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Review

A Review of Recent Developments and Applications of Compound Parabolic Concentrator-Based Hybrid Solar Photovoltaic/Thermal Collectors

Faisal Masood [1,2,*], Nursyarizal Bin Mohd Nor [1], Perumal Nallagownden [1], Irraivan Elamvazuthi [1], Rahman Saidur [3], Mohammad Azad Alam [4], Javed Akhter [5], Mohammad Yusuf [6], Mubbashar Mehmood [7] and Mujahid Ali [8]

[1] Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia; nursyarizal_mnor@utp.edu.my (N.B.M.N.); nperumal@gmail.com (P.N.); irraivan_elamvazuthi@utp.edu.my (I.E.)
[2] Department of Electrical Engineering, University of Engineering and Technology Taxila, Taxila 47080, Pakistan
[3] Research Center for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, Bandar Sunway, Petaling Jaya 47500, Selangor, Malaysia; saidur@sunway.edu.my
[4] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia; mohammad_18000664@utp.edu.my
[5] Department of Mechanical Engineering, University of Engineering and Technology Taxila, Taxila 47080, Pakistan; javed.akhter@uettaxila.edu.pk
[6] Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia; mohd_18002092@utp.edu.my
[7] School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK; m.mehmood@hw.ac.uk
[8] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia; mujahid_19001704@utp.edu.my
* Correspondence: faisal_17001061@utp.edu.my

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Abstract: The concentrating photovoltaic/thermal (PVT) collectors offer the benefits of the reduced per-unit price of electrical energy and co-generation of electrical and thermal energies by intensifying the solar irradiation falling on the hybrid receiving plane. The compound parabolic concentrating (CPC) collectors have appeared as a promising candidate for numerous applications in the field of solar energy due to their ability to collect both direct and diffuse solar radiation and suitability for stationary installation. Over the last few decades, various configurations of CPC collectors have been proposed and investigated by different researchers for the simultaneous generation of electrical and thermal energies. This article presents a comprehensive review of historical and recent developments and applications of CPC-based hybrid PVT systems. The review focuses on the heat extraction mechanisms and commonly used application areas of CPC-PVT systems. The innovative design configurations proposed by different researchers have been reviewed in detail. The outputs of CPC-PVT systems are generally found to be superior to their counterparts without CPCs, which justifies their increased popularity. Due to dual outputs, the hybrid CPC-PVT systems are considered to be suitable for rooftop and building façade integrated applications. Finally, future recommendations have been enlisted, highlighting the potential research opportunities and challenges for the prospective researchers working in the field of concentrating solar PVT systems.

Keywords: concentration ratio; acceptance half-angle; optical efficiency; building integrated concentrating photovoltaic/thermal; air heating collectors

1. Introduction

The combustion of hydrocarbons increases the emission of greenhouse gases in the atmosphere, resulting in adverse climate change. Simultaneously, exhaustion of such nonrenewable resources in nature causes an increment in their prices. Renewable energy has proved to be a promising solution to this situation. Solar energy is a prime renewable energy resource among renewable energy options to support sustainable development and rapid industrialization [1]. It is a pollution-free, nondepleting, and cheaper energy resource. Solar energy can be harnessed either by solar thermal collectors or solar photovoltaic panels [2]. However, the energy conversion efficiencies of PV panels are inherently lower, which further decrease with a rise in solar cells' temperatures [3]. The hybrid PVT collectors are developed by integrating heat exchangers at the back of PV cells. A working fluid circulates through the heat exchanger tubes and extracts the heat generated during the energy conversion process [4]. The extracted heat can be used in different processes of various industrial applications to satisfy their thermal needs [5]. Due to the co-generation of electricity and heat, the hybrid PVT collectors can achieve higher overall efficiencies than separate PV and thermal collectors [6]. Another obstacle hindering the widespread use of PV technology is the higher upfront cost of silicon semiconductor material which is the major constituent component of PV panels [7–9]. Optical concentrators serve the purpose of enhancing the intensity of solar radiation incidents on a target surface [10]. Due to intensified solar flux, the same output can be produced by a relatively smaller quantity of silicon material [11]. Thus, the costly silicon solar cells can potentially be replaced by relatively cheaper optical concentrating elements. Moreover, the maximum power generated by a concentrator-based hybrid PVT system is enhanced by a factor having a value equal to the geometric concentration ratio of its concentrator [12].

Optical concentrators can be broadly grouped into two categories, namely conventional concentrators and holographic concentrators [13]. The widely used conventional concentrators are further subdivided into different types, such as the refractive, reflective, hybrid, and luminescent concentrators [14], as depicted in Figure 1. The refractive and reflective concentrators follow the principles of refraction and reflection of sunlight from lenses and mirrors, respectively [15]. Another classification of optical concentrators is based on their geometrical concentration ratios. For example, high concentrating collectors are characterized by the geometric concentration ratios above 100× [16]. For medium and low concentrating collectors, the geometric concentration ratio lies in the range of 10–100× and 2–10×, respectively [17]. The incident solar flux on the PV receiver is apparently higher in the case of high concentrating collectors, but they are seldom used in ordinary applications due to the requirement of dual-axis accurate tracking systems, increased cooling power required to maintain the temperature of solar cells within limits and higher initial and maintenance costs [18]. On the contrary, the low concentrating systems are mostly stationary or quasi-stationary depending upon their acceptance angles and are relatively cheaper to manufacture [19]. The concentrators for low concentrating systems include V-troughs and linear Fresnel reflectors and compound parabolic concentrators. Due to their wider acceptance angles, higher optical efficiency, and the capability to gather both direct and diffuse solar radiation, CPCs are preferably employed in low concentration systems [20–22].

Right from the year 1974, when Winston [23] conceived the idea of the application of CPCs for gathering solar energy, these concentrators have found numerous applications in various fields, including solar thermal systems [24], wireless communication systems [25], infrared temperature sensing systems [26], and daylighting control systems [27–30]. In addition, CPCs have also found applications in the fields of thermoelectric generation [31–33] and solar cooking [34]. However, the dominant application of CPC collectors is in solar energy systems, including solar PV, thermal, and hybrid PVT collectors. Some review articles related to concentrating solar thermal collectors [35–38], solar PV systems [39], and PVT collectors [40–45] are available in the literature, which highlighted the importance of CPC as one of the concentrating devices for solar applications. Some authors dedicated their review articles to CPC collectors. In this regard, Tian et al. [46] published a generalized review highlighting the applications of CPCs in different fields of solar energy, including solar PV systems, solar thermal collectors, hybrid PVT collectors, daylighting systems, and photocatalytic water degradation and purification systems. However, the CPC-based hybrid PVT systems were not reviewed in detail. Another comprehensive review regarding applications of CPCs for solar photovoltaic conversion was conducted by Paul [47]. The author delineated various CPC design configurations related to generation of electrical energy only. However, the CPC based PVT systems were not considered at all in the review process.

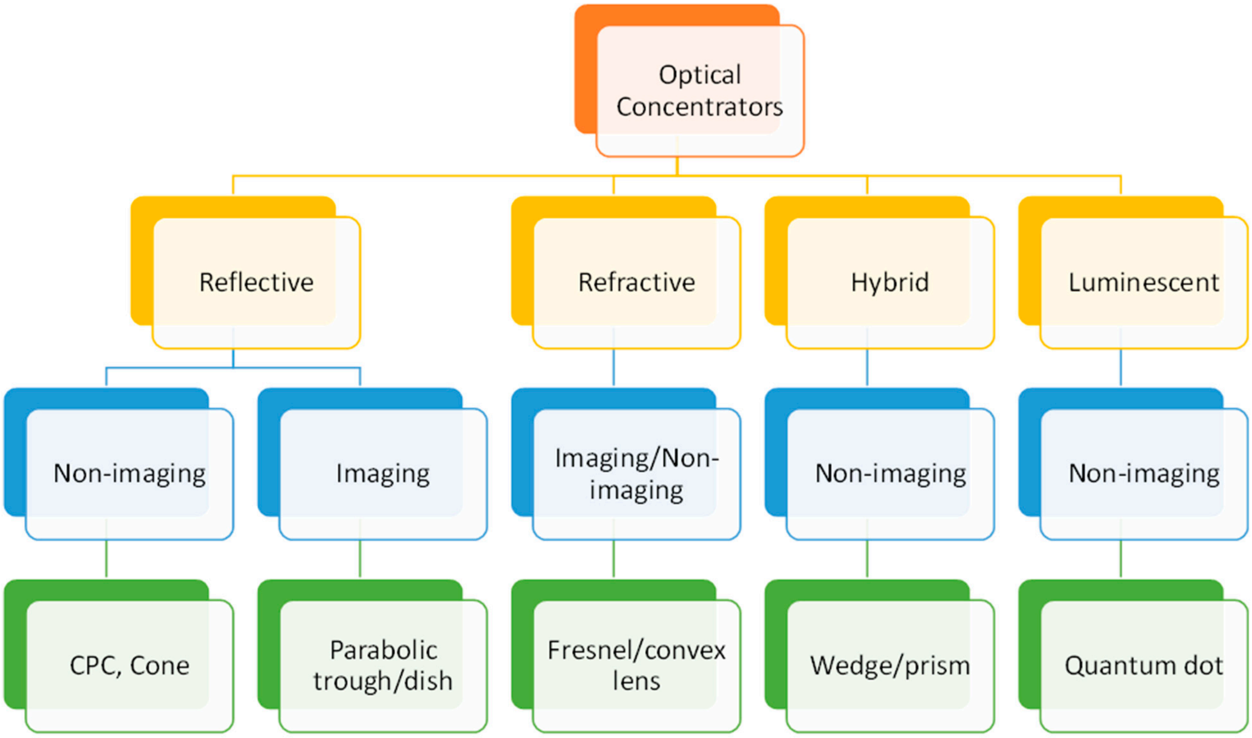

Figure 1. Classification of optical concentrators for PVT systems.

An increasing tendency towards empirical and experimental research publications related to CPC-based PVT systems has been observed in different parts of the world for the past few years. However, to the best of the authors' knowledge, no review is available in the literature about CPC-based PVT systems. This requires an updated and comprehensive review of the published research related to the recent developments and applications of CPC-based hybrid PVT systems, covering unique design configurations and heat extraction techniques. The present review article aims at conducting a detailed review of the available literature related to CPC-PVT systems, considering the recent research developments in the applications of CPCs in the relevant fields of solar energy. The review of CPC-based hybrid PVT systems includes different heat exchanger configurations as well as different heat extraction methods using heat transfer fluids such as air and water. Finally, the recommendations are made to serve as guidelines for prospective researchers based on the detailed review of available literature.

2. Historical Perspective

Optical concentrators are used in both solar thermal collectors and solar PV converters. However, the motivation for using optical concentrators is different for two major classes of solar energy collectors. In the case of solar thermal collectors, the key aspiration for employing concentrators is to elevate the performance at higher operating temperatures by reducing the heat losses due to a relatively smaller absorber area. Conversely, the major motivation for using optical devices in solar PV converters is the economic benefit achieved due to reduced solar cell area owing to the concentration of solar irradiation [48]. The silicon solar cell is the most expensive part of a solar PV-based electricity generation system which prohibits the widespread use of PV generators to fulfill domestic and industrial electrical load requirements [49]. However, the costly solar cells can be replaced by relatively cheaper optical concentrators to render the solar PV generators cost-effective.

After initial investigations in the USA during the 1970s, the technical feasibility and economic viability of CPCs for PV applications had been established. To further reinforce this, Mallick et al. [50] conducted an experimental study in the UK employing an asymmetric CPC of 2.0× concentration to demonstrate that maximum generated power increases by 62% due to CPC. Yousef et al. [51] conducted a performance assessment of a PV module integrated with 2.4× CPC for climatic conditions of Egypt using experimental and numerical methods. Their results indicated that the peak power produced by the CPC-based PV module increased by 18% compared to analogous non-concentrating PV modules. The authors also reported an increment of 32% in the short-circuit current. Nonetheless, the open-circuit voltage declined by 5% due to high temperature. The next research phase started to eradicate the problems observed during the first phase with different research goals. Various research groups and individual researchers investigated CPC-PV systems with versatile research objectives. For example, some authors proposed novel designs of CPCs for PV systems and conducted research to investigate their optical performance. In contrast, others explored the varieties of solar cells employed in the PV receiver, including monocrystalline, polycrystalline, or thin-film solar cells. Some research studies were devoted to the issue of non-uniform illumination of the receiver and how to mitigate its impact on the system's performance.

