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Review

Tracking-Integrated CPV Technology: State-of-the-Art and Classification

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Abstract: Concentrator photovoltaic (CPV) technology offers an alternative to conventional photovoltaic systems, focusing on the concentration of solar radiation through the optics of the system onto smaller and more efficient solar cells. CPV technology captures direct radiation and requires precise module orientation. Traditional CPV systems use robust and heavy solar trackers to achieve the necessary alignment, but these trackers add to the installation and operating costs. To address this challenge, tracking-integrated CPV systems have been developed, eliminating the need for conventional trackers. These systems incorporate tracking mechanisms into the CPV module itself. This review presents a detailed classification of existing designs in the literature and provides an overview of this type of system with different approaches to integrated tracking including tracking concentrator elements, using external trackers, or employing internal trackers (the most researched). These approaches enable the automatic adjustment of the CPV system components to follow the movement of the Sun. The various tracking-integrated systems have different designs and performance characteristics. Significant progress has been made in developing tracking-integrated CPV systems with the aim to make CPV technology more competitive and expand its applications in markets where traditional CPV has been excluded.

Keywords: concentrator photovoltaic; solar tracker; optics; tracking-integrated

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1. Introduction

Power generation using fossil fuels has been the traditional form for a considerable period. This mode of production faces significant challenges due to the limitation of these resources, and the growth of the population and industrial development has led to a rapid depletion of fossil fuel reserves. This situation raises both economic and environmental concerns, as the increase in demand for these fuels for energy generation coincides with a decrease in supply due to their scarcity. As a result, a country's economy can become increasingly unstable. Furthermore, the negative environmental impact caused by high greenhouse gas emissions during their combustion raises serious concerns [1]. Consequently, current environmental policy focuses on mitigating climate change by reducing carbon emissions and achieving the Net Zero Emissions by 2050 Scenario [2].

In this transition toward a more sustainable energy system, renewable energies are becoming the primary development direction supported by the scientific community. Among them, photovoltaic (PV) solar energy and wind energy stand out above the rest. These sources of clean energy are experiencing accelerated growth in their share of electricity generation as their use is essential in reducing emissions and ensuring a sustainable, carbon-free energy supply in the long-term.

In the case of PV solar energy, its production reached a record 270 TWh in 2022 [3], surpassing wind energy for the first time in terms of generation. Currently, the accumulated capacity of PV energy represents 14.7% of the total, and this upward trend is expected to continue in the coming years [4]. It is projected that by 2030, the accumulated capacity of solar energy will surpass all other technologies. It is important to note that while crystalline silicon solar panels are the most commonly used today, PV technology does not stop there. Other solar panel technologies such as flexible panels [5], thin-film panels, and concentrator systems are being constantly developed and improved.

Concentrator photovoltaic (CPV) systems have been presented as a promising renewable energy alternative [6] to conventional PV systems. This technology is characterized by being able to concentrate sunlight on small but highly efficient photovoltaic cells [7]. Although these high efficiency (η) cells are expensive, their use is compensated by the low cost of the concentrator optical elements used in the system design [8].

CPV technology mainly captures direct normal irradiance (DNI) from the Sun. Because of this, the modules must be correctly oriented with respect to the incident sunlight. The need for greater precision in module orientation depends on its concentration ratio (i.e., number of times sunlight is concentrated). CPV is classified as low (<10 suns), medium (10–100 suns), high (100–2000 suns), and ultra-high (>2000 suns) [9]. At higher concentration, systems become more susceptible to misalignment errors, and accuracy becomes more necessary.

Conventional CPV systems require precise alignment and normal incident radiation at the module input. This is usually achieved by an external solar tracker that follows the movement of the Sun [10]. However, solar trackers represent an additional cost for both assembly and annual maintenance, making them a necessary but costly element of CPV technology. Although CPV has achieved record efficiencies such as the laboratory η of 41.4% achieved by a high CPV (HCPV) module [11], and a commercial η of 34% [12], its economic viability is affected by the high installation and operating costs of the trackers. As a result, CPV is often considered to be economically uncompetitive with conventional PV systems [13]. In addition to increasing the costs, the use of solar trackers further exacerbates this problem, as their weight and size limit their installation in certain locations.

