and 3, the first three columns correspond to the year of publication, the author of the study and the journal. Column four denotes whether the study is theoretical or experimental. Column five details the main contribution of the study; a classification of seven different types of contributions was established for the summarized studies. This classification excludes contributions related to economic and environmental analyses. Finally, column five provides notes about modeling and simulation considerations.

Figure 2 provides a percentage representation of publishers and journals hosting studies focusing on PTCs and CPCs coupled to SRC-PVTs. Additionally, it presents the publication trend (within the period covered by the review) for the four journals with the highest number of studies and for publishers in general.

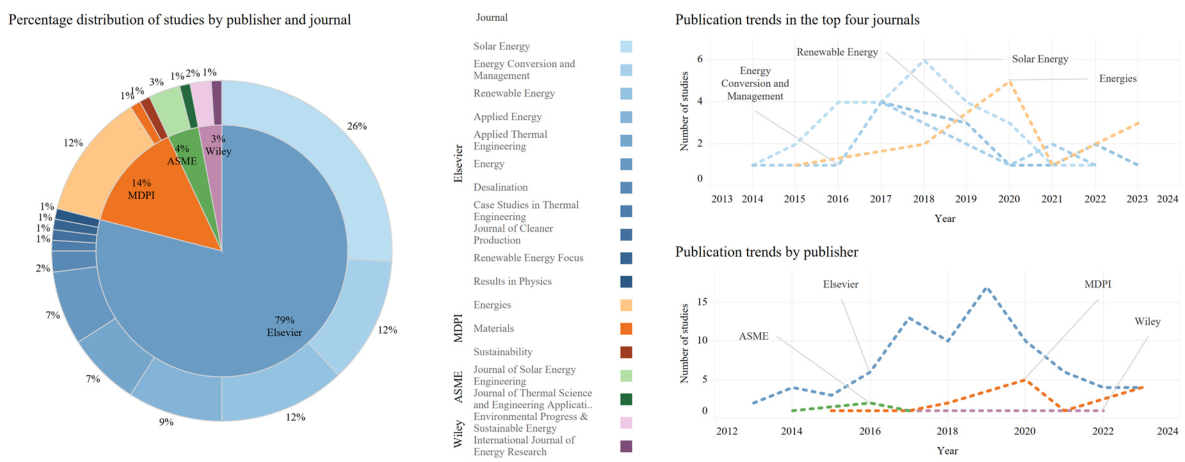


Figure 2. Percentage distribution of studies by publisher and journal; publication trends in the top four journals and by publisher.

The leading publisher for papers on PTCs and CPCs coupled to SRC-PVTs is Elsevier, with the following journals: *Solar Energy* with 26%, *Renewable Energy* with 12% and *Energy Conversion and Management* with 12%. Following this is MDPI, with the journal *Energies* (12%). These journals together account for 62% of the summarized studies of review.

The author has a high regard for the *Journal of Thermal Science and Engineering Applications*, published by ASME. Although it only includes 4% of the summarized studies in the review, it is a journal focused on solar energy issues; Brekke et al. [66] provide valuable information for SRC-PVT modeling. Therefore, it is recommended to consult his future studies [114,115], with the expectation that they will discuss other relevant aspects of PTC and CPC modeling.

As previously discussed, column five of Tables 2 and 3 established a classification of seven different types of contributions; each of the studies summarized in the review was classified into one of these seven types of contributions. The contribution assigned is a function of the main and most discussed contents in each of the papers. The classification excludes contributions related to economic and environmental analyses. These seven types of contributions are listed below:

- Simulation and/or validation of a mathematical model;
- Evaluation of thermal and/or electrical performance;
- Optical and spectral analysis;
- Energy and exergy analysis;
- Parametric and sensitivity study;
- Development and experimental testing;
- Study of geometries and/or solar tracking.

Figure 3 presents the distribution of studies according to the seven different types of contributions. Furthermore, it presents the distribution of studies within each journal. It also shows the publication trends of the studies for each of the seven types of contribution within the period covered by the review.

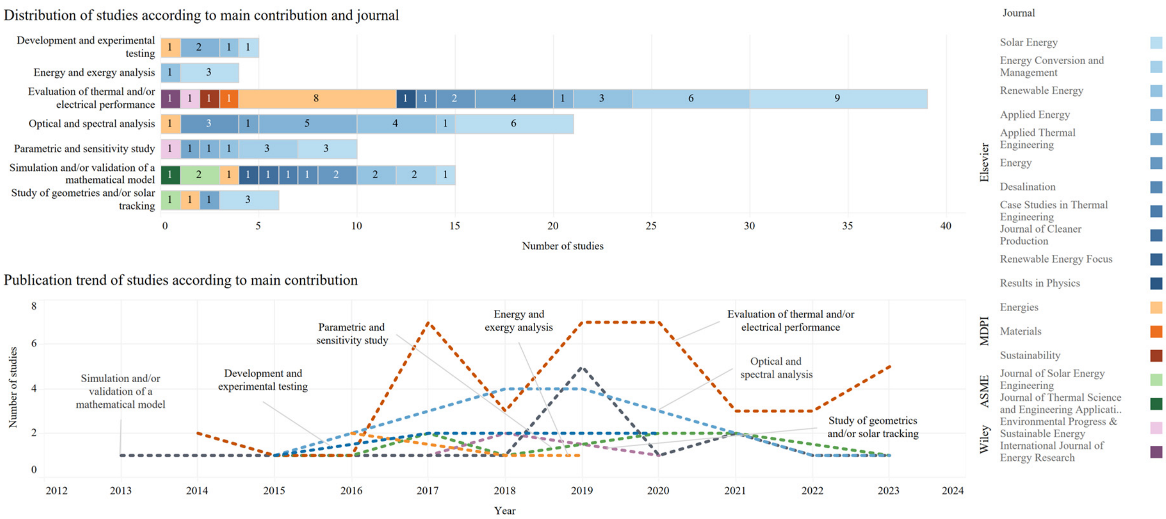


Figure 3. Distribution of studies according to main contribution and journal; publication trend of studies according to main contribution.

The exclusion of economic and environmental contributions is justified by the need to prioritize the information according to theoretical and experimental contributions, which are more related to the development of mathematical models, test prototypes and validation (which is the objective of this review paper). It is worth mentioning that among the studies summarized, there are contributions focusing on economic and environmental studies, as indicated in the following:

Herez provides a state-of-the-art review of CPV/T systems and presents an overview of power generation using PV and TEG [8]. Additionally, he proposes a model for a PTC collector coupled to SRC-PVT that includes case studies and economic and environmental analysis [25]. Finally, a parametric study of the proposed model is presented [26].

Acosta and Santana analyzed the thermal and electrical performance of a PTC collector coupled with an SRC-PVT for different applications. They conducted an economic feasibility analysis of these applications and provided mathematical formulae details for the calculation of thermal and electrical efficiencies [17,19,31].

Tripathi outlines his methodology for developing a mathematical model of SRC coupled to CPC. The proposed model is evaluated from an energy and exergy perspective, and is experimentally validated [99,104]. Additionally, a parametric study is conducted to determine the optimal configuration of a series of interconnected CPCs and their corresponding mass flow rate for a given operating temperature [105]. In the field of techno-economic feasibility, a lifecycle cost analysis is applied to determine the energy cost of the system [100].