3. Basic Construction and Classification of CPCs

The CPC collectors belong to a class of concentrators called non-imaging concentrators. These concentrators allow the design of optical systems that can attain maximum geometric concentrations permitted by laws of physical conservation for a given angular field. As opposed to imaging or focusing concentrators, the concentrators based on non-imaging optics are capable of achieving moderate levels of concentration without tracking the sun. Non-imaging optical concentrators are designed based on the edge ray principle, which asserts that sun rays emanating from the verges of the source are focused on the verges of the target surface [48]. Thus, all rays lying within a given acceptance angle have a chance to reach the receiver.

In its simplest form, the CPC consists of two parabolic reflecting segments that direct the sunrays arriving at the entrance aperture to a receiver surface positioned at the leaving aperture [52]. The left and right segments of CPC are parts of two parabolas, while the receiver is placed between the focus points of these parabolas. The axes of the parabolic segments are orientated away from the CPC axis by an angular range, known as an acceptance half angle, as illustrated in Figure 2. The solar radiation falling within this angular range of CPC would travel all the way to reach the receiver, directly or after one or more reflections [53–55].

The design process of an ideal CPC starts with specifying the values of acceptance half angle and width of the flat receiver. The resulting width of the entry aperture and total height of CPC are then calculated using the equations derived by Winston and his fellow researchers [57,58]. Afterward, the set of coordinates for one of the parabolic reflectors in the Cartesian coordinate system is determined [59]. The other side parabolic reflector is simply the mirror image of its counterpart [48] in a symmetric CPC. Some researchers have developed a new set of equations for designing a symmetric CPC having a flat receiver, e.g., Taneja et al. [60], Fraidenraich and Salcedo [61], and Tiruneh [62]. Paul [63] presented a detailed review of mathematical equations used to design different symmetric and asymmetric CPC collectors configurations for solar energy applications.

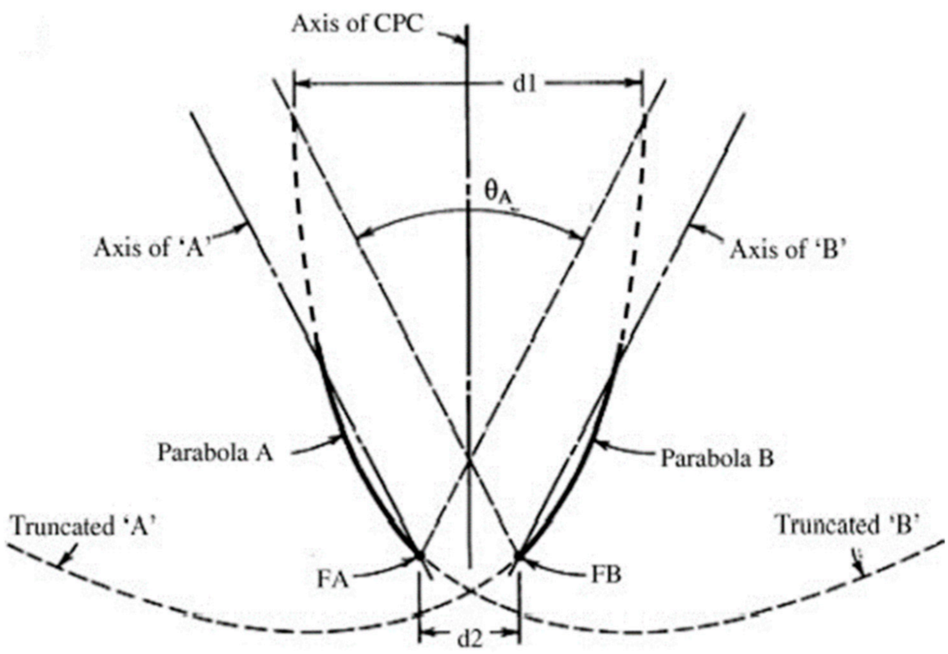

Figure 2. Profile of a symmetric 2D CPC [56].

The CPCs are generally categorized as either two-dimensional (2D) and three-dimensional (3D) or symmetric and asymmetric types [64]. The 2D CPC has a cylindrical trough-like shape formed by translating the primary geometry perpendicular to the page, whereas the 3D CPC is obtained by rotating a 2D CPC around its axis of symmetry. The symmetric 2D CPC is the basic CPC geometry, while all other variants can be derived from this basic shape [23]. The classification of CPCs is shown in Figure 3. While the concentration ratio of a symmetric CPC is fixed for all incidence angles within its acceptance angle range, an asymmetric CPC possesses a variable concentration ratio due to the fact that the acceptance half angles for left and right parabolic reflectors are not the same [65]. That is why it is not geometrically symmetric around its central axis. A 3D CPC causes increments in the geometrical concentration ratio compared to 2D CPC, due to which the size of solar cells is further reduced for a given output. However, the circular shape of entry and exit apertures of 3D CPC acts as a source of losses. Moreover, the circular shape of 3D CPC also causes hurdles in its integration with commercially available square-shaped silicon solar cells. To overcome the limitations of 3D CPC, a modified circular 3D CPC, crossed CPC, having square acceptance and exit apertures was proposed [66].

The economic feasibility of a CPC collector is dependent on its manufacturing cost, which is directly related to the area of reflecting surfaces. One weakness of basic CPC design is its relatively larger height in comparison to the width of the receiver surface. This problem can be solved by removing the portions of CPC parallel to its optical axis as they are contributing very little to the size of the entry aperture and concentration ratio [54,64]. The process of removing these least contributing portions without significantly reducing the acceptance half angle and hence the solar radiation collection by the concentrator is known as truncation. Truncation reduces CPC height, thus causing a reduction in total mirror area and the manufacturing cost. Truncation also causes a reduction in the number of reflections of incident rays before reaching the destination. About 50% truncation of full height offers a good agreement between CPC's concentration and mirror area [48]. Carvalho et al. [67] appraised the effect of truncation position on the monthly and annual average energy collected by 2D CPCs, taking into account the optical and thermal losses. The authors developed analytical equations for calculating the angular acceptance to observe the impact of truncation on the CPC field of view. Higher receipt of the beam and diffuse radiation and lower mean number of reflections were reported to be the optical gains resulting from truncation.

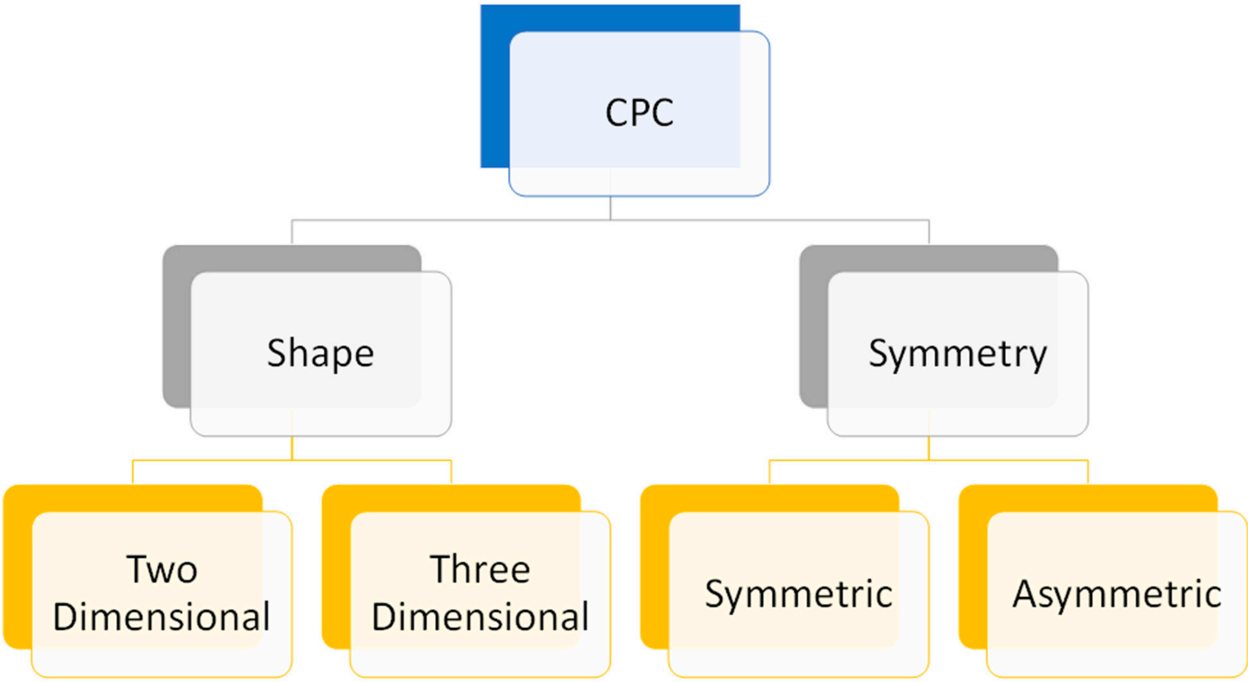

Figure 3. Classification of CPCs w.r.t. shape and symmetry.

3.1. Feasibility of CPC-Based Hybrid PVT Systems

A PVT system is a hybrid arrangement consisting of a thermal receiver combined with a PV module to remove the heat produced in the PV cells during the photovoltaic conversion process to lower their temperature and increase conversion efficiency. A hybrid PVT collector has the capability of simultaneously generating both electricity and heat. The schematic diagram of the CPC-PVT collector is illustrated in Figure 4. Diverse configurations of hybrid PVT systems are available in the literature [68–71]. Huang et al. [72] assessed the performance of an integrated PVT system consisting of a commercially available polycrystalline PV unit and a heat-gathering sheet. The authors demonstrated that the principal energy-saving efficacy of the integrated system was superior to that of an equivalent-sized traditional solar water heating system and PV panel working individually. The performance of a hybrid PVT system can be proficiently augmented by integrating optical elements with it. The research studies revealed that heat produced by a concentrating PVT system is always at higher temperatures than its non-concentrating or flat plate counterpart due to the concentration of sunlight on the PV surface and can be potentially used in low to medium temperature thermal applications [73]. Consequently, the quality of heat energy produced by a concentrating hybrid PVT system is superior due to the presence of an optical concentrating element within the hybrid system.

Zhang et al. [74] presented the design and performance estimation of a 4× CPC-based LCPVT system using simulations and experiments. The authors attached a baffle heat exchange channel at the back of PV cells to reduce the temperature gradient along the flow direction of the coolant. The performance of the proposed system was assessed by varying the baffle spacing, flow rate, solar irradiance, and inlet and ambient temperatures. The maximum thermal and electrical efficiencies on a typical day were recorded to be 55.11% and 12.5%, respectively. The performance comparison between low concentration and conventional hybrid PVT collectors can potentially reveal the benefits of low concentration PVT systems. In another study, Zhang et al. [75] compared the electrical and thermal performances of an LCPVT system, having a CR of 4×, with a typical flat plate hybrid receiver for climatic conditions of China. The comparison was made for fixed mass flow rate conditions. The authors experimentally proved that the LCPVT module generated three times more electrical power and approximately two times more thermal power compared to an equivalent nonconcentrating PVT module. As a result, CPC collectors have emerged as a preferred choice for researchers working in the field of hybrid LCPVT systems. To prove this, some authors have studied the benefits of integrating different CPC designs with PVT collectors.