In recent years, the research community has made a great effort to try to make CPV technology competitive, trying to introduce it into markets where traditional CPV had been excluded until now. To overcome this problem, the concept of tracking-integrated CPV systems has been developed. This type of tracking makes it possible to dispense with traditional solar trackers, taking advantage of other locations such as the roofs of buildings [14,15], and even implementing it in applications in the field of agrivoltaics (APV) [16].

This paper presents a review of the different approaches developed on tracking-integrated systems. Section 2 provides an overview of both traditional and tracking-integrated CPV systems, focusing mainly on integrated tracking within the module itself. Section 3 presents the summary and conclusions derived from the study.

2. Overview of CPV Tracking Systems

CPV systems mainly capture solar radiation through direct sunlight. Keeping the modules properly oriented is therefore necessary. To accomplish this, solar trackers are used to track the daily and annual position variation of the Sun. Several types of solar trackers have been developed, and they can be classified based on the tracking process as either external or internal to the concentration module. A basic classification of systems with integrated tracking has been proposed by Apostoleris et al. [17] (see Figure 1).

In this work, a complete classification of the different CPV tracking systems was proposed (Figure 2). These solar trackers were classified according to where the tracking took place and the specific devices involved.

Moreover, a more general classification divided the solar tracking systems into conventional trackers and integrated trackers. Within each category, the type of tracking that takes place is specified in more detail.

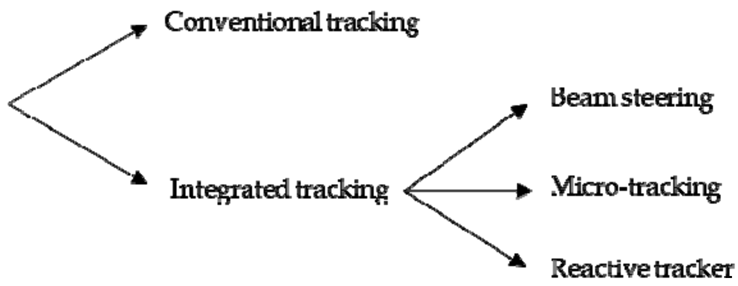

Figure 1. Basic classification proposed by Apostoleris et al. [17].

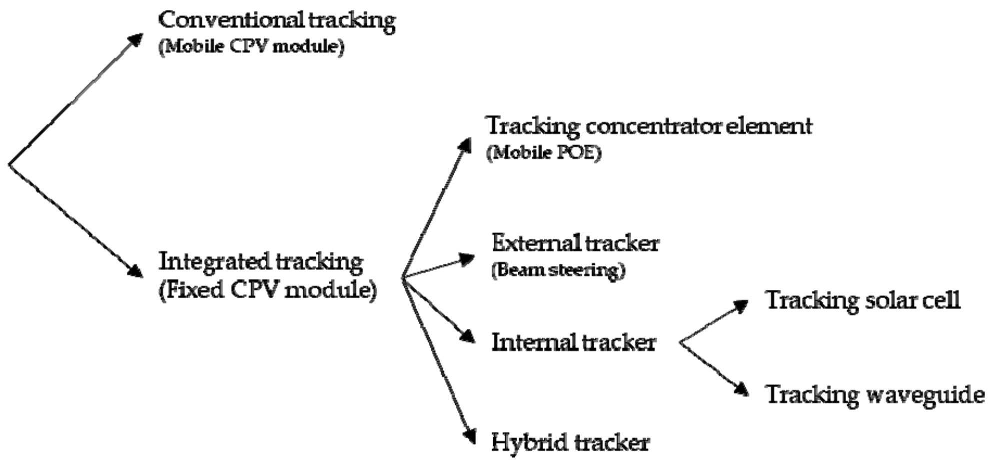

Figure 2. Complete classification proposed in this work for the different CPV tracking systems reported in the literature.