Otanicar and Brekke proposed retrofitting existing conventional PTC collector plants with an SRC-PVT. They conducted a study on the economic impact of this technology [37]. The researchers also conducted experimental tests on heat fluid transfer (HTF) with nanoparticles for the spectral splitting of radiation in the SRC-PVT [55]. Finally, they presented a strategy and mathematical model for SRC-PVT [66].

3. Fundamentals of PTCs and CPCs

PTC and CPC concentrators are derived from cylindrical geometry, as their name indicates. The analysis of these technologies encompasses various areas, including the incidence of the sun's rays on reflecting mirrors, temperature distribution throughout the concentrator and calculations of stresses on a device's structure. Therefore, it is suggested to adopt the procedure shown in Figure 4 in order to study and design solar collector systems.

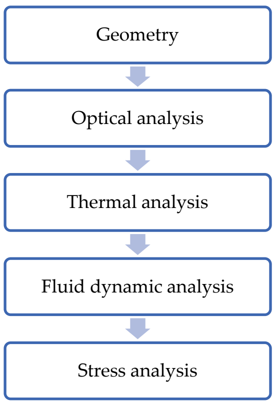


Figure 4. Analysis and design procedure for solar collector systems.

3.1. Geometry for PTCs and CPCs

In this section, the study details the relationship between reflecting parabolic mirrors and the SRC. Duffie et al. [116] and Kalogirou [117] recommend books that provide equations on this topic. The following section presents the proposed geometry equations for PTC.

The focal length, denoted by f_{PTC}, is determined using Equation (1):

$$f_{PTC} = \sqrt{\phi_r{}^2/4}, \tag{1}$$

The aperture radius, denoted by $r_{r,PTC}$, is determined using Equation (2):

$$r_r = \frac{2f}{1 + cos\phi_r}, \tag{2}$$

The aperture width, denoted by a_{PTC}, is determined using Equation (3):

$$a_{PTC} = 2f tan(\phi_r/4), \tag{3}$$

The edge angle, denoted by ϕ_r, can be obtained from the focal length (f_{PTC}) and the aperture width (a_{PTC}), which is determined using Equation (4):

$$\phi_r = \tan^{-1}\left(\frac{8(f/a)}{16(f/a)^2 - 1}\right), \tag{4}$$

The width of the image, denoted by W, projected on a flat SRC is determined using Equation (5):

$$W = \frac{2\ r_r sin0.267}{cos\left(\varnothing_r + 0.267\right)}, \tag{5}$$

The diameter of SRC with cylindrical geometry, denoted by D, is determined using Equation (6):

$$D = \frac{asin0.267}{sin\varnothing_r}, \tag{6}$$

For the CPC collector, the following geometry equations are proposed. The focal length, denoted by f_{CPC}, is determined using Equation (7):

$$f_{CPC} = a'(1 + sin\theta_c), \tag{7}$$

The aperture ratio, denoted by a_{CPC}, is determined using Equation (8):

$$a_{CPC} = \frac{a'}{sin\theta_c}, \tag{8}$$

The height ratio, denoted by h_{CPC}, is determined using Equation (9):

$$h_{CPC} = \frac{fcos\theta_c}{sin^2\theta_c}, \tag{9}$$

The truncated aperture ratio, denoted by $a_{T,CPC}$, is determined using Equation (10):

$$a_{T,CPC} = \frac{fsin(\theta_T - \theta_c)}{sin^2(\theta_T/2)} - a', \tag{10}$$

The truncated height ratio, denoted by $h_{T,CPC}$, is determined using Equation (11):

$$h_{T,CPC} = \frac{fcos(\theta_T - \theta_c)}{sin^2(\theta_T/2)}, \tag{11}$$

3.2. Optical Analysis for PTCs and CPCs

Regarding the optical analysis, the following equations are proposed for the PTC. The radiation absorbed by the SRC, denoted by S_{PTC}, is determined using Equation (12):

$$S_{PTC} = I_b\left(\rho_a \tau_g \alpha_r \gamma\right) K(\theta_i) X_{ex}, \tag{12}$$

The incident angle modifying factor, denoted by $K(\theta_i)$, is determined with Equation (13):

$$(\theta_i) = cos\theta_i + 0.000884(\theta_i) - 0.00005369(\theta_i)^2, \tag{13}$$

The end loss effect, denoted by X_{ex}, is determined using Equation (14):

$$X_{ex} = 1 - \frac{f}{L} tan\theta_i, \tag{14}$$

For the CPC collector, the following optical equations are proposed. The radiation absorbed by the SRC, denoted by S_{CPC}, is determined with Equation (15):

$$S_{CPC} = G_{b,\ CPC}\tau_{c,b}\tau_{CPC,b}\alpha_b + G_{d,\ CPC}\tau_{c,d}\tau_{CPC,d}\alpha_d + G_{g,\ CPC}\tau_{c,g}\tau_{CPC,g}\alpha_g, \quad (15)$$

The incident angle modifying factor, denoted by $G_{b,\ CPC}$, is determined with Equation (16):

$$G_{b,\ CPC} = FG_{bn}\cos\theta, \quad (16)$$

The incident angle modifying factor, denoted by $G_{d,\ CPC}$, is determined with Equation (17):

$$G_{d,\ CPC} = \begin{cases} \frac{G_d}{C} & si\ (\beta+\theta_c) < 90^\circ \\ \frac{G_d}{C}\left(\frac{1}{C}+\cos\beta\right) & si\ (\beta+\theta_c) > 90^\circ \end{cases}, \quad (17)$$

3.3. Thermal Resistance Analysis of the SRC-PVT

The research conducted by Kalogiruo [117,118], Forristall [119] and Behar [120] provides a description of the analysis procedure for conventional SRCs. This information is crucial for comprehending the thermal resistance method and its energy balance equations between the environment and the HTF.

There are studies that analyze the SRC-PVT using their own thermal resistance models. For example, Herez et al. [26] discuss a triangular geometry SRC-PVT model and consider the PV to be in direct contact with the environment. In contrast, Karathanassis et al. [45] present a model of a rectangular-geometry SRC-PVT with seven different layers. The first layer is a glass cover that isolates the PV from the environment. Another example is the study by Brekke et al. [66], which also considers a model of SRC-PVT with rectangular geometry, but on the side exposed to the environment there is a nanofluid that acts as a selective solar radiation filter for the PV.

This review article summarizes several SRC-PVT models focused on different considerations, such as selective filters, TEG and vacuum layers. However, only Forristall [119] considers the conduction heat losses in the SRC supports with the collector, for a conventional SRC model. Therefore, it is appropriate to study this consideration in an SRC-PVT model to evaluate its impact on the overall model response.

Figure 5 shows a cross-section of a simple rectangular SRC-PVT. The diagram indicates the energy flows and considers the conduction heat losses in the supports. This information enables the establishment of the energy balance:

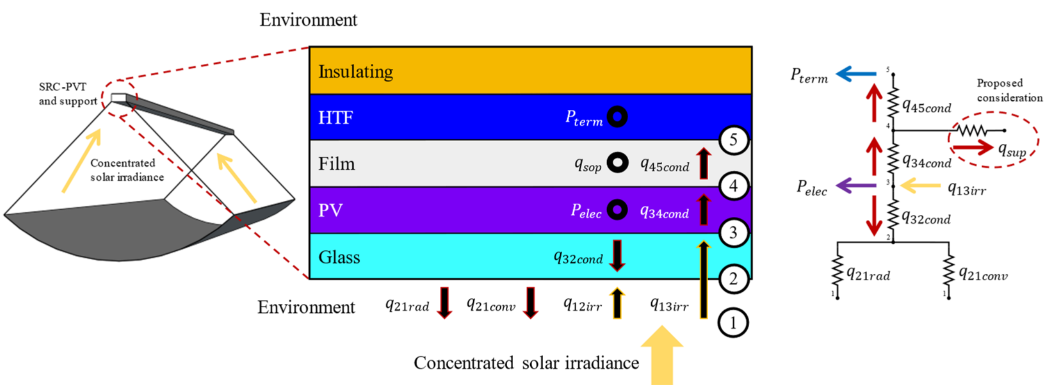


Figure 5. The thermal resistance model of an SRC-PVT, including the conduction heat losses in the SRC-PVT supports with the collector.