Bahaidarah et al. [76] evaluated the impact of cooling on the performance of nonconcentrating and CPC-based concentrating PV modules. The authors demonstrated that cooling enhanced the output power by 49% and 100% in the case of nonconcentrating and CPC-based concentrating PV modules, respectively. The heat energy extracted from the concentrated receiver can be used in low-temperature thermal applications causing an increment in the overall performance of the LCPV system. Yousef et al. [74] conducted a similar comparative performance evaluation for Egypt's hot and arid climatic conditions. As reported by the authors, the temperatures of nonconcentrating and CPC-based concentrating PV systems were lowered by 25% and 30%, respectively, causing significant increments in the output power of both systems. Moreover, the CPC-based PV system generated 52% more power in comparison with the flat PV module when the cooling mechanism was employed. Thus, the cooling causes dual benefits by increasing the electrical performance and simultaneously providing valuable thermal energy.

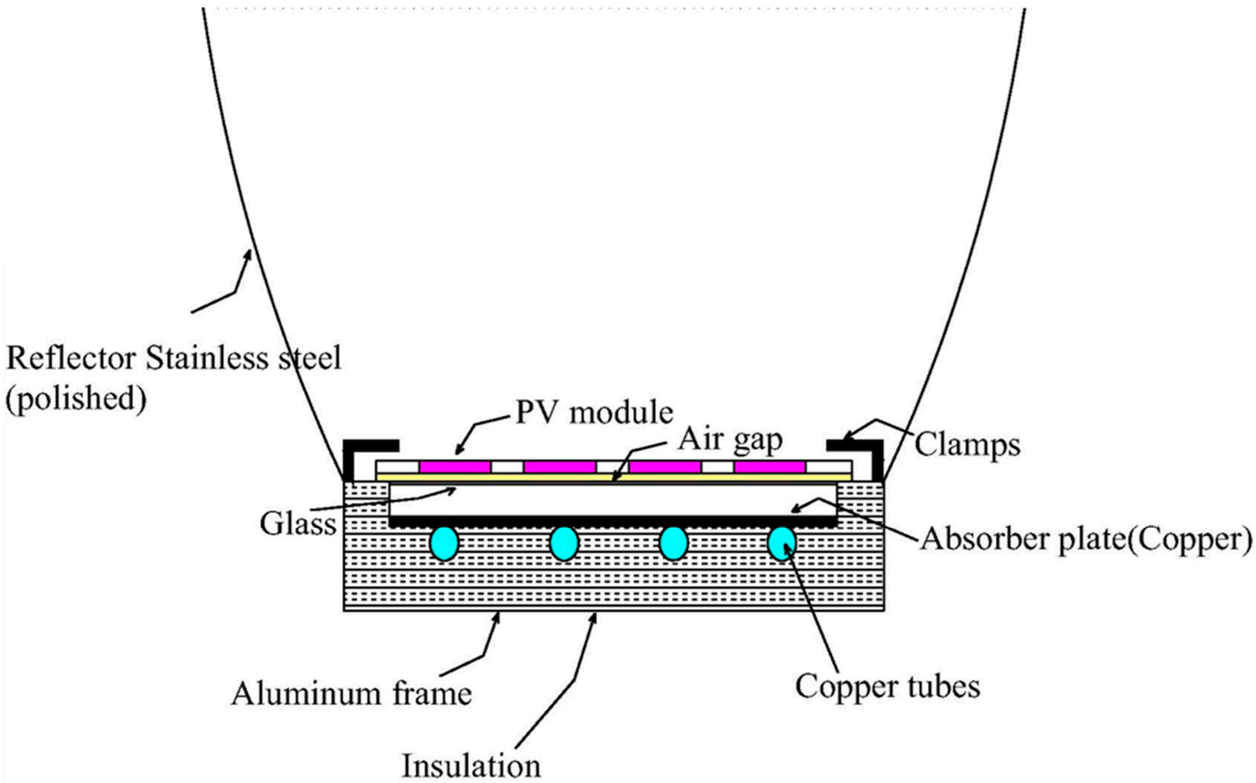

Figure 4. A Sketch of CPC-based PVT System [77].

3.2. *Performance Enhancement Using Phase Change Materials*

The phase change materials (PCM) can absorb and disperse substantial amounts of latent heat during the transformation in their physical condition. Therefore, the integration of PCM with the PVT systems offers dual benefits of PV cooling and storage of thermal energy. Al-Imam et al. [78,79] used PCM for improving the performance of the CPC-PVT system for the climatic conditions of Bangladesh. The authors [78] conducted experimental investigations on clear sky and semi-cloudy days using a CPC integrated PVT collector fitted with a tank having PCM for energy storage. The thermal efficiency was found to vary from 40 to 50% and around 40% on clear sky and semi-cloudy days, respectively, whereas the overall efficiency varied between 55–63% and 46–55% for clear sky and semi-cloudy weather conditions. It was concluded that the integration of CPC and PCM caused an increment in the performance of hybrid PVT system.

Liu et al. [80] numerically estimated the performance of a CPC-based PVT collector utilizing a microencapsulated phase change effluent as the cooling agent. The proposed system's electrical and thermal efficiencies attained their peak values when the solar radiation was at minimum. A comparative analysis of the cooling performance of the water and microencapsulated phase change effluent was conducted. As reported by the authors, the thermal and electrical efficiencies were incremented by 9.24% and 1.8%, respectively, due to the proposed cooling method.

4. Optical Performance Evaluation

The electrical and thermal efficiencies of concentrating PVT collectors depend upon the optical performance of their reflectors. The optical performance is usually evaluated by measuring optical efficiency, angular acceptance, and solar flux distribution at the receiver surface [81]. The angular acceptance can be described as the portion of incident solar radiation that reaches the receiving surface for different incidence angles without contemplating losses within the concentrator. The Monte Carlo ray tracing is an effective method for optical performance evaluation and has been used by many researchers [82,83]. Yu et al. [84] established a mathematical procedure for predicting the optical performance of CPCs. Some researchers developed their own codes for optical performance evaluation. However, the optical analysis using ray tracing photometric analysis software is superior and more beneficial than using a programming language code due to several advantages [85]. Baig et al. [86] assessed the optical performance of a CPC-based PVT collector with and without glazing cover for the climatic conditions of the Kingdom of Saudi Arabia using ray-tracing simulations. The optical efficiency of the collector without a glazing cover was found to be above 90%, while that of the system with a glazing cover was limited to 80%. However, the authors preferred the system with a glazing cover due to its long-term advantages.

Chandan et al. [87] measured the peak local flux concentration at the receiver surface of 2.5× and 2× CPCs having optimized flux homogenizers for uniform solar flux distribution, called elongated CPCs (ECPCs). The authors conducted optical simulations to demonstrate that local flux concentration on the receiver surface decreased by 55% and 66% for 2.5× and 2× CPCs, respectively, at normal incidence angles, due to the integration of flux homogenizers. The experimental values of peak electrical efficiency were found to be 14.1% and 13.9% for 2× and 2.5× ECPCs, respectively. In contrast, the peak electrical efficiency was limited to 13.9% and 13.6% for standard CPCs of 2× and 2.5×, respectively. Guiqiang et al. [88] appraised the optical performance of an innovative static-incorporated CPC-based PVT collector using ray-tracing simulations at different incidence angles followed by experimental validation. The authors developed the expression for calculating optical efficiency at several transverse angles. The average value of optical efficiency within the acceptance half angle was found to be 83%.

Zhang et al. [89] established a combined optical–thermal–electrical model to analyze the impacts of non-uniform radiation and temperature distributions on the performance of a linear concentrating system comprising truncated CPCs. First, the authors found the irradiance distributions by conducting a ray-tracing analysis of two previously designed CPCs with different concentration ratios, LEMR and HEMR CPCs. These irradiance profiles were later used as inputs to the coupled thermal–electrical model established to foresee the performance of the CPC-PV collector. Through simulation and experiments, the authors demonstrated that LEMR CPC experiences a rapid increase in non-uniform radiation and temperature distributions compared to HEMR CPC, with an increase in concentration ratios of both concentrators. For a CR of 8×, the fill factor and conversion efficiency of LEMR CPC decreased by 2.6% and 2.1%, respectively, in comparison with HEMR CPC. In another study, Zhang et al. [90] theoretically evaluated the effects of truncation positions of EMR-CPC on the thermal and electrical performances of a concentrating PVT system consisting of specially designed EMR-CPCs. The authors used a 2D coupled thermal-electrical model to predict the temperature dispersion across PV modules and the energy and exergy efficiencies of the proposed concentrating PVT system. The optimum height of EMR-CPC for producing the best energy and exergy efficiencies was determined. As reported by the authors, when the height was truncated below optimum value, the non-uniformity in radiation and PV temperature distribution along the hybrid receiver increased swiftly. When compared with an equivalent flat PV panel, the overall exergy efficiency of the proposed concentrating EMR-CPC-PVT system was found to be slightly higher.

5. Heat Exchanger Configurations for CPC-PVT Collectors

The heat extraction method should ensure effective heat removal from the concentrating PV cells for controlling their temperatures within the permissible limits. Guiqiang et al. [91] conducted a comparative performance analysis between a CPC-PVT collector with a U-type pipe pasted at its backside and an equivalent nonconcentrating hybrid PVT collector, considering water as heat transfer fluid. Based on simulation results, the authors demonstrated that the CPC-PVT collector with a U-type pipe performed better than its flat-plate counterpart by reducing the number of PV cells for the same power generation and supplying higher temperature heat for thermal applications. Moreover, the authors calculated thermal and electrical efficiencies of the proposed CPC-PVT collector at different concentration ratios and proved that overall system efficiencies increased by 28% for a concentration ratio of 3×. Jaaz et al. [92] observed the impact of jet impingement of water on the electrical and thermal efficiencies as well as the electrical power produced by a CPC-PVT system for the climatical conditions of Malaysia. The experimental results suggested that electrical efficiency and output power increased by 7% and 36%, respectively, due to the integration of CPC and jet impingement cooling technique with a hybrid PVT collector for solar radiation of 1050 W/m^2 and an ambient temperature of 33.5 °C. Moreover, the combination of CPC and jet impingement caused an increment of nearly 28% in the short circuit current produced by the PVT module. In another study, Jaaz et al. [93] evaluated the electrical efficiency, thermal efficiency, total efficiency, and total power produced by CPC-PVT collector using the jet impingement technique. The authors reported an increment of 7% and 81% in electrical and thermal efficiencies, respectively, whereas total power was found to increase by 31%.

Proell et al. [94] developed the prototype of a CPC-based PVT collector with an angular acceptance of ±25° for measuring the angle-dependent electrical and thermal efficiencies for the climatic conditions of Germany. The authors measured the thermal coupling between solar cells and heat transfer fluid in a laboratory-scale experiment. The thermal efficiency of the proposed collector attained a value of 34% in comparison to its value of 17% for a glazed flat PVT collector of the same dimensions. However, electrical efficiency was found to decrease from 15% to a lower value of 9%. The possible reasons for this decrement were reported to be the errors in optical equipment, temperature rise, and the non-uniform solar flux dispersion on the PV surface. The cooling fluid inadvertently causes a temperature gradient across the PV cells in hybrid PVT systems, causing a reduction in PV output. Chen et al. [95] proffered a microchannel heat pipe array as a heat sink in a CPC-based PVT collector to homogenize the heat flux. The authors experimentally demonstrated increments in thermal and electrical efficiencies due to the microchannel heat sink. Baig et al. [96] estimated the performance of a low concentration PVT collector consisting of five units of CCPC attached to a heat exchanger. The authors used a bespoke rotating table for a detailed optical performance evaluation of the CCPC-PV system as a function of its angular orientation. A CFD model of the proposed system was developed to assess the usefulness of the heat exchanger. Based on simulations, the rate of fluid flow was found to be a key parameter in optimizing the low concentration PVT collectors. The average electrical efficiency of the proposed collector was shown to attain a value ranging from 10 to 16% for five different cities in Europe.