2.1. Conventional Tracking

Conventional tracking makes use of a mechanical structure, an additional external element on which the CPV module is placed, in order to follow the daily and/or annual movement of the Sun. These devices are divided into two groups, single or two-axis trackers [9], depending on whether they move in one or two directions. From the above division according to the concentration ratio, low CPV (LCPV) and medium CVP (MCPV) systems use single-axis systems such as horizontal or inclined-axis trackers. These types of trackers allow for higher levels of incident irradiance, although they do not keep the CPV modules perpendicular to the direct beam at all times. For a higher level of concentration, CPV systems are more sensitive to misalignments. In this case, two-axis solar trackers such as pedestal-mounted, carousel, and tilt-and-roll, are used to achieve greater daily and seasonal adjustment. A design of some of these types of solar trackers can be seen in Figure 3.

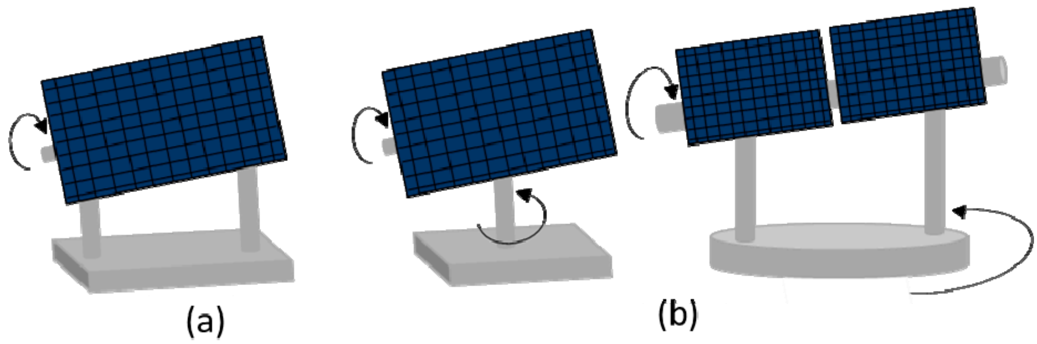

Figure 3. Some designs of solar trackers: (**a**) single-axis, and (**b**) two-axis pedestal-mount (**left**) and carousel (**right**) [9].

2.2. Integrated Tracking

Incorporating tracking mechanisms into a CPV module provides a distinctive approach for aligning the system with the trajectory of the Sun. Rather than relying on conventional tracking devices, the CPV module itself can perform the task by automatically adjusting its components to the movement of sunlight. In this scenario, the concentrator module maintains a fixed inclination while the mobile components enable it to sweep through a specific range of angle of incidence (AOI) as the Sun moves across the sky. This innovative approach has been investigated in numerous research publications, and the objective of this article is to further explore this concept. Tracking can be accomplished through various methods: an external tracker, tracking of the concentrator elements, an internal tracker, or hybrid tracking. Each of these tracking systems is discussed below.

2.2.1. Tracking Concentrator Elements

As a first case, the idea of tracking using the primary optics that are part of the CPV system is presented. Thus, the primary optical element (POE) [18] becomes the moving component, or one that can change its internal properties, with the motion of the Sun.

Refractive elements are mainly the components used for a basic CPV system design, and by means of mechanical displacement of the lens, mobile optics are achieved. One option to achieve tracking and focus the incident beam onto the solar cell is through the combination of two plano-convex lenses and by lateral translation of both elements [19]. However, achieving free-form optics instead of a simple preset geometry would improve the performance of the system with a concentration greater than 500x in which monochromatic light is incident, while maintaining the full field of view ($\pm 24^\circ$) [20]. Considering the full solar spectrum, the concentration ratio will be considerably lower due to scattering. This problem can be solved by including an additional concentrator on the top of the solar cell [21,22], thus achieving a more uniform radiation distribution over the solar cell surface [23–25].