- Effective concentrated solar irradiance (q_{12irr}) is incident on the side of the glass exposed to the environment, while a heat flux emitted by the PV (q_{23cond}) is incident on the opposite side;

- A fraction of the incident irradiance on the crystal is converted into heat (q_{12irr}), which is added to the heat flux from the PV (q_{23cond}). Both of these are then emitted to the environment as radiation (q_{21rad}) and convection (q_{21conv});
- The irradiation passing through the crystal is incident on the PV (q_{13irr}) and is converted into electrical energy (P_{elec}) due to the photoelectric effect;
- A fraction of the irradiance incident on the PV (q_{13irr}) is emitted as two heat fluxes, the first in the crystal direction (q_{23cond}) and the second through the film to the HTF (q_{34cond});
- The heat arriving at the film is again divided into two fluxes, the first in the HTF direction (q_{45cond}) and the second corresponding to the conduction heat losses in the supports (q_{sup});
- The heat flow conducted through the PV and the film to the HTF (q_{45cond}) is extracted as thermal energy (P_{term}).

In Figure 5, both the effective concentrated solar irradiance and the different heat transfer modes (conductive, "*cond*"; radiative, "*rad*"; and convective, "*conv*") are represented as energy or heat fluxes, with arrows indicating their direction. The energy balance result is expressed as Equations (18)–(21):

$$q_{12irr} + q_{32cond} = q_{21rad} + q_{21conv}, \tag{18}$$

$$q_{13irr} = q_{32cond} + q_{34cond} + P_{elec}, \tag{19}$$

$$q_{34cond} = q_{45cond} + P_{sup}, \tag{20}$$

$$q_{45cond} = P_{term}, \tag{21}$$

The model presented takes into account the following considerations:

- The energy balance is one-dimensional and steady-state. Uniformity is assumed for all temperatures, heat fluxes and thermodynamic properties. Furthermore, the insulation on the opposite side of the glass is assumed to prevent any heat loss;
- Effective concentrated solar irradiation refers to the amount of solar energy that remains following the consideration of optical and geometrical losses of the concentrator. The energy balance excludes terms that represent concentrator losses;
- The energy flux resulting from effective concentrated solar irradiation corresponds to the amount of light absorbed by the glass and PV (absorbance). This phenomenon is volumetric in nature, but for ease of analysis it is treated as a surface phenomenon under the assumption that the resulting error is relatively minor [119].

It is important to mention that there are defined criteria for modeling each of the three heat transfer modes (Table 4); a more detailed explanation can be found in the book by Incropera et al. [121].

Table 4. Heat transfer modes and their general modeling equations [121].

Mode	Mechanism	Equation or Model	
Conduction	Diffusion of energy due to random molecular motion	$q_{cond} = -k\frac{dT}{dx}$	(22)
Convection	Diffusion of energy due to random molecular motion plus energy transfer due to global motion (advection)	$q_{conv} = h(T_s - T_\infty)$	(23)
Radiation	Energy transfer by electromagnetic waves	$q_{rad} = \varepsilon\sigma\left(T_1^4 - T_2^4\right)$	(24)

3.4. Description of the SRC-PVT Energy Balance Equations

The modeling equations in Table 4 define the terms for the three types of heat transfer modes described in Equations (18) and (20), as well as those concerning heat absorption through solar irradiation. It is important to note that the modeling equations are adapted to the characteristics of the SRC-PVT, such as the geometry.

Equation (18) corresponds to the energy balance of the heat flows in the SRC-PVT crystal and is composed of the following terms of the Equations (25)–(28):

The heat absorbed by the crystal, denoted by q_{12irr}, is determined by the following parameters, according to [26,45]:

$$q_{12irr} = a_{glass} G_{beam} A_{glass} \eta_{optical}, \tag{25}$$

The conduction heat loss of the crystal, denoted by q_{32cond}, is determined by the following parameters, according to [26,45]:

$$q_{32cond} = \frac{T_{PV} - T_{glass}}{R_{cond,glass}}; \quad R_{cond,glass} = \frac{t_{glass}}{K_{glass} A_{glass}}, \tag{26}$$

The radiation heat losses of the crystal, denoted by q_{21rad}, is determined by the following parameters, according to [26,34,50,66]:

$$q_{21rad} = \varepsilon_{glass} \sigma A_{glass} \left(T_{glass}^4 - T_{environment}^4 \right), \tag{27}$$

The convective heat losses of the crystal, denoted by q_{21conv}, are determined by the following parameters, according to [26]:

$$q_{21conv} = \frac{T_{glass} - T_{environment}}{R_{conv,glass}}; \quad R_{conv,glass} = \frac{1}{h_{glass} A_{glass}}, \tag{28}$$

Equation (19) corresponds to the energy balance of the heat flows in the PV and is composed of the following terms of the Equations (29) and (30):

The heat absorbed by the PV, denoted by q_{13irr}, is determined by the following parameters, according to [26,45]:

$$q_{13irr} = \left(1 - a_{glass}\right) \tau_{glass} \, a_{PV} \, G_{beam} \, A_{PV} \, \eta_{optical}, \tag{29}$$

The conduction heat loss of the PV, denoted by q_{34cond}, is determined by the following parameters, according to [26,45]:

$$q_{34cond} = \frac{T_{PV} - T_{film}}{R_{cond,PV}}; \quad R_{cond,PV} = \frac{1}{h_{PV} A_{PV}} \tag{30}$$

Equation (20) corresponds to the energy balance of the heat flows in the film and is composed of the following terms of the Equation (31):

The conduction heat loss of the film, denoted by q_{45cond}, is determined by the following parameters, according to [26,45]:

$$q_{45cond} = \frac{T_{film} - T_{HTF}}{R_{cond,film}}; \quad R_{cond,film} = \frac{1}{h_{film} A_{film}} \tag{31}$$

For the modeling of the terms "P_{elec}" and "P_{term}", which correspond to the electrical power produced by the PV and the thermal power extracted by the HTF, as well as the modeling of the conduction heat losses in the supports "P_{sup}", the following assumptions are made.

3.4.1. Electrical Model of the PV

The electrical power ($P_{electrical}$) generated by the PV is part of the energy balance of Equation (19). It has been defined in different ways depending on the complexity and accuracy assumed for the mathematical model. Table 5 presents a summary of the different equations proposed in the studies to model the electrical power produced by the PV.

Table 5. Summary of equations for modeling PV electrical power proposed in previous studies.