El-Samie et al. [97] numerically simulated a low concentrated hybrid PVT system employing CPC as the concentrating element, shown in Figure 5, using the finite volume method. The effects of using different heat sink designs like U-type and Z-type, as well as different heat transfer fluids like water, ethyl glycol, and therminol were examined numerically. Moreover, the economic viability of the proposed system was also evaluated and compared with equivalent-sized nonconcentrating PV modules. The proposed system's total energy and exergy efficiencies were found to be 57.66% and 7.94%, respectively. The authors reported that the Z-type heat sink produced better results by decreasing the average solar cell temperature as compared to the U-type heat sink, subsequently increasing the output electrical power. A negligible effect on the energy and exergy efficiencies was reported by changing the type of HTF due to low CR.

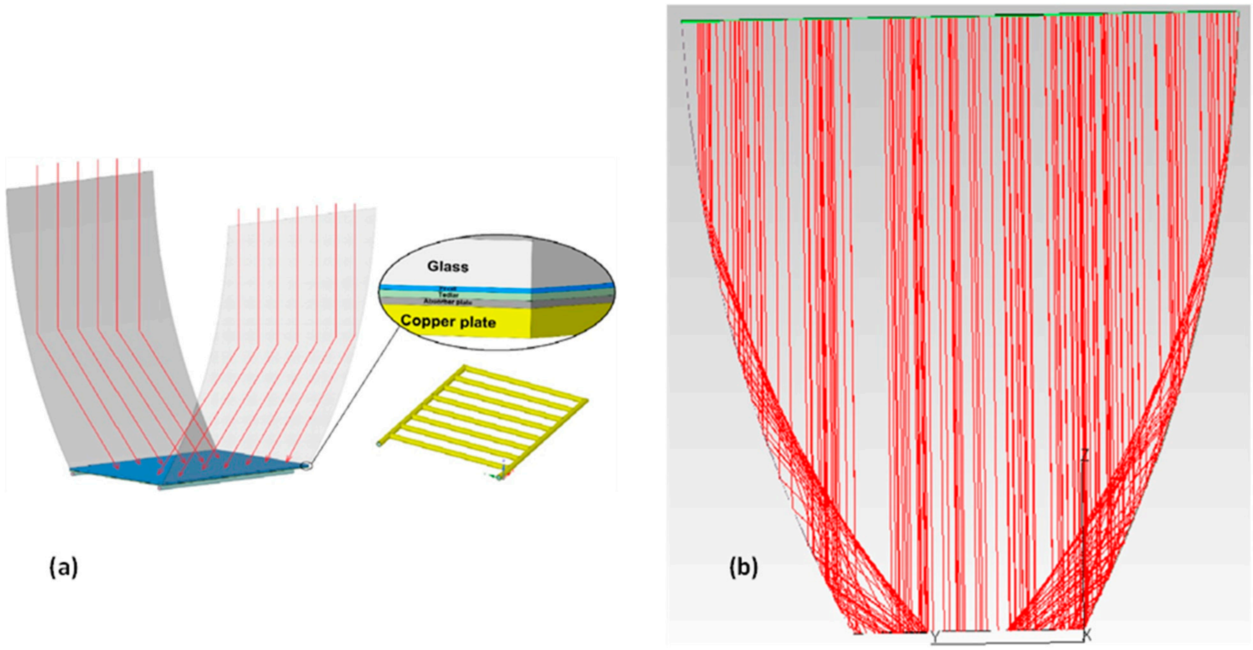

Figure 5. (**a**) Schematic diagram of CPC-PVT system with the cooling arrangement (**b**) Ray trace diagram of CPC collector [97].

Kai et al. [98] compared the performance of a 4× CPC-PVT collector using different configurations of crystalline silicon solar cells with diverse cooling channels. The authors performed theoretical and experimental investigations using ordinary and sliced silicon solar cells integrated with three different cooling channels: a glass channel, an aluminum channel, and a heat pipe. The authors demonstrated that slicing the ordinary silicon solar cells enhanced their electrical performance when subjected to concentration. The pros and cons of different cooling channels were listed. The electrical efficiency of the heat pipe integrated LCPVT collector was highest compared to the aluminum and glass channels. However, the thermal performance manifested by the glass channel was found to be pretentious due to low thermal resistance.

6. Applications of CPC-Based Hybrid Solar PVT Collectors

Different working fluids, including air, water, PCM, nanofluids, etc., are commonly used as HTFs in CPC-based systems [99,100]. The hybrid PVT collectors integrate PV modules with thermal collectors, having fluid circulation, e.g., air or water. They are capable of producing electrical and thermal energies simultaneously as opposed to CPC-based thermal systems, which produce thermal energy only. The integration of CPC with a hybrid PVT collector causes an increment in working fluid temperature, rendering it useful for medium-temperature solar thermal applications. CPC-based PVT systems are appropriate for domestic and industrial applications; e.g., air-cooled and water-cooled CPC-PVT collectors are generally used for indoor space heating and domestic hot water production [101]. The choice of CPC-based PVT hybrid collector for a particular application depends upon different factors like CR of CPC, temperature, type of working fluid, and the ability of CPC to track the sun. Besides usual domestic hot water production and space heating/cooling applications, CPC-PVT systems are also appropriate for desalination, crop drying, pool heating, and building integrated/attached applications. This section presents an extensive review of research articles focused on applications of CPC-based PVT hybrid collectors. Firstly, different heat extraction methods are presented, followed by the details of renowned application areas.

6.1. CPC-PVT Air Heating Collectors

The purpose of air heating collectors is to supply hot air at specific temperatures for different process industries. Garg and Adhikari [102,103] developed electrical and thermal models of PVT air heating collectors to predict hybrid system performance with and without CPC integration. The authors combined several CPC troughs with a single PVT air heating collector. It was reported that the integration of CPC with conventional PVT air collectors was appurtenant for relatively higher temperature applications. Hj. Othman et al. [104] developed a steady-state analytical model for forecasting the electrical and thermal performances of a double pass CPC-PVT air heating collector consisting of a series of CPC troughs integrated with PV cells having fins attached to their backsides. The authors illustrated that electrical energy production decreased with increased air temperature due to the concentration of solar radiation by CPCs. However, a trade-off between maximum electricity generation and temperature of hot air for useful thermal applications was recommended. The theoretical results were validated by indoor experiments using the developed prototype. A double pass CPC-PVT system is illustrated in Figure 6.

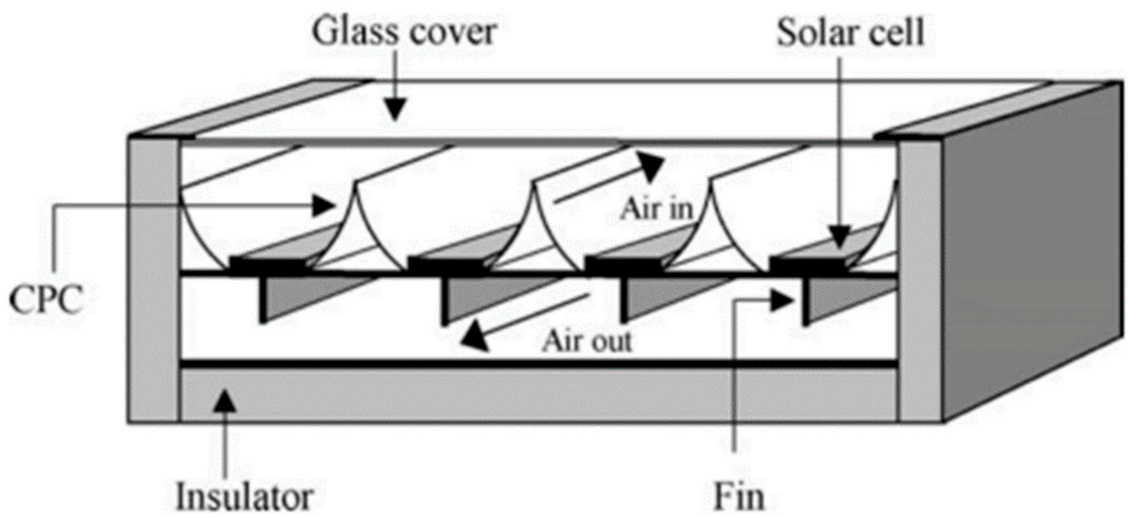

Figure 6. Double-pass CPC-PVT air collector with fins [104].

Sun et al. [105] numerically evaluated the performance of a single pass CPC-based PVT collector consisting of three CPC troughs having a concentration of 2×. The impact of key design and operational parameters on the thermal and electrical performance of the proposed system was investigated. The results indicated that the thermal efficiency, electrical efficiency, and exergy of the proposed CPC-PVT systems were directly related to the air mass flow rate and the span of the collector. The electrical efficiency was found to increase with the increasing packing fraction of the PV receiver. However, the thermal efficiency was negatively affected by increasing packing fraction. Elsafi and Gandhidasan [106] compared the performance of a nonconcentrating double pass PVT module with an equivalent CPC-PVT module, with and without fins for the climatical conditions of Dhahran metropolis in Saudi Arabia. The authors developed mathematical models of different system components. A parametric study was carried out to observe the impact of different design and operation parameters on proposed configurations' thermal and electrical performances.

The results demonstrated that nonconcentrating PVT system with fins generated 3% and 1% higher electrical and thermal powers, respectively, than its unfinned counterpart. The CPC-PVT system with fins was found to have 3% and 8% more thermal and electrical powers, respectively, as compared to the equivalent system without fins.

6.2. Hybrid CPC-PVT Collectors Using Water as HTF

Water is most commonly used as HTF in low concentrating solar collectors due to its superior heat-removal properties. Hedayatizadeh et al. [107] conducted a comprehensive thermal and electrical performance analysis of a hybrid PVT system integrated with symmetric 2D CPC by developing thermal and electrical models of system components. Based on numerical simulations, the authors estimated thermal, electrical, and overall efficiencies as well as temperatures of solar cells and cooling water. A parametric analysis was conducted to observe the impact of different design and operating parameters on the thermal and electrical performances of the collector. Proell et al. [108] evaluated the impact of CPC mirrors on the electrical efficiency of CPC integrated hybrid PVT collectors. The effect of solar flux dispersion on the PV efficiency was measured using an experimental prototype in outdoor conditions. The authors developed an integrated system model combining the proposed system's optical, thermal, and electrical models to evaluate the temperature distribution and incident angle modifier of electrical efficiency for three different concentrations. Shah and Patel [109] assessed the feasibility of using a CPC-based PVT collector for the weather parameters of the Indian state of Gujarat. Based on the experimental data, the thermal and electrical efficiencies of the CPC-based PVT collector were reported to be 53.92% and 13.52%, respectively, whereas the overall efficiency was found to be 79.18%.

Ustaoglu et al. [110] compared the performances of PVT systems consisting of compound hyperbolic-trumpet (CHCT), CPC, and V-trough collectors. Ray-tracing simulations were conducted to estimate the solar flux on the receiver surface, whereas solar cell temperature was determined numerically. As reported by the authors, the CHCT-based PVT system produced almost the same power as CPC and V-trough-based PVT systems for normal incident rays, while the material required by the CHCT collector was nearly half of that required by conventional non-imaging concentrators. Chandan et al. [111] numerically examined the performance of ECPC based low concentration PVT system by developing optical, electrical, and thermal models of the proposed system. The heat transfer between different layers is shown in Figure 7. The peak values of thermal and electrical efficiencies were found to be 40% and 12%, respectively, at a flow rate of 38 liters per hour. A 3% increment in electrical efficiency was reported when the flow rate was increased from 22 L per hour to 38 L per hour.