By replacing the primary concentrator with a GRIN (GRadient-INdex) spherical lens [26], the system is able to capture radiation within an AOI range of $\pm 60^\circ$ while maintaining high-concentration levels. There is a lateral and vertical shift to the POE, describing a curve in its trajectory. The use of this type of concentrator optic reduces losses due to dispersion compared to a conventional lens, along with only 1–2% losses due to alignment issues.

Tsou et al. employed a different concentrator than the typical solid lens. They used a liquid lens (LC) that when placed on the surface with electrodes, focused light on the solar cell as the AOI changed [27]. Activating the electrodes that formed the system caused a deformation or movement of the LC in the direction of the activated electrode, with a maximum AOI of $\pm 25^\circ$.

Figure 4 shows the various above-mentioned tracking-integrated systems, where the tracking element is the POE.

2.2.2. External Tracker

By keeping the POE fixed, tracking can be carried out before concentration takes place. In this type of design, the basic CPV module (consisting of the POE and the solar cell) has an additional external component attached to it that performs solar tracking.

The objective of the external trackers is to collimate the incident light beam reaching the surface of the POE at an AOI different from the normal incidence. In this way, the direct radiation incident with any AOI within the tracking range is redirected and collimated toward the surface of the POE. This type of tracking utilizes a concept known as beam steering [28,29]. Several studies have explored the use of mechanical movements using mirrors, prisms, or even beam-steering lens arrays (BSLA) to achieve this goal [30–35]. In the case of the BSLA system, an experimental study was conducted where, despite recording a lower than expected performance, the proof-of-concept demonstrated the feasibility of this type of tracking system. This proof-of-concept achieved a 10% reduced η compared to the values simulated by the authors. Alternatively, and with the same purpose of collimating the beam, some systems have made use of prism-shaped liquid crystals [28,36,37] to change the angle formed between two immiscible liquids with different refractive indices, instead of resorting to mechanical displacements. The latter can be electrically modified or controlled via electro-wetting to change the angle formed between the two materials. Since the basic CPV system is maintained in a fixed horizontal position relative to the ground, it offers several advantages such as a considerable reduction in the wind loads on the system. This tracking method may have a disadvantage compared to other trackers mainly due to the additional cleaning required for the optical components, both the fixed Fresnel lens and the external components redirecting the beam. Figure 5 illustrates a schematic representation of some of these systems.