Researcher	Parameters	Equation or Model	
Herez [26]	P_{elec} = Electrical power of the PV. A_{PV} = Area of the PV. CR_{PV} = PV concentration ratio. IAM_{elec} = Incidence angle modifier. I_b = Solar radiation beam. η_{PV} = PV efficiency. η_{opt} = Optical efficiency.	$P_{elec} = I_b\ A_{PV}\ CR_{PV}\ \eta_{opt}\ IAM_{elec}\ \eta_{PV}$	(32)
Karathanassis [45]	P_{el} = Electrical power. η_{el} = Electrical efficiency. Q_{irr} = Radiation flux incident on the surface of the solar cells. A_a = Aperture area. a_{cell} = Solar cell absorption. a_{gl} = Glass absorption. G_b = Direct solar radiation flux. η_{opt} = Optical efficiency. τ_{gl} = Glass transmittance.	$P_{el} = \eta_{el} Q_{irr};\quad Q_{irr} = \left(1 - a_{gl}\right)\left(\tau_{gl}\ a_{cell}\right) G_b\ A_a\ \eta_{opt}$	(33)
Maatallah [47] Ben Youssef [53,54]	P_{elec} = Electrical output power. G_c = Concentration ratio. G = Beam radiation. A_{pv} = PV area. η_{op} = Optical efficiency. η_{mod} = Module efficiency. η_{inv} = Inverter efficiency. η_{pv} = PV efficiency.	$P_{elec} = G_c\ G\ A_{pv}\ \eta_{op}\ \eta_{mod}\ \eta_{inv}\ \eta_{pv}$	(34)
Alayi [32] Calise [71]	P_{el} = Electrical power. C_{PVT} = PVT concentration ratio. A_{PVT} = PVT area. I_b = Beam radiation. η_{opt} = Optical efficiency. η_{PV} = PV efficiency. IAM_{el} = Electrical angle of incidence modifier.	$P_{el} = C_{PVT}\ A_{PVT}\ I_b\ \eta_{optic}\ \eta_{PV}\ IAM_{el}$	(35)
Yazdanifard [65]	I_B = Beam radiation intensity. CR = Concentration ratio. ρ_{con} = Reflection coefficient of the concentrator. γ_t = Intercept factor. α_{pv} = PV absorption coefficient. τ_g = Transmission coefficient of the glass cover. pa = Packing factor. $A_{PV/T}$ = PV/T area. η_r = Reference efficiency of solar cells. β_r = Reference temperature coefficient. T_{pv} = PV temperature. T_r = Reference temperature.	$P_{elec} = I_B\ CR\ \rho_{con}\ \gamma_t\ \alpha_{pv}\ \tau_g\ pa\ A_{PV/T}\ \eta_r\ (1 - \beta_r(T_{pv} - T_r))$	(36)
Ji [122]	P_{elec} = PV electric power. I_L = Photocurrent. I_0 = Diode saturation reverse current. I = Current. n = PV pieces. q = Elemental charge. V = Load voltage. R_s = Series resistance. A = Diode quality factor. k = Boltzmann constant. T_p = Average working temperature of the PV.	$P_{elec} = I\left[\frac{n\ A\ k\ T_p}{q}\ ln\left(\frac{I_L - I}{I_0} + 1\right) - n\ I\ R_s\right]$	(37)
Acosta [19,31]	P_e = Electrical power. A_a = Aperture area. F_R = Collector heat removal factor. K_T = Temperature coefficient. T_a = Room temperature. T_i = Intermediate temperature. U_L = Collector heat loss coefficient. S = Incident solar irradiance. η_{PV} = PV efficiency. η_{PV_r} = Reference PV efficiency. α = Absorbance.	$P_e = \frac{\frac{A_a S \eta_{PV}}{\alpha}}{\sqrt{\left\{1 - \frac{\eta_{PV_r} K_T}{\eta_{PV}}\left[F_R(T_i - T_a) + \frac{S}{U_L}(1 - F_R)\right]\right\}}}$	(38)

3.4.2. Thermal Model of the HTF

The thermal power ($P_{thermal}$) extracted by the HTF is part of the energy balance of Equations (20) and (21); it is defined by Equation (39). This model is generally accepted and has been used in different studies: Ji [122], Haiping [83], Xinxin [85], Karathanassis [45] and Herez [25].

$$P_{thermal} = \dot{m}C_{HTF}(T_{HTF,outlet} - T_{HTF,inlet}), \quad (39)$$

3.4.3. Model of the Conduction Heat Losses in the Supports

The thermal resistance that represents the conduction heat losses in the supports of the SRC with the collector can be modeled by considering an "infinite fin", as proposed by Forristall [119]. Equation (40) defines the parameters that represent the conduction heat losses in the supports "P_{sup}", which are present in the energy balance of Equation (20).

$$P_{sup} = \sqrt{h_{sup}P_{sup}k_{sup}A_{cs,b}}(T_{sup} - T_{environment})/L_{SRC-PVT}, \quad (40)$$

3.5. Modeling and Simulation Strategies

In the previous sections, fundamental information has been provided to understand the analysis of CPV/T systems based on PTC and CPC. It is important to note that this information is limited to the thermal analysis step (Figure 4) and is valid for one-dimensional stationary models. Introducing the concept of other modeling strategies would substantially prolong this review paper; moreover, most of the studies summarized are based on the steady-state model. Nevertheless, Figure 6 presents a classification of the strategies found in the state-of-the-art review to be used in the modeling and simulation of PTC and CPC. This classification can be extended to other types of collectors.

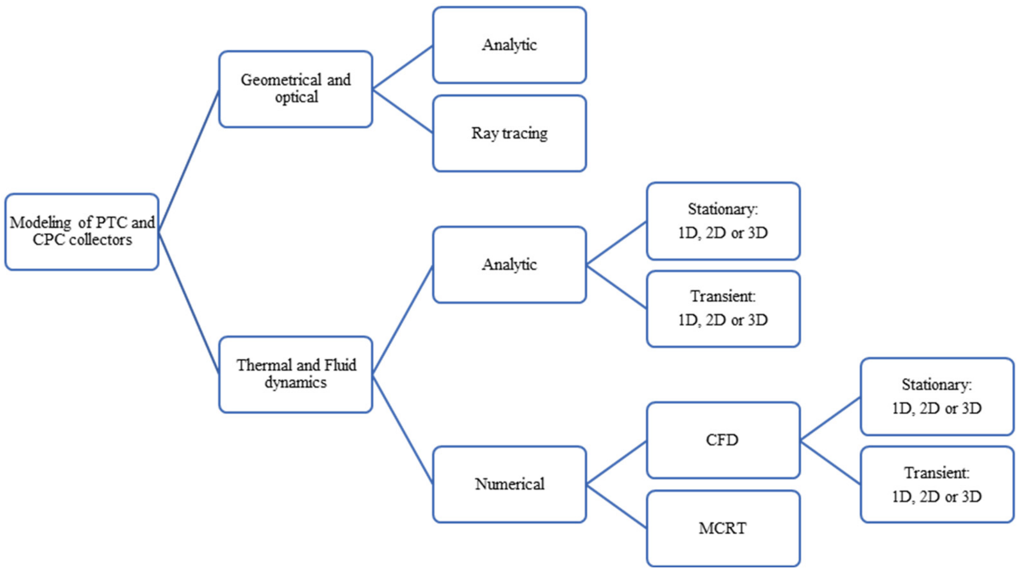


Figure 6. Modeling strategies for solar collector systems.

3.5.1. Simulation Software

Previous review papers have provided summaries of the main software used to simulate the different steps in the analysis of CSP systems. This is the case for Masood et al. [10], who provide a scheme with the main simulation software focused on the optical analysis of CSP systems. In this review paper, Table 6 presents software focused on optical analysis using numerical and ray tracing techniques, while Table 7 corresponds to the software focused on thermal analysis using numerical and analytical techniques.