6.3. Rooftop and Building Façade Integrated CPC-PVT Systems

Due to the lower space requirements, CPC-based PV or hybrid solar systems can either be integrated with building facades or installed on rooftops. Guiqiang et al. [112] assessed the optical, thermal, and electrical performances of an ALCPC based PVT system, shown in Figure 8, for building façade integration. The authors conducted the theoretical and experimental investigations of the proposed system for the atmospheric conditions of Heifi city in China, considering two typical days of the months of March and May. The average electrical and thermal efficiencies were recorded to be 6% and 35%, respectively, for actual outdoor conditions, whereas the average optical efficiency was found to be 83% within the acceptance half angle of ALCPC for normal irradiance. The thermal and electrical efficiencies obtained through curve fitting under zero reduced temperature were reported to be 52% and 6.6%, respectively. Li et al. [113] developed a coupled optical, thermal, and electrical model for predicting the performance of a hybrid PVT collector consisting of CCPCs, for rooftop applications. The authors used the developed model to predict the electrical performance and solar cells' temperature on specific days for climatic conditions of three different locations in Europe, namely Jaen, Penryn, and Glasgow. The authors demonstrated that the proposed model reasonably predicted the electrical energy generated by the system with a mean error lying in the range of 2–14%. Furthermore, the effects of transient terms in diffuse solar radiation and heat transfer models on electrical energy prediction were identified. The model exhibited better performance for weather data of Jaen as compared to Penryn and Glasgow.

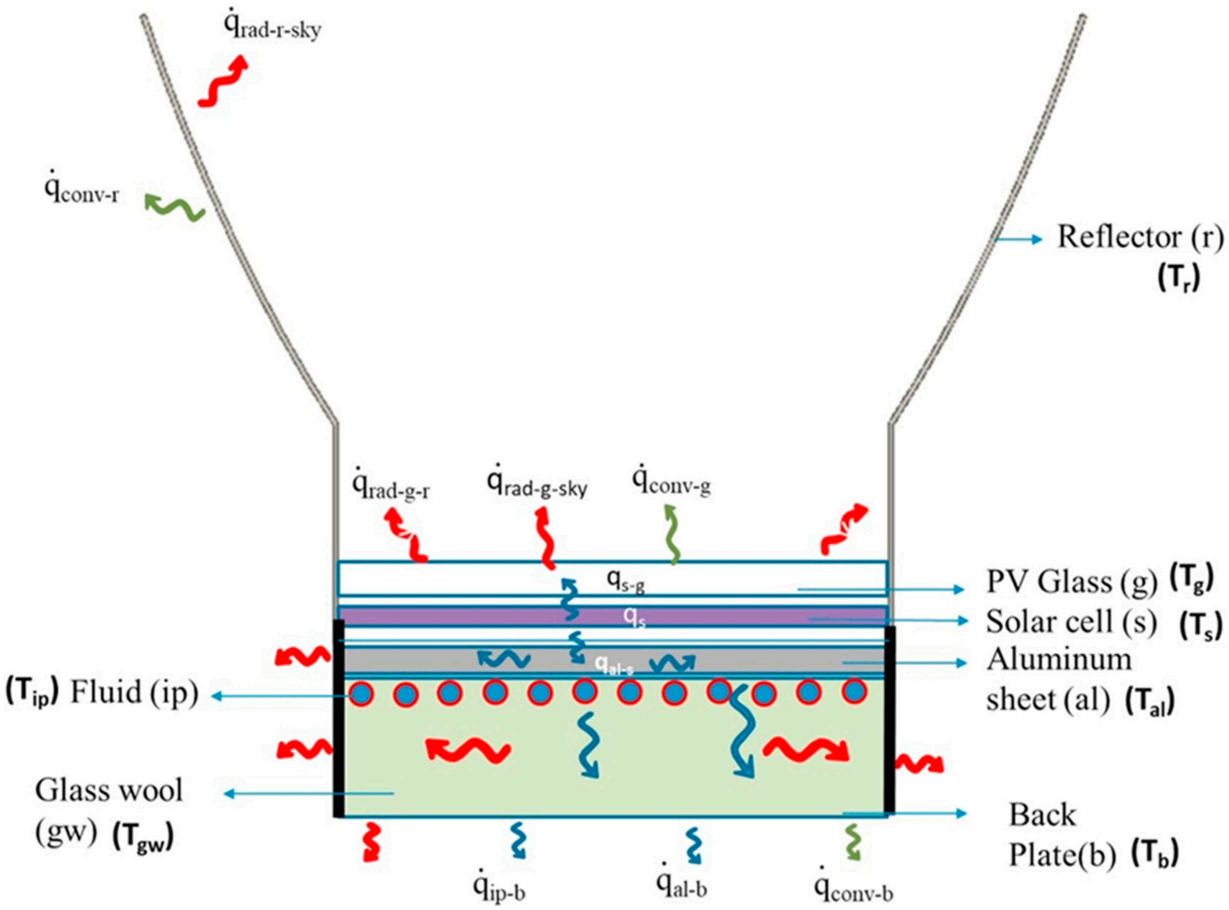

Figure 7. Heat transfer between different layers across the CPC-PVT system [111].

Koronaki and Nitsas [114] analytically and experimentally assessed the performance of a CPC-PVT collector consisting of five asymmetric CPCs connected in a series, mounted on a rooftop with a tilt angle of 30°. As reported by the authors, the maximum value of optical efficiency was observed for an incidence angle of 37°. This was due to the asymmetric nature of the concentrator and the position of the absorber. As demonstrated by the authors, the system produced the maximum useful energy at the solar noon. In addition, the collector exhibited a nearly constant efficiency of 30% during the steady-state period. The authors concluded that the maximum thermal efficiency resulted when the collector was operated in the open circuit mode. Li et al. [115] proposed a three-point-based electrical modeling approach for extracting the five model parameters of a low concentration PVT system consisting of CCPCs, based on the voltages and currents at short circuit, open circuit, and maximum power points. The authors used the five model parameters, together with other optical and thermal parameters, for predicting the hourly electrical performance of the CCPC-PV system for the weather data of four different sunny days of the summer season in England. As reported by the authors, the model predicted hourly absorbed electrical energy with an error of 5.53% as compared to the experimental data.

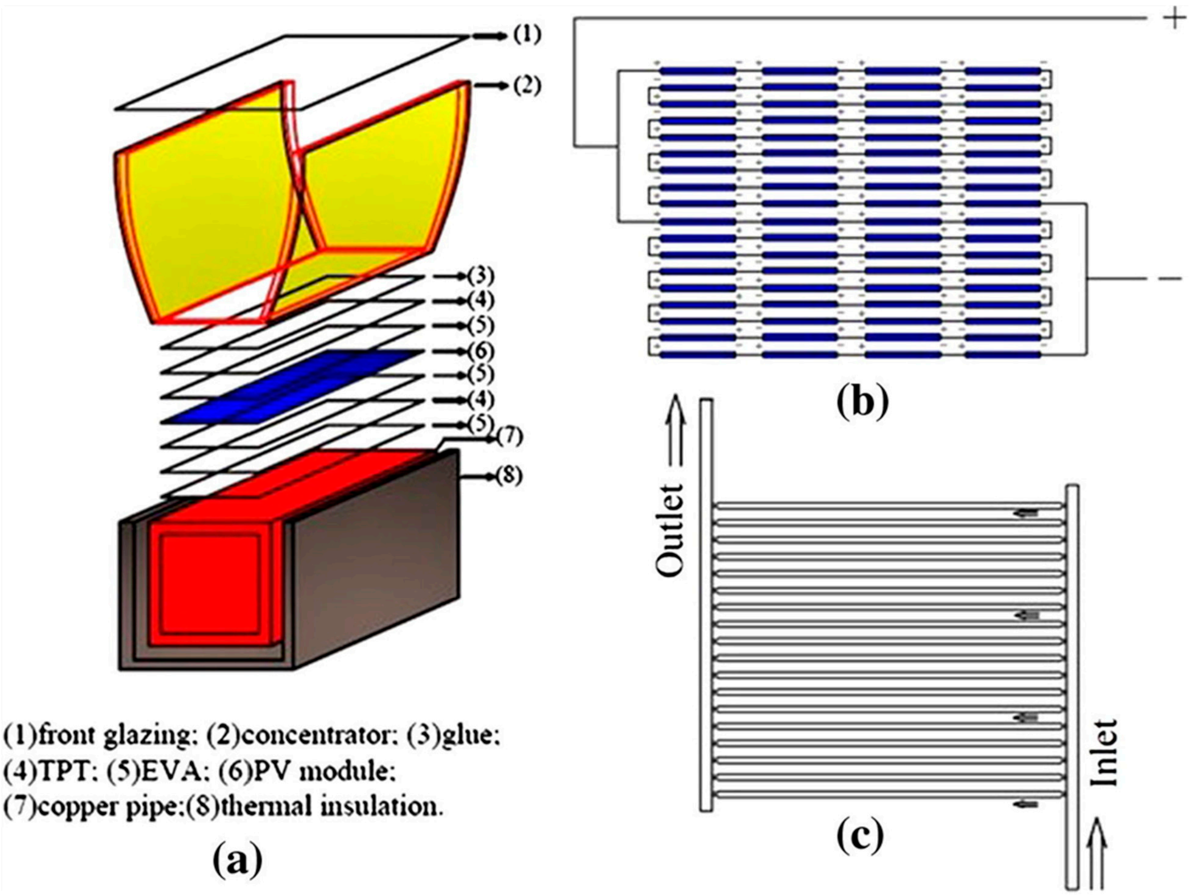

Figure 8. (**a**) Structural details of ALCPC-PVT collector (**b**) Solar cells connection diagram (**c**) Direction of coolant flow [112].

Yang et al. [116] evaluated the annual performance of a novel tri-generation CPC-based low concentration PVT system designed for heating, cooling, and electricity generation. The simulations were performed using the Transient System Simulation (TRNSYS) software package, whereas the experiments were performed on the roof of a building in Beijing, China. The electrical and thermal efficiencies of the proposed system were reported to be 10% and 60–69%, respectively. In contrast, the coefficient of performance of the absorption chiller was found to have an average value of above 0.5. Alamoudi et al. [117] proposed the design of an absorptive, reflective CCPC based (AR-CCPC) PVT system for building integrated applications. A thermal absorber was placed at the top of the CCPC structure to collect and store thermal energy. For higher angles of incidence, a significant portion of incident radiation was collected as thermal energy. The authors performed ray-tracing simulations and demonstrated that the optical efficiency of AR-CCPC varied between 60% and 90%. Compared to an identical CCPC, the energy generated by AR-CCPC was found to be higher, due to thermal absorber. Table 1 presents a summary of research articles related to the performance evaluation of CPC-PVT systems.

Table 1. Summary of research articles related to performance evaluation of CPC-PVT systems.

Ref	Type of CPC	CR	Receiver/Solar Cells	Methodology	Results	
					Thermal Efficiency	Electrical Efficiency
[91]	Symmetric 2D	1.5, 2, 2.5, 3	Single-crystalline silicon solar cells with a U-type pipe pasted on the backside	Steady-state thermal-electrical modeling	67.6%	12.6%
[92]	Symmetric 2D	-	36 polycrystalline silicon solar cells of 156 × 156 mm with nozzles connected at the back for jet impingement cooling	Experimental	84%	14.5%
[95]	Symmetric 2D	4.00	Silicon solar cells pasted on Al plate connected to microchannel heat pipe array	Experimental	54.48%	14.49%
[96]	3D CCPC	3.60	LGBC silicon solar cells directly bonded to a conductive heat exchanger	Numerical modeling, Indoor experiments	-	16%
[97]	Symmetric 2D	2.40	Polycrystalline silicon cells pasted on an Al absorber sheet	3D numerical modeling	48.84%	7.12%
[98]	Symmetric 2D	4.00	Monocrystalline silicon solar panel bonded with three different cooling channels (i) glass channel (GC), (ii) aluminum channel (AC) and (iii) heat pipe (HP)	Experimental	73% (GC) 66% (AC) 51% (HP)	12.5% (HP) 11.21% (AC) 9.92% (GC)
[107]	Symmetric 2D	2.00	Polycrystalline silicon	Numerical modeling	51.46%	9.6%
[109]	Symmetric 2D	3.00	Transparent solar cells	Experimental	53.92%	13.52%
[111]	ECPC	2.50	315 W commercial solar panel	Numerical and experimental	40%	12.5%
[112]	ALCPC	2.40	Two sets of 36 series connected PV cells bonded with Cu pipe cooling channel	Simulation/Experiment	52%	6.6%
[116]	Symmetric 2D	4.00	Monocrystalline silicon solar cells bonded with Al cooling channel	Simulation/Experimental	69%	10%
[118]	MaReCo	1.52	A parallel combination of two strings of 38 series connected silicon cells on both sides of the receiver	CFD modeling	52%	13.3%
[119]	EMR-CPC	4.00	20 series-connected 156 × 78 mm polycrystalline silicon solar cells	Steady-state and unsteady state thermal modeling	55%	13%