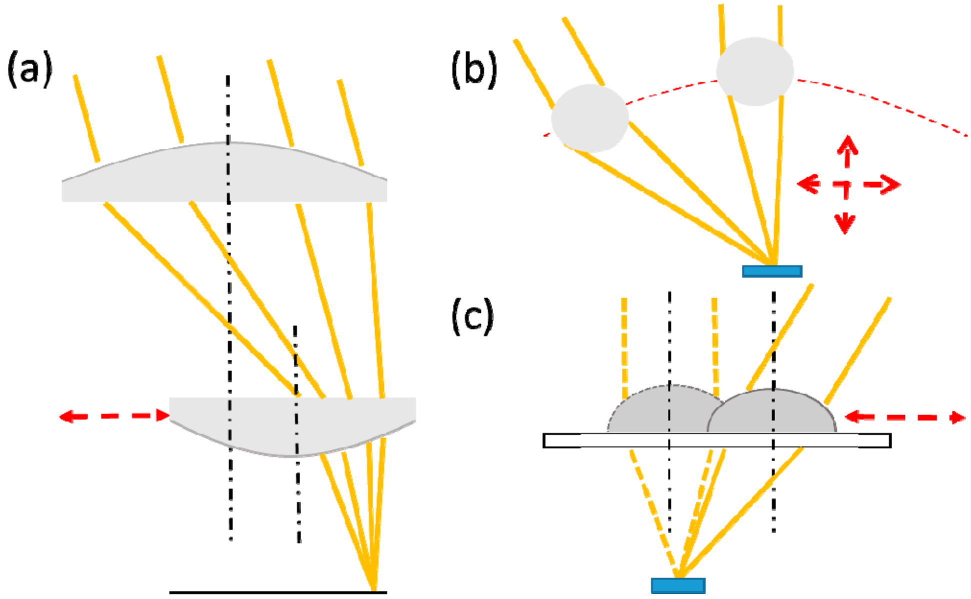

Figure 4. Sunlight tracking performed by the concentrator optics of the tracking-integrated system. (**a**) Lateral displacement of two plano-convex lenses. (**b**) Spherical GRIN lenses with two-directional displacement. (**c**) LC as a concentrator element with electrode-activated displacement.

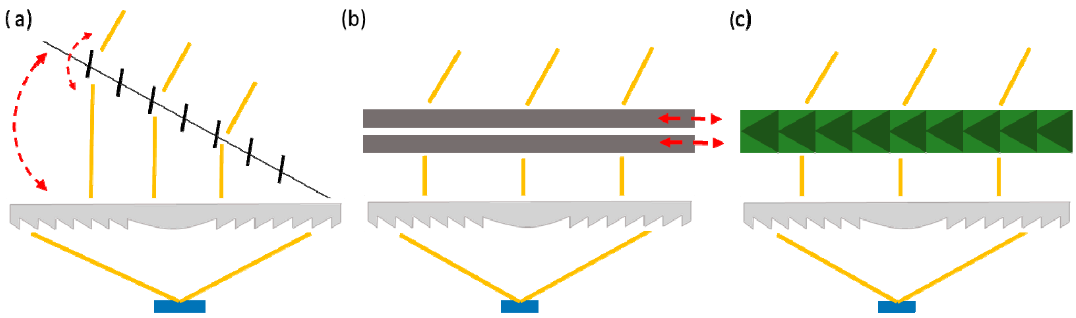

Figure 5. Scheme of different systems with external tracking to the CPV module (beam steering). It shows the representation of the basic CPV system with the addition of mirror rotation and elevation of the micro-heliostat array (**a**), lateral displacement of the second lens array (**b**), and prism-shaped liquid crystals with a different refractive index (**c**).

2.2.3. Internal Tracker

As an alternative to the external tracker, and once the radiation passes through the POE, an internal tracker can be employed. In this way, solar tracking takes place after beam concentration by the static POE. By using point-focus lenses, the variation in the AOI of sunlight on the surface of the concentrator element causes the radiation to focus on a different location. Changing the AOI shifts the focal point of the POE to a new position. In this case, tracking is performed after the concentrator elements, and can be carried out by the solar cell itself or by an additional optic such as a waveguide, which directs the radiation toward the solar cell.

Tracking Solar Cell

The simplest tracking-integrated system consists of the concentrator optics and the moving cell. Using a convergent lens as the POE, as the incident beam changes its inclination, the spot generated by the convergence of the beams changes its position. This new location leads to a lateral displacement and a decrease in the focal length of the lens. As can be seen in Figure 6, the motion described by the spot has a curved shape, a displacement known as Petzval curvature [38]. If the receiver only moves laterally, as the AOI increases, part of the concentrated radiation falls outside the cell (see Figure 6) and will not be collected by the cell. It is necessary for the cell to move both horizontally and vertically to be located at the focal point of the lens at any time [39]. Tracking can be carried out using an automated dual-axis planar solar tracker [40]. Despite the moment in two directions to compensate for the focal shift, conventional convergent lenses (e.g., the Fresnel lens) are not a good choice in these systems. In addition to surface curvature, there is the problem of spherical aberration in these optical elements. This aberration is more noticeable the higher the AOI. Therefore, their tracking range is limited to a few degrees. Research has succeeded in resolving this aberration by using bi-convex aspheric lenses [41]. Using this type of optics, it is possible to measure an AOI range of up to $\pm 50^{\circ}$ with an optical efficiency (η_{opt}) higher than 70% within that range [42]. A schematic of this type of configuration can be seen in Figure 6. Based on this type of configuration, the start-up Insolight was the first to develop a micro-CPV module with bi-aspheric lenses and a hybrid III-V/Si receiver to capture both direct and diffuse radiation. This is the first module of this type in commercial development, with plans for industrialization in the short-term. A first evaluation of the 0.1 m^2 prototype was conducted at the Solar Energy Institute of the Polytechnic University of Madrid (UPM-IES), showing an η of 29% in CSTC for direct capture [43,44]. In addition to this commercial module, Insolight has developed an alternative tracking module architecture by placing a transparent backplane with only III–V solar cells. This type of translucent PV system allows for use in APV, integrating the module into static structures such as the roofs of greenhouses. Compared to conventional Si panels, the inherent splitting of direct/diffuse light by CPV optics combines high-efficiency electric generation from direct light and a homogeneous illumination distribution over the crops from transmitted diffuse irradiance. This reduces excess radiation reaching the crops that can damage them, and has a positive impact on temperature, relative humidity, etc. [45].