Table 6. Software focused on the optical analysis of CSP systems.

Software	Main Characteristics	Simulation Method	Type of License
Tonatiuh 2.2.4	Tailored for modeling sunlight behavior with solar collectors and concentrators	Ray tracing	Open Source
SolTrace 3.4	Developed by NREL for analyzing solar concentrating systems like parabolic troughs, dish collectors and linear Fresnel systems	Ray tracing	Free
TracePro 23.3	Versatile optical simulation software applicable to a wide range of applications, including solar collectors	Ray tracing	Commercial (paid license)
SolView 2021.0	Allows visualization and analysis of solar ray paths in concentrating systems; evaluates shadows and losses	Ray tracing	Commercial (paid license)
Tracer 8.2.1	Offers advanced optical modeling and analysis capabilities	Ray tracing	Commercial (paid license)
Zemax 24.1	Commercial optical design and analysis software used for various optical systems, including solar collectors	Ray tracing	Commercial (paid license)
LightTools 9.1	Another commercial optical design and analysis software suitable for simulating optical behavior of solar collectors	Ray tracing	Commercial (paid license)
RayTracing	Models light propagation through optical components	Ray tracing	Varies (open source and commercial)
SolarGIS 1.4.4	Provides solar resource data and modeling tools, including tools for assessing solar concentration systems	Varies (depending on tool)	Commercial (paid license)
TASCSim V4.00	Developed by Sandia National Laboratories for analyzing the optical and thermal performance of concentrating solar power (CSP) systems	Ray tracing and more	Free
OptisWorks	Software suite for optical simulation and virtual prototyping, applicable to optical analysis of solar collectors	Ray tracing	Commercial (paid license)

Table 7. Software focused on the thermal analysis of CSP systems.

Software	Main Characteristics	Simulation Method	Type of License
TRNSYS 18.05	Provides a wide range of components for system modeling	Numerical methods	Commercial (paid license)
RETScreen 9.1.0.24	Developed for analyzing clean energy projects with modules for solar thermal collector simulations	Numerical methods	Free
SAM 2022.11.21	Versatile tool for modeling the financial and energy performance of solar thermal systems including collectors	Numerical methods	Free
PVSyst 7.4	Known for photovoltaic simulations; it also offers thermal modules for solar collectors	Numerical methods	Commercial (paid license)
HOMER	Optimizes and analyzes renewable energy systems, including solar thermal collectors	Energy balance analysis	Commercial (paid license)
RETScreen Expert eighth version	An advanced version of RETScreen with additional features for detailed solar thermal system simulations	Numerical methods	Free

Table 7. *Cont.*

Software	Main Characteristics	Simulation Method	Type of License
Transol 3.2	Specialized software for simulating solar thermal collectors and domestic hot water systems. Commonly used in the solar thermal industry	Numerical methods	Commercial (paid license)
EnergyPlus 8.4	Building energy simulation software that can model solar thermal systems integrated into buildings	Numerical methods	Free
EES 10.2	The software is a general equation solver used for a wide range of engineering and thermodynamic simulations	Numerical methods	Commercial (paid license)

3.5.2. Structure for Simulation Development

The development of CPV/T system simulations requires a series of steps based on the analysis procedure detailed in Figure 4, as well as iterative strategies for solving energy balance equations and other numerical methods. A flowchart is an effective tool for defining the structure of simulation development.

Several studies in the review provide examples of a proposed flowchart for simulation development: Malan presents a flowchart detailing the operation of the algorithm used by the Soltrace software for incident irradiance distribution in a PTC using ray tracing techniques [11]. Herez presents a flowchart describing the iteration procedure of the non-linear equations that constitute his mathematical model [25,26]. Haiping presents a flowchart demonstrating the implementation of a procedure for calculating the thermal and electrical performance of his proposed SRC-PVT using MATLAB software [83]. Meanwhile, Ju presents a flowchart detailing the optical analysis, iteration of energy balance equations and thermal and electrical performance calculations for a CPV/T system and a TEG [123].

Programming languages such as Fortran or software such as MATLAB can be used for simulation development. For complex systems, a combination of languages and software is useful to facilitate the development of simulations and mathematical models. Figure 7 shows a flowchart illustrating the procedure for simulating a PTC or CPC coupled to an SRC-PVT using TRNSYS and EES.

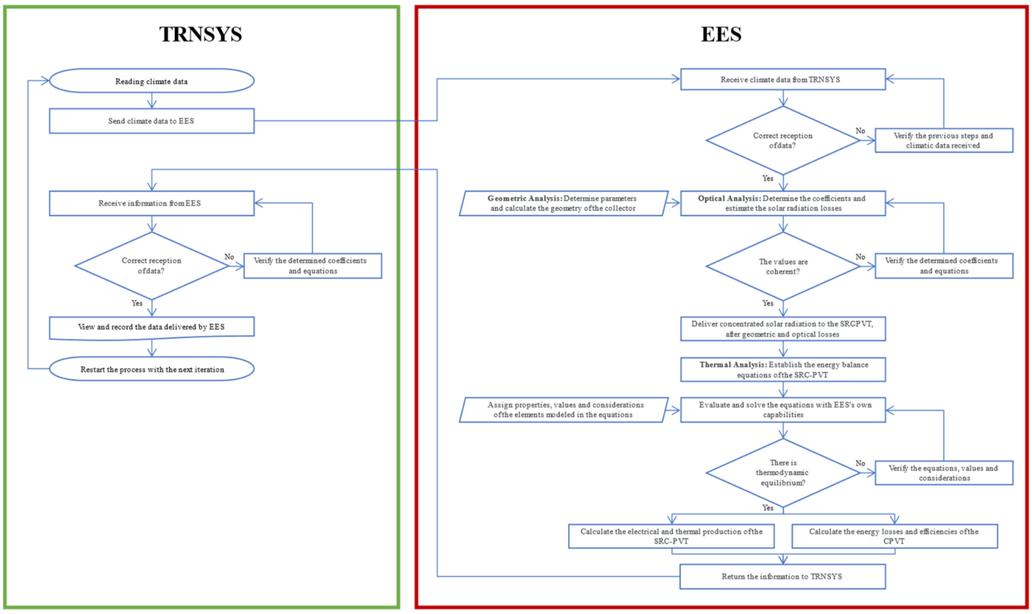


Figure 7. Diagram proposed by the author to simulate a PTC coupled to SRC-PVT with TRNSYS 18.05 and EES 10.2 software together.

The flowchart broadly describes the following procedure: The climate data of a given region are read from TRNSYS, and subsequently transferred to EES for geometrical, optical and thermal analysis (using energy balance equations). Energy production and losses, as well as thermal and electrical efficiencies, are calculated. The data are then returned to TRNSYS for storage and visualization. The process is then repeated, with a new iteration that updates the climate data.

The reasons for using the two software packages together are as follows:

- TRNSYS is a software with a stage called "kernel" that reads and processes input files (e.g., climate files), solves iteratively, determines convergences and plots variables in conjunction with another stage, which is a library containing a set of mathematical models [124]. It allows the development of renewable energy systems through quasi-dynamic simulations (stationary models iterated several times). However, it does not have a model representing a PTC or CPC coupled to SRC-PVT.
- EES is software focused on solving systems of equations. It includes a database of highly accurate thermodynamic and transport properties for several substances [125]. This attribute facilitates the researcher in considering relevant aspects in their mathematical models. Hence, it is convenient to develop energy balance equations that represent the SRC-PVT in ESS and connect it to TRNSYS.