6.4. Special Applications Involving Hybrid CPC-PVT Collectors

Low concentrating hybrid solar collectors are usually employed in domestic applications or small industrial enterprises for supplying electricity and low-quality heat. However, some researchers used these collectors for special applications like running biogas plants, solar distillation, and desalination. Singh et al. [118] developed an analytical model for forecasting the electrical and thermal performances of a CPC-PVT collector integrated with a fixed dome biogas plant, shown in Figure 9. The authors evaluated the effects of mass flow rate, the packing factor of the PVT receiver, and the total number of CPC-PVT modules on the optimum sludge temperature for atmospheric conditions of northern India. The authors illustrated the increment in sludge temperature with an increasing number of CPC-PVT modules. The role of the packing factor in optimizing the electrical and thermal energies produced by the proposed collector for the adequate performance of the biogas plant was also highlighted. Moreover, the optimum mass flow rate for a fixed capacity biogas plant having six hybrid collectors for weather conditions of the Indian city of Srinagar was calculated. Arora et al. [119] analytically conducted the performance and cost analysis of a solar still combined with a CPC-PVT collector designed for desalination applications using single wall and multiwall carbon nanotubes-water based nanofluids for the metrological conditions of New Delhi. The authors used dual-slope solar, still having *N*-series connected, partly covered CPC-based PVT collectors equipped with a helically coiled heat exchanger carrying nanofluids for analytical modeling purposes. As reported by the authors, total yield produced by the proposed system increased by an amount of 65.7% and 28.1% for single wall carbon nanotubes (SWCNT) and multiwall carbon nanotubes (MWCNT), respectively, whereas the daily production cost was found to be minimal.

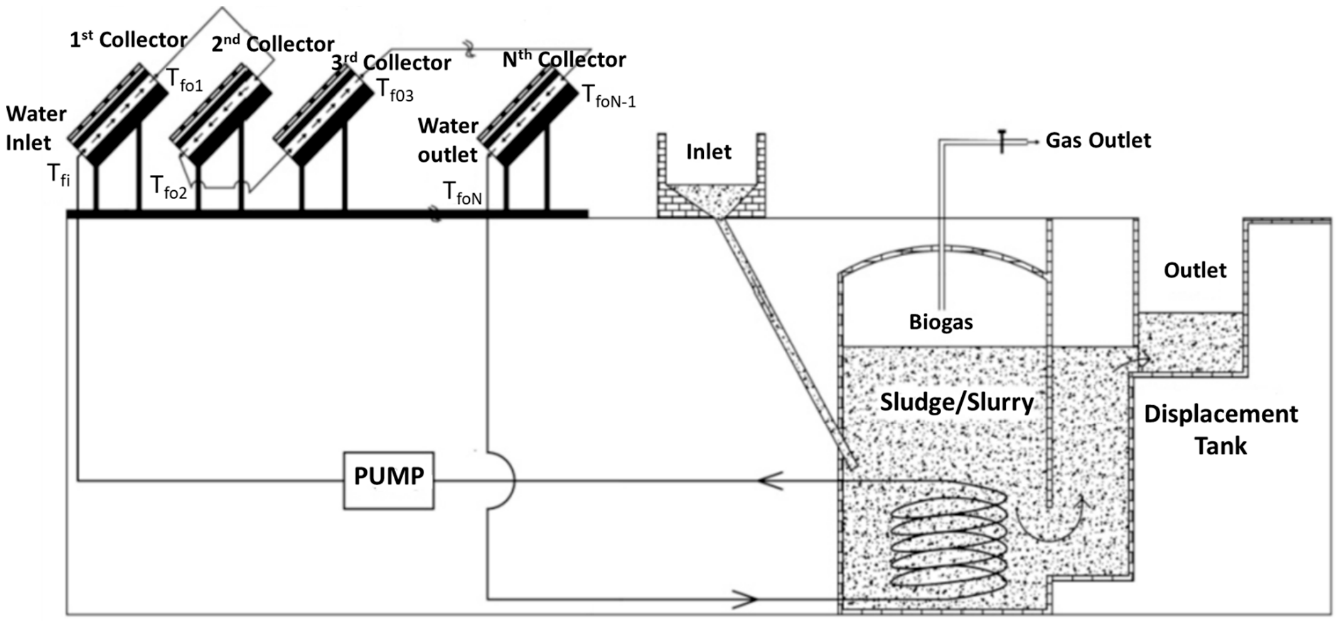

Figure 9. Schematic diagram of a CPC-PVT-based fixed dome bio-gas plant [118].

In another study, Wang et al. [120] proposed an innovative hybrid joint cooling heating and power system (CCHP) driven by CPC-PVT collectors. The authors evaluated the performance of the proposed system by developing thermodynamic models and conducting thermal simulations. The energy and ecological benefits obtained by using the hybrid collector were assessed. It was demonstrated that the integration of the CPC-PVT collector with the CCHP system caused an increment of 8.1% and 0.9% in the energy and exergy efficiencies of the proposed hybrid system, respectively. Compared to the CCHP system with no solar energy, the Levelized primary energy saving ratio and the maximum carbon dioxide diminution ratio attained by the proposed hybrid system were 28.6% and 36.7%, respectively. Thus, the hybrid system was confirmed to be more beneficial as compared to the traditional gas-fired CCHP system.

Haiping et al. [121] used a CPC-based low concentration PVT system for preheating the saline water, which was further heated by a series-connected solar thermal collector. The performance parameters of the system, including vaporization coefficient, electric power and efficiency, and freshwater yield, were determined experimentally. Chen et al. [122] optimized the thermo-ecological cost (TEC) of a novel internal combustion engine (ICE)-based CCHP system integrated with a CPC-PVT collector. The goal was achieved by optimizing the operational strategies as well as the designs and installations of ICE and CPC-PVT collectors. Two operational modes called the following electrical load (FEL) and the following thermal load (FTL) were used to compare the TECs of different outcomes of the proposed system. From the results of a case study, the authors demonstrated that the system employing 400 kW ICE and 100% PV-covered ratio attained the minimum value of TEC.

7. Innovative Design Configurations

Following innovative design, configurations have been proposed by different researchers.

7.1. Hybrid CPC-PVT Collectors with Special CPC Designs

Some authors evaluated the performance of hybrid PVT systems using unique CPC designs. In this regard, Nilsson et al. [123] assessed the performance of a specially designed ACPC based PVT collector, called MaReCo (Maximum Reflector Concentration) collector, shown in Figure 10, manufactured by Solarus corporation for the atmospheric conditions of a Swedish city, Lund, using two different reflector materials, i.e., anodized aluminum and laminated aluminum steel. The experimental data indicated that the front ACPC reflector collected the most radiation in the summer season, whereas the back reflector collected maximum radiation in the spring and autumn seasons. However, no notable difference was found between the annual output of the two reflectors. The configuration, including PV cells facing the front side reflector, was reported to be optimal. Nasseriyan et al. [124] performed the numerical and experimental study of the MaReCo CPC-PVT collector for Swedish atmospheric conditions. The numerical research consisted of computational fluid dynamics (CFD) modeling of the low concentrating PVT collector. The CFD results were validated by performing experiments at the University of Gavle, Sweden. The authors demonstrated that both thermal and electrical efficiencies exhibited a decreasing trend with increasing heat-transfer fluid temperature. The temperature of PV cells was reported to decrease from its stagnation value of 105 °C to 42 °C by circulating HTF at a mean temperature of 35.1 °C and flow rate of 2.2 L/min, allowing a 25% increment in electrical efficiency of solar cells. Moreover, the thermal and electrical yields were shown to increase by 3% and 2%, respectively, by using back insulation and removing the front glass from the solar receiver.

Alves et al. [125] developed 2D and 3D finite element models of MaReCo collectors for evaluating the effect of different climatic zones on the energy efficiency of concentrating PVT systems in Europe. The authors demonstrated that the shape of cooling channels and rate of fluid flow controlled the thermal and overall performances of hybrid concentrating PVT systems. Cabral et al. [126] estimated the performance of an ACPC-PV collector consisting of 20 MaReCo collectors attached to the building's south wall in a Swedish university. The thermal and electrical outputs of the hybrid collector were connected to the district heating structure and the regional grid, respectively. The yearly thermal and electrical yields of the collector were assessed from simulations and experimental data.

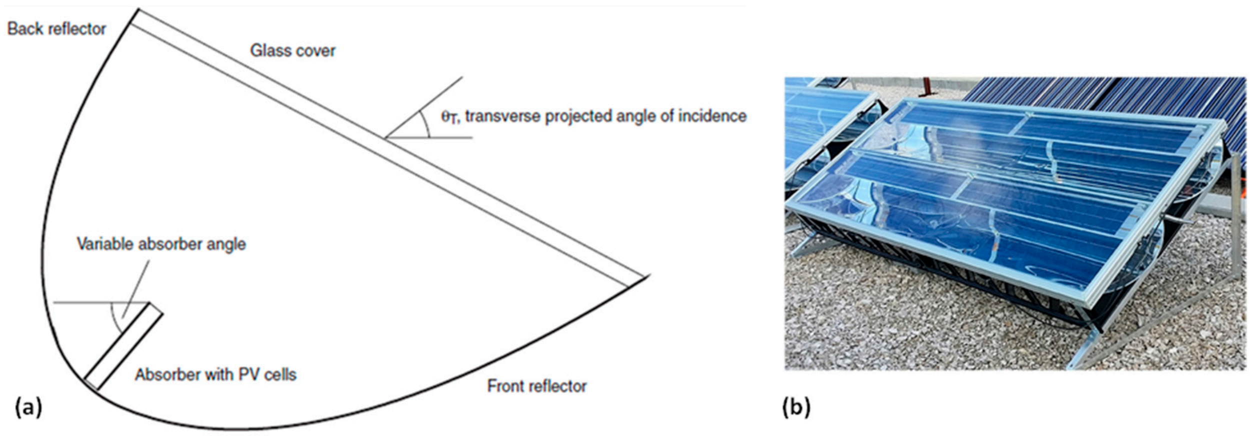

Figure 10. (**a**) Design details of MaReCo hybrid PVT collector [123], (**b**) Installed MaReCo collector [127].

Wang et al. [128] presented the design and detailed performance evaluation study of an EMR-CPC-based concentrating PVT system using an unsteady-state thermal model. The authors tested two identical EMR-CPC-PVT units fitted with two-axis and single-axis tracking devices and found the conversion efficiencies to be 13% and 12%, respectively. The thermal efficiencies calculated using steady-state and unsteady-state models were found to be 55.3% and 55%, respectively. As reported by the authors, the steady-state model failed to precisely forecast the proposed system's full-day variation of thermal efficiency. The EMR-CPC system is shown in Figure 11.