To avoid double displacement of the receiver, an alternative design has been presented. This is a system consisting of two arrays of lenses, the first plano-convex and the second plano-concave, between which a flat transparent surface is inserted in a sandwich configuration. The first lens array realizes the first convergence of the incident radiation toward the surface of the second lens array. This surface is coated with a reflective material in charge of reflecting the beam onto its focal point. This reflected radiation is concentrated on the transparent surface, located at the focal point of the reflector. The GaAs solar cell used is placed on this transparent surface, moving only with lateral movements to follow the spot [46], thus eliminating the Petzval curvature (see Figure 6). With this configuration (geometrical concentration (C_g) = 225x), it is possible to measure an η_{opt} higher than 79% for an AOI range of $\pm 60^{\circ}$. A subsequent study conducted a proof-of-concept of this type of tracking-integrated configuration. It achieved an effective concentration (C_{eff}) >660 in a field of view of $\pm 70^{\circ}$, exceeding the 30% maximum energy conversion η, with losses of 5% due to cell heating [47].

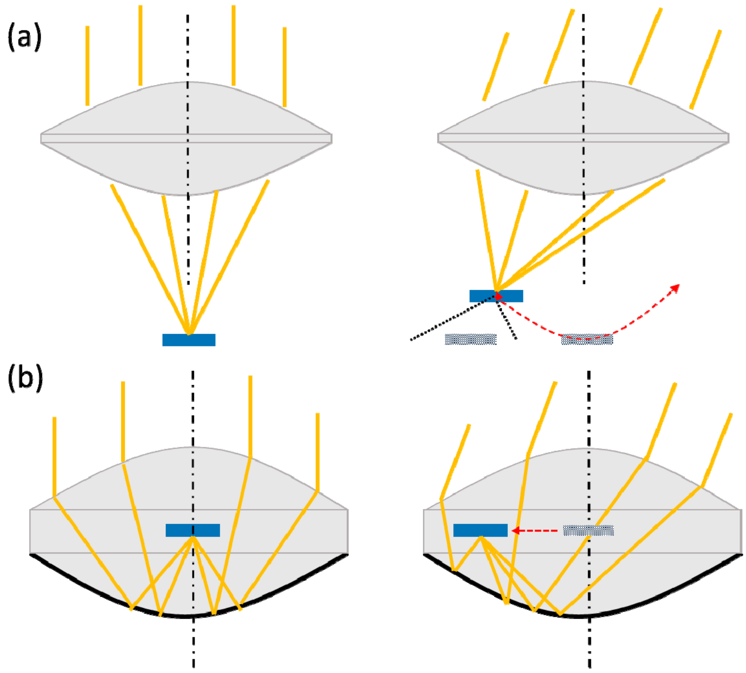

Figure 6. Diagram of the integrated tracking systems with mobile solar cells. (**a**) Focusing system using aspherical bi-convex lenses. The dashed line describes the movement in two directions (Petzval curvature) made by the focal point of the lens. (**b**) Focusing system with sandwich configuration to achieve only a lateral displacement of the receiver.