4. Review Studies Focusing on SRC-PVT Models

4.1. Geometry of SRC-PVTs

There are many options and designs available for an SRC-PTV. These options are determined by electrical or thermal production requirements, manufacturing complexity and heat extraction mechanisms. Table 8 provides a summary of the SRC-PTVs found in the review studies according to their main geometries, a graphical example and a brief description.

From the geometries for SRC-PVT listed in Table 8, the following are of interest:

The "Simple Rectangular" geometry type has been reported by several authors, including Xinxin [85], Haiping [83], Xu [70], Hou [15] and Ben Youssef [54]. Xinxin [85] and Haiping [83] focused on desalination at low concentrations and temperatures, presenting energy balance equations of SRC-PVT considering a steady state in one-dimension. Ben Youssef [54] proposed a new mathematical model with differential equations and in two dimensions.

Table 8. Summary of SRC-PVT geometries reported in previous studies.

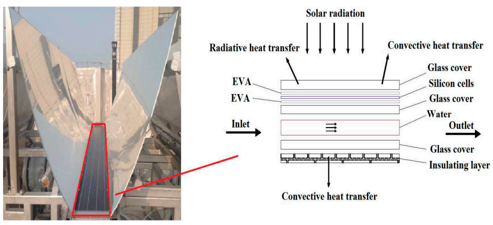
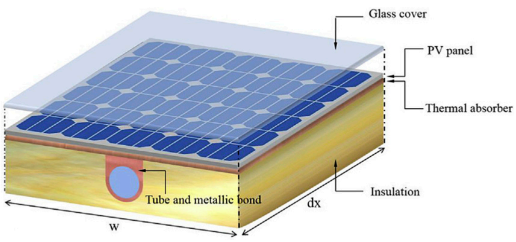
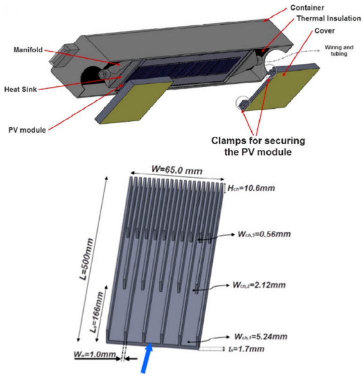
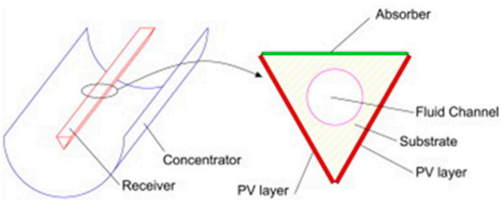
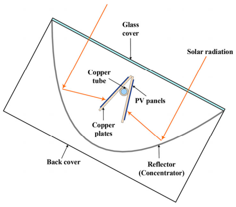
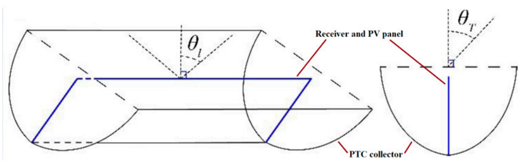
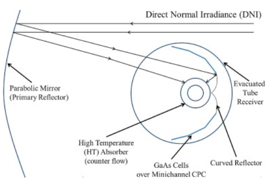
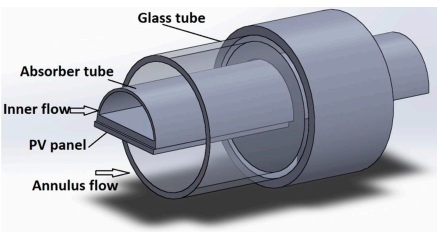
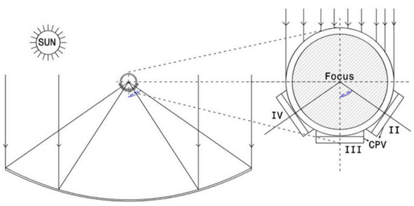
Geometry of SRC-PTV	Example	Description
Simple Rectangular: Xinxin [85]; Haiping [83]; Xu [70]; Hou [15]; Maatallah [47]; Ben Youssef [54].		It has a rectangular prism structure, with one of the larger rectangular sides mounted with a PV and situated at the focal point of a CPC or PTC. Behind the PV, a rectangular trough is installed for circulating the HTF.
Rectangular with cylindrical pipe: Yazdanifard [65]; Cabral [80]; Ji [122].		It adopts the same geometry and trough as the SRC-PTV "Simple Rectangular", but inside the trough there is a substrate that acts as a thermal insulator and one or more cylindrical absorber pipes in which the HTF circulates.

Table 8. *Cont.*

Geometry of SRC-PTV	Example	Description
Rectangular with fins: Karathanassis [45].		The SRC-PTV "Simple Rectangular" has identical geometry and trough design to the one mentioned above, but inside the trough there are fins to enhance heat transfer between the HTF and the PV cell.
Triangular: Herez [25]; Calise [71]; Zheng [18]; Santana [17]; Mohsenzadeh [61].		It has a triangular prismatic structure in which the two lower sides are equipped with PVs and are oriented to the focal point of a PTC, while the upper side is equipped with a heat absorber. An absorber pipe is placed within of triangular prism, where the HTF circulates.
Wedge: Gorouh [21]; Cabral [24].		The geometry of the trough is in the form of a "V" or wedge. An absorber tube is placed at the inner bottom of the trough, where the HTF circulates. PVs are mounted on the exterior sides of the trough.
Bifacial: Cabral [73,87].		It consists of two PVs positioned opposite each other and facing each side of a PTC or CPC. A series of pipes are placed between the backs of the PVs to circulate the HTF.
Cylindrical with internal CPC: Widyolar [64].		It has cylindrical geometry that can adopt the dimensions of a conventional SRC-PTV for industrial thermal applications. It incorporates a CPC with PVs at its extremities and an absorber pipe with the HTF at its focal point.
Cylindrical with intermediate PV: Gakkhar [34].		It has cylindrical geometry that can adopt the dimensions of a conventional SRC-PTV for industrial thermal applications. The difference is that the absorber pipe in the center of the cylinder is replaced by a PV. The HTF circulates on the front and back of the PV.
Cylindrical with PVs on pipe: Srivastava [62]; Felsberger [33].		It has cylindrical geometry that can adopt the dimensions of a conventional SRC-PTV for industrial thermal applications. Within the cylinder resides an absorber pipe surrounded by PVs.

The "Rectangular with cylindrical pipe" geometry has been studied by Ji [122] and Yazdanifard [65] using energy balance equations and steady state in one dimension. Yazdanifard [65] has proposed equations to analyze the SRC-PVT with and without a glass envelope. Meanwhile, Karathanassis [45,60,72] studied the "Rectangular with fins" geometry in detail to enhance heat transfer to the HTF.

The "Triangular" geometry has been considered by Herez [25], Calise [71], Zheng [18], Santana [17] and Mohsenzadeh [61]. Herez [25] and Calise [71] have proposed steady state in one-dimensional models for this type of SRC-PVT.

Two lesser-known variants of SRC-PVT geometries are the "Wedge" type studied by Gorouh [21] and Cabral [24] and the "Bifacial" type, which has also been studied by Cabral [73]. Both geometries have the objective of enhancing the angle of incidence of solar radiation.