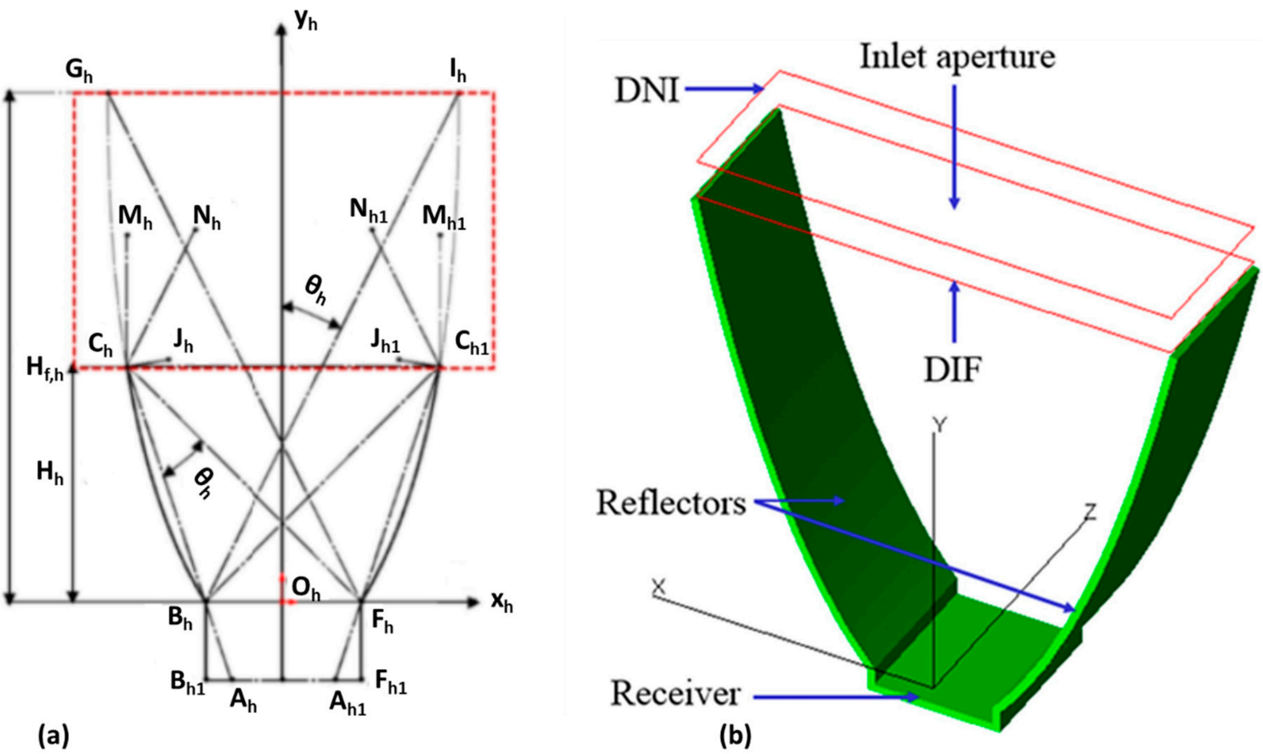

Figure 11. (**a**) Half EMR truncation position of CPC (**b**) EMR CPC during ray tracing process [89].

Zhang et al. [90] theoretically evaluated the effects of truncation positions of EMR-CPC on the thermal and electrical performances of a concentrating PVT system consisting of specially designed EMR-CPCs. The authors used a 2D coupled thermal-electrical model to predict the temperature dispersal across PV modules and the energy and exergy efficiencies of the proposed concentrating PVT system. The optimum height of EMR-CPC for producing the best energy and exergy efficiencies was determined. As reported by the authors, when the height was truncated below the optimum value, the asymmetry in PV temperature and irradiance distribution along the hybrid receiver increased swiftly. When compared with an equivalent flat PV module, the overall exergy efficiency of the proposed concentrating EMR-CPC based PVT system was found to be slightly higher.

7.2. Bifacial Absorbers in CPC-PVT Collectors

Bifacial solar cells have the potential to generate electricity from both front and back surfaces, thus increasing the generation of electricity per square meter of solar cell [129]. The integration of an optical concentrator with bifacial solar cells was found to generate 50% more electrical power due to the simultaneous collection of direct and albedo radiation [130]. Joao et al. [131] evaluated the performance of bifacial solar cells integrated with symmetric and asymmetric CPCs. The authors built three separate prototypes comprising symmetric/asymmetric CPCs and bifacial solar cells. Two prototypes were used for indoor testing under a solar simulator. The performance parameters like fill factor, open-circuit voltage, and electrical efficiency were the same for both reflectors. However, the short circuit current was higher in the case of an asymmetric concentrator due to a non-uniform illumination issue. In the case of both designs, the fill factor was found to be lower compared to conventional solar cells. The third prototype with an asymmetric CPC was used for outdoor experiments. Some researchers have proposed asymmetric compound parabolic concentrating collectors with vertical bifacial absorbers for better optical performance [132–134].

Cabral and Karlsson [135] evaluated the thermal and electrical performances of symmetric truncated CPC-based PVT collectors having vertical bifacial receivers using ray-tracing simulations and numerical modeling. The authors compared the performance of a CPC-based PVT system with a pure parabolic reflectors-based system. The CPC-based system was shown to yield relatively 8% to 13% more energy than an equivalent parabolic system. In another study, Cabral et al. [136] evaluated the impact of uneven solar flux distribution incidents on the surface of a PV module in a CPC-PVT system with a vertical bifacial receiver, shown in Figure 12.

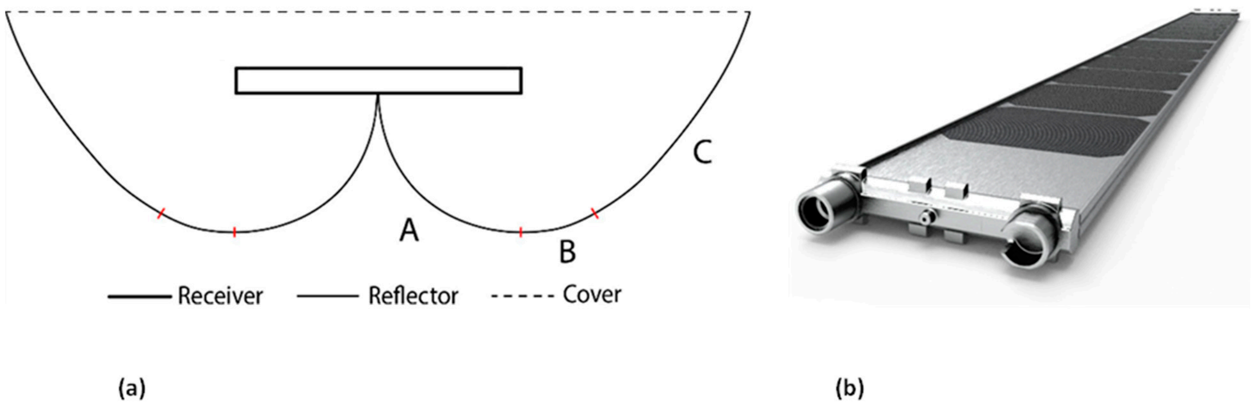

Figure 12. (**a**) Cross section of CPC geometry for bifacial absorber, (A) circular section 90°, (B) circular section 30°, (C) parabolic section; (**b**) Bifacial PVT receiver [136,137].

The authors also evaluated the thermal and electrical performances of the proposed collector for supplying hot water to a single-family residence in Egypt by employing numerical modeling techniques. It was demonstrated that the performance of CPC collectors was susceptible to partial shading conditions, due to higher incidence angles. Arnaoutakis et al. [138] integrated a dielectric-filled CPC to the back side of a planar bifacial silicon solar module. The authors used a hexagonal sodium yttrium fluoride doped with 25% Er^{3+} as an upconversion phosphor. The external quantum efficiency increased from 1.33% to 1.8%

by integrating concentrating optics with upconversion solar cells when the solar irradiance was 0.024 W/cm^2 with excitement at 1523 nm.

7.3. Partially Covered Hybrid CPC-PVT Collectors

In partially covered hybrid solar collectors, a fixed percentage of the total receiver area is covered by PV cells, whereas the rest of the space acts as a thermal collector by directly converting the solar radiation into heat energy. Atheaya et al. [139] derived the characteristic equation for a partially covered CPC-based PVT collector using the energy balance principle. The comparative performance analysis between the partially covered CPC-PVT collector and the conventional CPC thermal collector indicated that overall exergy efficiency was maximum for the CPC-PVT collector, whereas the thermal efficiency was maximum for the conventional CPC thermal collector, considering water as HTF for both systems. In a later study, Atheaya et al. [140] evaluated the exergy of a partially covered CPC-PVT system for fixed temperature mode, shown in Figure 13. The authors developed an analytical expression for electrical efficiency and mass flow rate for performance prediction under constant temperature mode. A comparative performance analysis was conducted among the proposed system and the fully covered CPC-PVT system, standard CPC thermal collector, and partially covered PVT water collectors for the weather of New Delhi, India. The fully covered CPC-PVT collector was found to have lower mass flow rate as compared to other collectors under consideration during performance comparison.

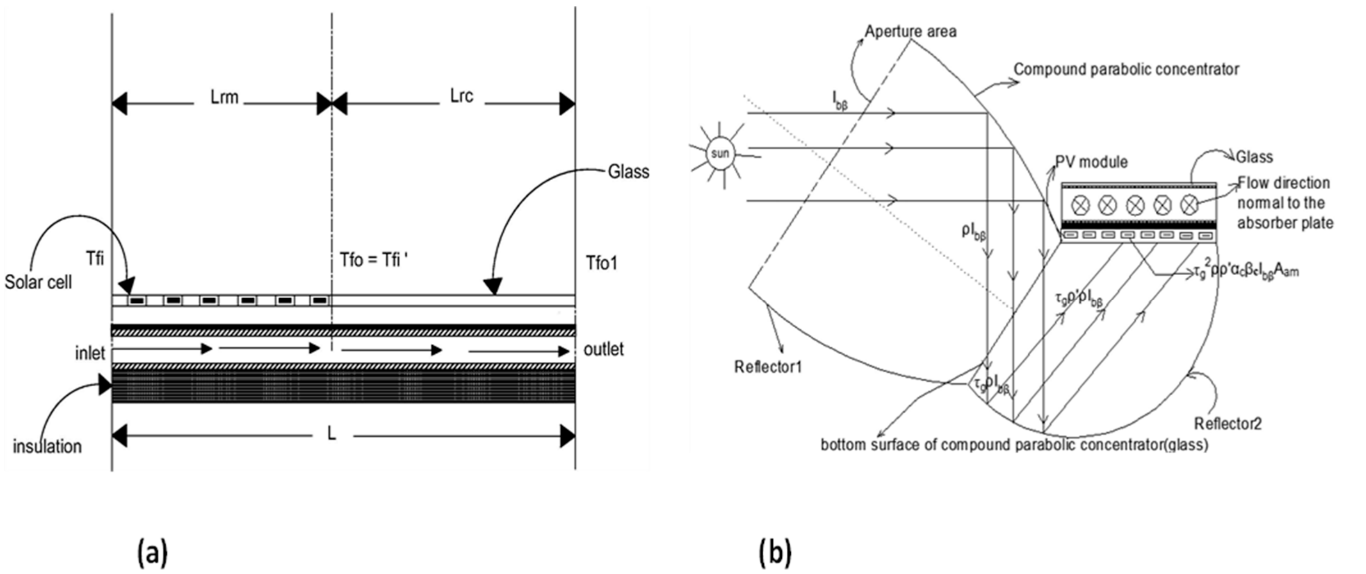

Figure 13. (**a**) Partially covered PVT collector, (**b**) Inverted absorber CPC-PVT collector [140,141].

Tripathi and Tiwari [142] performed a comparative energy and exergy performance assessment between different arrangements of *N* partially covered series-connected CPC-PVT collectors utilizing water and molten salt as a cooling medium. The performance of 25% covered CPC-PVT collector with molten salt was found to be suitable for solar cooking purposes. However, maximum net overall thermal energy and exergy gains were observed to be maximum for CPC integrated thermal collectors. Atheaya et al. [141] evaluated the performance of a partially covered CPC-based PVT collector having an inverted absorber for constant flow rate. The authors estimated the fluid outlet temperature, thermal and electrical energies, and electrical and overall exergy efficiencies of the proposed system from the analytical models. As reported by the authors, the partially covered CPC-PVT water collector having a glazed inverted absorber exhibited the highest thermal efficiency. Tripathi et al. [143] compared the total energy and exergy performance of *N* CPC-PVT partially covered collectors and *N*-CPC thermal collectors connected in series by using ethylene glycol as HTF at constant outlet temperature mode. The comparative analysis revealed that *N* series-connected CPC collectors' maximum annual overall energy and exergy efficiencies were higher than those of *N* partly covered CPC-PVT collectors joined in series.