Tracking Waveguide

By incorporating an additional optical element to the CPV system such as a waveguide, the distribution of radiation on the photovoltaic cell becomes uniform. The light guide is now the device in charge of tracking the movement of the focal point. The tracking can be mechanical, by means of a lateral displacement of the guide as the AOI varies throughout the day [48], as can be seen in Figure 7. This micro-optical concentrator has been tested experimentally to study the tracking that the system can perform. The tracking element moves as much as 1.6 mm for angles of ±30°, although high efficiencies are limited to ±10° [49]. The lateral shift to follow the daily movement of the Sun can be accompanied by a seasonal adjustment (±23.5°). This is carried out by an additional lateral shift of a lens array of the two pairs that are part of the radiation concentrator system [50]. Although the average transmission of the study was 90.7%, this system, with a concentration ratio of 500x, is more complex due to the double translation.

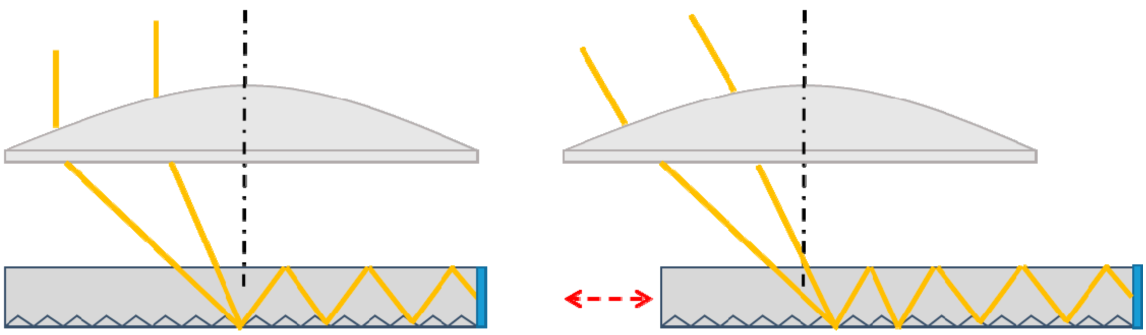

Figure 7. Lateral displacement of the waveguide when the AOI is different from the normal angle.

The mechanical tracking of the light guide can be suppressed by a different tracking concept. To achieve this, the characteristic response of the materials forming the waveguide is used. Baker et al. [51] first presented this type of tracking, known as reactive tracking or self-tracking systems.

Exploiting the phase change properties of materials is one way to achieve this. A polydimethylsiloxane (PDMS) membrane placed under the waveguide can be included in the design of a CPV system. This membrane contains within it a prism-shaped dichroic structure [52], and the material of which it is composed sets a wavelength limit value of the concentrated radiation. Wavelengths shorter than this limit are reflected, while for longer wavelengths, the radiation is absorbed. This absorption increases the temperature, generating a phase change in the material and increasing its volume. The increase in volume pushes the membrane over the waveguide, causing the reflected radiation to couple to it, driving it into the cell located at the edge of the waveguide. The angular range of the system achieves an acceptance angle of ±16° for a C_g of 280x. In the theoretical case, the C_{eff} = 8x versus a C_{eff} = 3.5x measured by the setup had an η of 2.8% and 1.25%, respectively [53]. These data, according to the researchers, are disparate; the C_g is artificially high, while the η is artificially low as a consequence of the small size of the solar receiver. If instead of a small receiver size, a full-size one is used, there is an increase of C_{eff} = 10x, which translates into a C_g value of 27x and an η of 37%. Even so, the work described in the paper shows the operational demonstration of a concentrator integrating an automatic tracking system. Figure 8a shows a diagram of this integrated tracking system.