Recently, there has been notable interest in the study of SRC-PVTs with a cylindrical envelope, which can be coupled to industrial PTCs or CPCs. Studies on these geometries have been conducted by the following authors: Widyolar [52,57,58,64], for the "Cylindrical with internal CPC" type, and Gakkhar [34] for the "Cylindrical with intermediate PV" type. Meanwhile, Srivastava [62] and Felsberger [33] have conducted both studies and simulations on the "Cylindrical with PVs on pipe" type.

4.2. Thermal and Electrical Efficiency Equations

Table 9 illustrates a summary of the equations for the calculation of electrical and thermal efficiency proposed by different authors of the review studies.

Table 9. Summary of equations proposed for electrical and thermal efficiency in previous studies.

Author	Electrical Efficiency Equation		Thermal Efficiency Equation	
Herez [25,26]	$\eta_{elec} = \frac{P_{elec,PV}}{I_b A_{ap}}$	(41)	$\eta_{th} = \frac{q_f}{I_b A_{ap}}$	(42)
Karathanassis [45,60,72]	$\eta_{el} = \frac{V_{MPP} I_{MPP}}{A_a G_b}$	(43)	$\eta_{th} = \frac{Q_{th}}{A_a G_b} = \frac{\dot{m} c_p \left(T_{f,out} - T_{f,in}\right)}{A_a G_b}$	(44)
Haiping [83]	$\eta_{el} = \frac{UI}{CGA_c}$	(45)	$\eta_{th} = \frac{C_p \dot{m} (T_{out} - T_{in})}{CGA_c}$	(46)
Xinxin [85]	$\eta_e = \frac{P_e}{CI_r A_c}$	(47)	$\eta_{th} = \frac{P_{th}}{CI_r A_c}$	(48)
Xu [122]	$\eta_e = \frac{P_{max}}{I_d A_m}$	(49)	$\eta_t = \frac{mc_{p,f} (T_{out} - T_{in})}{I_d A_m}$	(50)

4.3. Parameters and Values for the Validation of Mathematical Models

Several experimental studies were excluded from the holistic study due to their publication date. However, some researchers have used their experimental results to validate their mathematical models. Table 10 presents a group of studies with experimental results, divided according to the type of collector and whether it is included in the review or not.

Table 10. Studies with experimental results for the simulation and validation of SRC-PVT models.

Studies Included in the Review that Report Experimental Results	
PTC collectors	Felsberger [33] Gakkar [34] Otanicar [37] Mohsenzadeh [61]
CPC collectors	Probell [97] Tripathi [99] Li [76,78,108] Bahaidarah [111]
Studies not included in the review that report experimental results	
PTC collectors	Ji [122] Bernardo [126]
CPC collectors	Othman [127]

For the author's consideration, this section presents information from studies conducted by Herez [25,26,128,129], Maatallah [47] and Yazdanifard [65]. These authors demonstrate a method for validating a mathematical model and provide a compilation of relevant parameters and experimental results. Their studies hold significance for future modeling, simulation and validation works.

In Table 11, the parameters used in the simulation by Herez [128] of their SRC-PVT model of a triangular geometry are presented, coupled to PTC. The values correspond to the boundary conditions of the system (determined by the environment) and the intrinsic characteristics of the different components that constitute the SRC-PVT, such as the PV or a TEG.

Table 11. Parameters used in the simulation of the SRC-PVT model proposed by Herez [128].

Component	Parameter	Value	Unity
PTC	Aperture area	60	m^2
	Absorptance	0.03	-
	Emissivity	0.30	-
	Concentration ratio	10	-
PV	Area	6.0	m^2
	Thermal conductivity	50	W/mK
	Absorptance	0.97	-
	Emissivity	0.20	-
Absorber	Area	3.0	m^2
	Thermal conductivity	205	W/mK
	Absorptance	0.90	-
	Emissivity	0.20	-
Substrate	Thermal conductivity	250	W/mK
TEG	TEG area	0.0025	m^2
	Thermal conductivity	1.4	W/mK
	Absorptance	0.4	-
	Emissivity	0.60	-
HTF pipeline	Pipe diameter	0.06	m
	HTF specific heat	4183	J/kg K
	Mass flow rate	0.15	Kg/s
	IAM electrical coefficient	0.28	-
	IAM thermal coefficient	0.14	-
Boundary conditions	Total radiation	1000	W/m^2
	Beam radiation	800	W/m^2
	Sky temperature	25	°C
	Ambient temperature	25	°C
	Fluid inlet temperature	25	°C
	Air velocity	5	m/s
	Incident angle	0	°

The author Herez [128] references the experimental results of Calise [130] and Mohsenzadeh [61] to validate the simulation of their SRC-PVT model. Table 12 details the percentage of variation between the simulated model results and the reference experimental results considered.

Table 12. Comparison of the results of the SRC-PVT model proposed by Herez [128] and the reference results.

Parameter	**Results from Thermal Model**	**Reference [130]**	**Deviation**
Thermal power	177.9 W	176.3 W	−0.9%
Total electrical power	20.9 W	19.6 W	−6.6%
PV temperature	94.75 °C	90.75 °C	−1.1%
Parameter	Results from thermal model	Reference [61]	Deviation
HTF outlet temperature	77.7 °C	79.3 °C	0.45%
PV temperature	82.56 °C	82.3 °C	−0.07%
Absorber temperature	78.8 °C	82.7 °C	1.10%
Substrate temperature	78.7 °C	80.5 °C	0.51%

Meanwhile, listed in Table 13 are the parameters required by Yazdanifard [65] to simulate their SRC-PVT model of rectangular geometry and a cylindrical tube coupled to PTC.

Table 13. Parameters used in the simulation of the SRC-PVT model proposed by Yazdanifard [65].

Component	**Parameter**	**Value**	**Unity**
PTC	Concentration ratio	15	-
	Reflection coefficient	0.8	-
	Intercept factor	0.95	-
Glass cover	Thickness	0.004	m
	Transmittance	0.92	-
	Absorptance	0.04	-
PV	Super-thermal conductivity	150.0	$(W\ m^2)/°C$
	Super-absorbance	0.80	-
	Super-emittance	0.35	-
	Super-thickness	0.30	mm
	GaAs thermal conductivity	55.0	$(W\ m^2)/°C$
	GaAs absorbance	0.85	-
	GaAs emittance	0.30	-
	GaAs thickness	0.70	mm
	Reference efficiency	15	%
	Reference temperature coefficient	−273.1455	$°C^{-1}$
	Reference temperature	24.85	°C
HTF	Inlet temperature	24.85	°C
	Mass flow rate in laminar regime	0.02	$kg\ s^{-1}$
	Mass flow rate in turbulent regime	0.12	$kg\ s^{-1}$
Boundary conditions	Wind velocity	1.5	$m\ s^{-1}$
	Collector slope	30	°
	Ambient temperature	24.85	°C
	Solar radiation intensity	700	$W\ m^{-2}$
	Packing factor	0.9	-
	Pump efficiency	0.8	-

Maatallah [47] and Yazdanifard [65] validated their mathematical model simulation using experimental results from Ji [122]. Table 14 displays the variations between the simulated model results and the experimental reference results based on HTF outlet temperature and PV temperature.

Table 14. Comparison of the results of the SRC-PVT model proposed by Yazdanifard [65] and the reference results.