Tiwari et al. [144] evaluate the hourly thermodynamic performance of organic Rankine cycle integrated with inverted absorber CPC-PVT collector for varying concentrations using Heptane/R245fa as HTF. The maximum outlet temperature, thermal efficiency, exergetic efficiency, and heat gain were observed for a concentration ratio of 6.0. Singh et al. [145] conducted the sensitivity analysis of a single gradient solar distiller unit integrated with *N* similar partly covered CPC-PVT collectors, using computational programming for the meteorological conditions of New Delhi, India. The effects of mass flow rate variation, number of collectors, packing factor, and water depth on the electric and thermal outputs were evaluated. The authors demonstrated that electrical output increased by 81.63% when the packing factor was increased from 0.4 to 0.6 for constant values of other parameters. Similarly, electrical power was shown to increase with increasing values of mass flow rate when other parameters were maintained at fixed values. Joshi and Tiwari [146] evaluated the impact of cooling condensing jackets on the energy and exergy yields of single slope solar still integrated with different configurations of *N* similar CPC-PVT systems. The authors optimized the design parameters of the proposed system for maximizing annual energy and exergy yields. The highest energy yield was obtained in the case of a flat plate thermal CPC-PVT collector integrated solar still.

Meraj et al. [147] established the numerical model of a milk pasteurization system fitted with *N* fully covered CPC-PVT systems for evaluating its performance in the meteorological conditions of New Delhi, India. The authors analyzed the effect of operating parameters such as packing factor, number of collectors, and mass flow rate on the pasteurization temperature of the milk. The milk pasteurization temperature was found to increase with an increase in the number of collectors with a lower packing factor. Saini et al. [148] numerically assessed the thermal and electrical energy yields of *N* partially covered series-connected CPC-PVT collectors using five different solar cell materials, including monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper-indium-gallium-selenide. The authors compared the electrical efficiency of the proposed system using all the above-mentioned types of solar cells on an hourly basis for weather circumstances in New Delhi, India. The electrical and thermal energy and exergy gains of proposed system using monocrystalline silicon solar cells were found to be superior in comparison with other solar cell types.

8. Observations and Future Prospects

A comprehensive review of the available literature related to the design and applications of CPCs for solar PV and hybrid PVT applications was conducted to explore the challenges being faced by the research community and for making appropriate recommendations for future research and development in this field, leading to the commercialization of CPC-based solar systems.

8.1. Observations about Existing Systems

Although several research articles related to the applications of CPCs are available in the literature, this review article focused on the CPC-based hybrid PVT systems only. Various databases were searched to identify the relevant research data. The country-wise number of publications for different years is plotted in Figure 14. The data for the years up to 2015 are combined together due to a low number of publications per year during this period. Figure 14 shows that the number of relevant published research articles was limited to below 15 up to the year 2015. Beyond the year 2015, the number of publications per year started increasing. This indicates the increased interest of the research community in the applications of CPC-based solar PVT systems. The increased research interest can be attributed to the efforts for exploring renewable energy sources to reduce the share of conventional fossil fuels-based power stations in the total energy generation. The published research data achieved the highest value in the years 2019 to the present date. Although the research on CPCs started in the United States, the hybrid PVT systems were not tested experimentally in the United States. With the passage of time, the research and development projects related to CPCs also started in other parts of the world. At present, India, China, and the UK are contributing the highest in terms of published research articles.

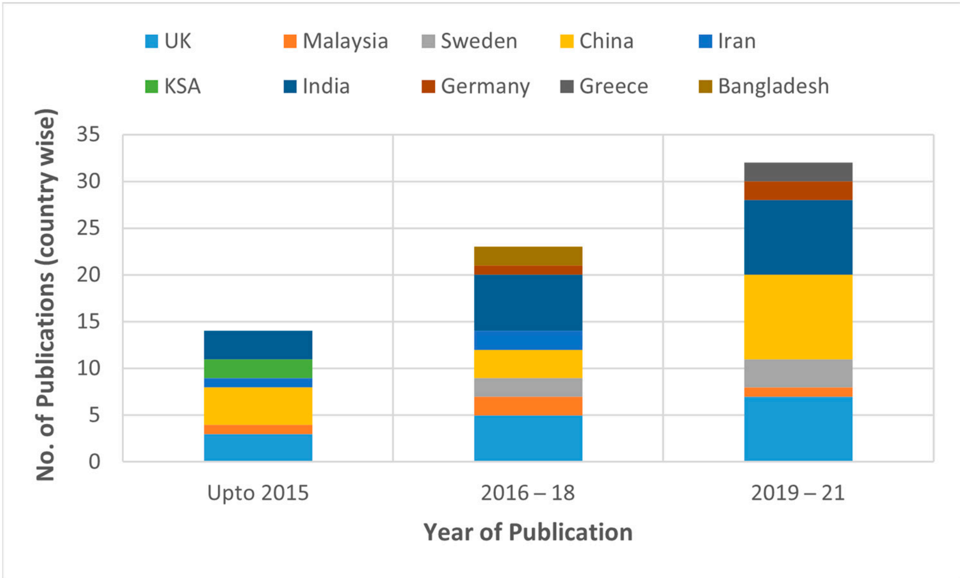

Figure 14. The number of publications yearly.

The number of research articles published by different countries expressed as a percentage of total published research articles for the period starting from 1976 to date is shown in Figure 15. It is evident from Figure 15 that India, China, and the UK are the leading research contributors with 25%, 23%, and 22% of research publications, respectively. In comparison, the share of Sweden and Malaysia in the total published research is 7% and 6%, respectively. The percentage of the rest of the countries is below 5%.

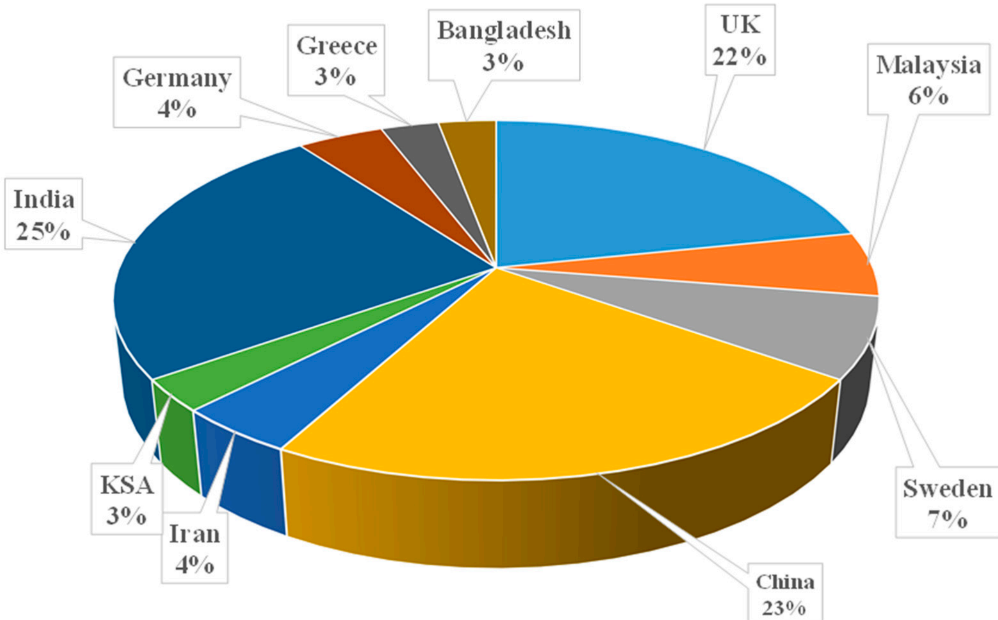

Figure 15. The percentage of country-wise research contribution.

8.2. Recommendations for Prospective Systems

The possible future research opportunities and challenges are mentioned below.

- A variety of CPC designs are available in the literature ranging from simple 2D troughs to more complex 3D geometries. Each design configuration has its own pros and cons. Optimization studies using efficient computational algorithms are required to be performed for the design optimization of existing designs. The parabolic shape of reflectors gives rise to non-uniform solar flux distribution at the receiver surface, which in turn causes a reduction in net outputs of CPC-based systems. Despite extensive research, the problem of non-uniform illumination has still not been fully solved and requires the attention of prospective researchers.
- The increased temperature of concentrated solar cells is responsible for lower electrical outputs of CPC-PVT systems. Air and water are currently being used as HTFs for removing the excess heat generated in the solar cells during the photovoltaic conversion process. With the development of nanofluids possessing superior thermophysical properties, the heat extraction process from concentrated solar cells can be accomplished more efficiently. Future research should focus on the thermal and electrical performance assessment of CPC-PVT systems using different nanofluids and diverse heat exchanger configurations.
- A noticeable obstruction in the universal acceptance of concentrated solar systems is the comparatively higher upfront costs associated with these systems. Research studies using modern optimization techniques should be conducted with the sole intention of minimizing the cost functions of low concentrating PVT systems purposely designed for single-family houses and smaller multi-family apartment buildings. This will not only reduce the burden on the national grid but also provide a chance for exporting the surplus power to the grid network through net metering technology, resulting in a financial benefit to the consumers, which can potentially act as a motivational factor in multiplying the share of solar systems in the energy mix of a country.

9. Conclusions

A comprehensive review of available research articles related to CPC-based hybrid solar PVT collectors was conducted, emphasizing recent developments in the concerned area. The review started with the basic constructional details and classification of CPCs. The feasibility of CPC-based hybrid PVT collectors was established, followed by optical performance evaluation and different heat exchanger configurations and applications of CPC-PVT systems. The following conclusions have been drawn:

- Most researchers used CPCs having geometric CR < 5, whereby sun tracking was not required. However, due to low CR, the quality of heat generated by these systems was relatively lower. The produced heat energy was thus suitable only for low-temperature process heat and preheating applications.
- The CPC-PVT systems produced higher electrical and thermal outputs than equivalent nonconcentrating collectors. However, a trade-off often has to be made between electrical and thermal outputs in hybrid systems because an increment in one of the products is usually achieved at the cost of the other.
- A 3D CPC caused a higher concentration on the target surface than its 2D counterpart. However, the circular shape of 3D CPC resulted in higher losses.
- The PCM can be employed for the efficient removal and storage of heat energy in hybrid CPC-PVT collectors.
- Although expensive, active cooling techniques caused effective heat removal from solar cells and improved the systems' performance.
- Bifacial absorbers were found to have more output per unit area of the absorber. However, more research studies are still required for the performance evaluation of bifacial absorbers in CPC-PVT systems.
- The CPC-PVT systems have found numerous applications in rooftop and building integrated systems for simultaneously producing heat and electricity.

- The upcoming research should focus on designing and developing technically feasible and economically viable CPC-based PVT systems to fulfill future energy requirements through renewable resources.

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Abbreviations

PVT	Photovoltaic/thermal
CPC	Compound Parabolic Concentrator
ACPC	Asymmetric Compound Parabolic Concentrator
CCPC	Crossed Compound Parabolic Concentrator
AR-CCPC	Absorptive, Reflective Crossed Compound Parabolic Concentrator
ALCPC	Air-gap Lens-walled Compound Parabolic Concentrator
CHCT	Compound Hyperbolic trumpet
CR	Concentration Ratio
CCHP	Combined Cooling, Heating, and Power
LCPV	Low Concentrating Photovoltaic
LCPVT	Low Concentrating Photovoltaic/thermal
PCM	Phase Change Materials
ECPC	Elongated Compound Parabolic Concentrator
EMR	Eliminating Multiple Reflections
LEMR	Lowest Truncated—Eliminating Multiple Reflections
HEMR	Highest Truncated—Eliminating Multiple Reflections
CFD	Computational Fluid Dynamics
HTF	Heat Transfer Fluid
TRNSYS	Transient System Simulation
SWCNT	Single-walled Carbon Nanotubes
MWCNT	Multi-walled Carbon Nanotubes
ICE	Internal Combustion Engine
FEL	Following Electrical Load
FTL	Following Thermal Load
TEC	Thermo-ecological Cost
MaReCo	Maximum Reflector Collector
DNI	Direct Normal Irradiance

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