PV Type	Parameter			Value		
	Reference [122]	Model Result	Deviation	Reference [122]	Model Result	Deviation
Substrate	50.1 °C 39.0 °C	50.9 °C 37.2 °C	1.6% −4.6%	83.2 °C 57.6 °C	81.7 °C 62.7 °C	−1.8% 8.8%
GaAs	39.1 °C 38.2 °C	38.3 °C 37.4 °C	−2.0% −2.1%	61.4 °C 59.4 °C	62.9 °C 61.2 °C	2.4% 3.0%

Further studies which provide the necessary parameters for mathematical models of SRC-PVT and collector geometry are Alayi [32], Otanicar [37], Karatanasis [45], Valizadeh [50] and Ben Youssef [53,54] for PTC collectors, while Saberi [75], Haiping [83], Xinxin [85] and Yousef [107] provide values for CPC collectors.

5. Discussion and Conclusions

This review did not examine the correlation between the price of fossil fuels and the studies summarized over the period analyzed. However, studies such as the one presented by the International Renewable Energy Agency [131] demonstrate that concentrating solar power and photovoltaic technologies has reduced their installed cost by 62% and 80%, respectively. This makes them economically viable power generation options compared to their fossil-fuel-based counterparts.

This review paper identifies a group of studies that focus on analyzing the technical–economic feasibility of different proposals for collectors coupled to SRC-PVTs. These studies generally evaluate the levelized cost of energy (LCOE) to determine the payback time. It is generally expected that the costs and payback times will be lower for CSP technology compared to its fossil-fuel-based counterparts. A review of technical economic analyses could be conducted to determine the relationship between technological developments in this field and fossil fuel prices.

5.1. Geometry and Type of Collector

Regarding the geometries of solar collectors, it has been observed that CPCs are commonly used in experimental prototype tests at temperatures of around 100 °C [83,85,97]. These prototypes are typically "handmade", using a truncated geometry CPC collector and a rectangular SRC (due to the PV structure). Another common CPC configuration involves integrating it into the vacuum layer of a SRC, as seen in the "heat pipe" collector technology or the prototype presented by Widyolar et al. [64].

On the other hand, there is potential in adapting SRC-PVTs for industrial production [34]. The PTC is the dominant collector in this case, with temperature ranges from 100 °C to 400 °C [6]. However, the electrical efficiency of PVs depends on temperature, with significant losses above 120 °C [132]. This limits the operating range of an SRC for industrial applications. To improve the thermal energy transfer and harvesting of the SRC, various solutions have been proposed.

5.2. Solutions

Optically selective filters allow only wavelengths that the PV materials can efficiently convert into electricity to pass. This reduces heating in the PV, maintaining good electrical efficiency. The energy of wavelengths less useful to the PV is rejected by the selective filter, if it is a film, or is absorbed by the selective filter itself if it is a nano-fluid.

Nanofluids are utilized to improve energy quality and heat transfer from SRC to HTF. These fluids contain particles of different materials that can exhibit solar radiation absorption properties, making them useful as selective filters. This allows for the direct absorption of energy by the HTF, preventing its loss to the PV.

Research into nanofluids and their formulation to achieve desired behaviors is of great interest. Nanofluids offer the advantage of being able to handle multiple HTFs for the same collector [55,67]. A first HTF with nanofluid can be used as a selective filter to be irradiated directly by the solar collector. This first HTF can reach higher temperatures than those recommended for PVs. In the background, the PV will be irradiated by the previously filtered wavelengths. A second HTF can be used to cool the PV, which improves its electrical efficiency. However, this may cause the second HTF to reach a lower temperature and energy quality. This configuration is a very attractive solution to the trade-off between the temperature limitations of PVs and the high operating temperatures of industrial PTCs.

Piping with fins can be used to improve power quality and heat transfer from the SRC to the HTF. This can be achieved by developing surfaces and geometries that increase the contact area between the SRC and the HTF [60]. This strategy can even promote phase changes in a fluid, as in the case of MultiEffect Distillation (MED) spray nozzles.

Vacuum layers have been shown to improve thermal efficiency in SRC-PVTs by reducing conduction losses to the atmosphere. However, this can have a negative impact on the electrical efficiency of the PV due to the encapsulation in an isolated environment at a higher temperature.

TEGs are capable of generating an electrical potential difference when exposed to high temperatures. They can replace or complement PVs within an SRC-PVT. However, their electrical energy production is lower compared to that of PVs. Therefore, they have received less research attention.

5.3. Modeling

Mathematical models of SRC-PVT include considerations related to the aforementioned solutions: vacuum layers, glass covers, selective filters, nanofluids or even more accurate mathematical representations of the PV to determine its electrical output. A conventional SRC model presented by Forristall [119] takes into account the conduction heat losses in the SRC supports with the collector. However, previous proposals for SRC-PVT models have not taken this into account. Therefore, Sections 3.3 and 3.4 of this review paper propose a thermal resistance model that takes into account the conduction heat losses in the SRC-PVT supports with the collector.

5.4. Strategies for Use

On the topic of evaporative desalination, multi-generation "MED" machines are being developed that can produce fresh water, cooling and electricity [133]. The production of electrical energy in these devices is obtained by recycling the residual steam from the process inside a steam turbine. The heating of the seawater before it enters the first effect of the MED can be undertaken with a collector field. It would be interesting to compare the production of electrical energy using the conventional strategy and that produced using a collector field with SRC-PVT, and how this "SRC-PVT + MED" configuration can affect the other dynamics of the process, such as the temperature and pressure of the seawater entering the MED, or the dimensioning of the collector field itself, with an SRC-PVT instead of a conventional collector field.

According to Acosta et al. [31], the main energy production of a collector field with SRC-PVT is as thermal energy. The production of electrical energy is considered "residual" and it is recommended to use it for electricity consumption to receive a discount from the electricity supplier's tariff. However, thermal energy consumption profiles vary throughout the year, which requires the strategic dimensioning of the collector field. "If the field is dimensioned for the most critical point of the year, it will be oversized for the rest of the year, while if it is dimensioned for the least critical point, it will be undersized". To ensure optimal performance throughout the year, it is important to find a middle ground when dimensioning a collector field for thermal demand. Typically, a collector field that provides about 80% of the most critical demand of the year will be used. The remaining thermal demand is supported by auxiliary equipment.

In view of the aforementioned considerations, it is reasonable to research the versatility that SRC-PVTs can offer in the dimensioning of the collector field. The same collector field with SRC-PVTs can prioritize thermal or electrical energy production depending on the demand profile. "For example, if thermal demand is low, the mass flow of the HTF can be adjusted to increase PV electrical efficiency. If thermal demand is high, the quality of energy obtained from the HTF can be prioritized over electrical efficiency of the PV".

In conclusion, future research should consider the following points:

- The impact on the overall response of the SRC-PVT model when considering thermal conduction losses due to the SRC-PVT supports with the collector;
- The impact on collector field dimensioning and MED systems when using SRC-PVTs;
- Strategies and configurations that enable the SRC-PVT to achieve higher temperatures without compromising the electrical efficiency of the PV. These include the use of selective filters, nanofluids and dissipative fins.

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Abbreviations

CSP	Concentrated Solar Thermal Power
CPVT	Concentrated Photovoltaic Thermal
LCOE	Levelized Cost Of Energy
MED	Multi-Effect Distillation
PV	PhotoVoltaic cell
PVT	PhotoVoltaic Thermal
SRC	Solar Receiver Collector
HCE	Heat Collector Element
HTF	Heat Fluid Transfer
PTC	Parabolic Trough Collector
CPC	Compound Parabolic Collector
TEG	ThermoElectric Generation

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