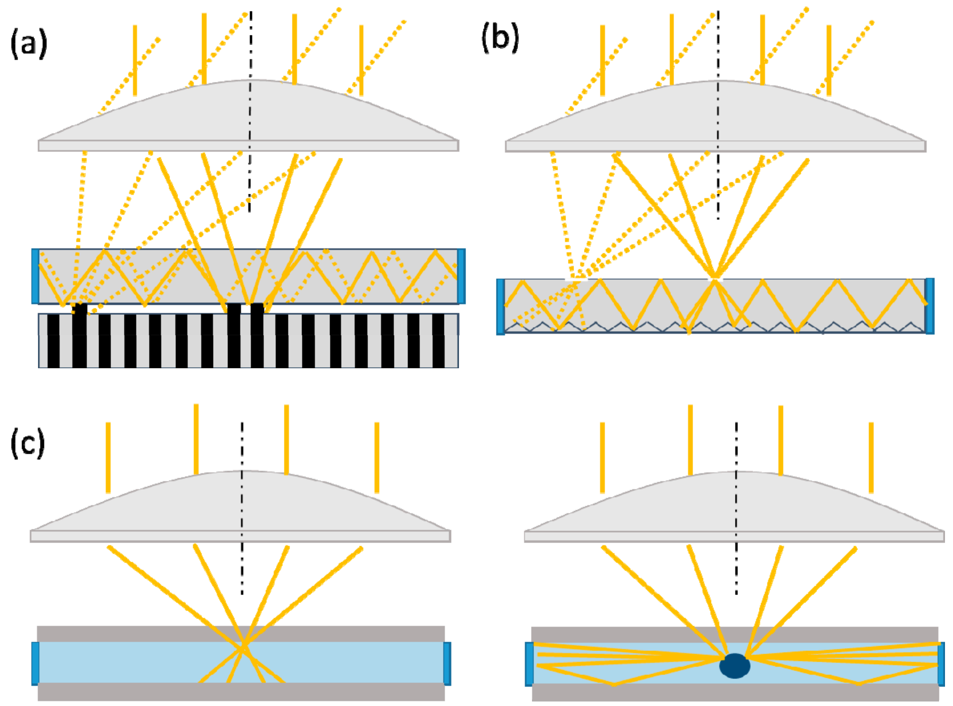

Figure 8. Self-tracking systems using solid waveguides by means of the phase changes of materials (**a**) or switchable transparency properties (**b**), and using liquid waveguides (**c**).

Another way of tracking the movement of the focus can be carried out with a light guide wrapped with a passive top coating and a smart bottom coating [54]. As the radiation is concentrated on one point, the tension between the layers is reduced due to the increased temperature. This opens an optical path to the reflective surface just below the array, reflecting the radiation into the waveguide where it is trapped and travels through it to the PV solar cell. With this configuration, the researchers achieved an η_{opt} of up to 72% and self-tracking at angles of up to ±25°.

Replacing these coatings with a switchable transparency layer on the top surface of the waveguide [55] follows the variation in the AOI. This fully opaque material becomes locally transparent when the concentrated radiation is incident on it (Figure 8b). When this happens, the rays reach the waveguide and are reflected until they reach the solar cell. In the ideal case, a capture η of 25.7% is obtained. Another type of secondary optics such as a compound parabolic concentrator (CPC) [56], covered with the same switchable material [57,58], has been investigated instead of employing light guides. Theoretically, an η_{opt} of 95% can be achieved with an angular range of $\pm 23^{\circ}$ and an approximate concentration of 31 suns.

Although the waveguide is normally solid, a self-tracking system with a liquid guide can be found in the literature [59,60]. Composed of methanol, it is enveloped by a glass top layer and an infrared (IR) absorber on the bottom. This absorber causes the infrared part of the concentrated solar spectrum to be exploited to realize the self-tracking mechanism. The absorption of this part of the beam provides the energy necessary for the generation of vapor bubbles in the waveguide. The remaining radiation focused on the bubble is then reflected by the total internal reflection at the liquid–gas interface to couple to the guide and travel to the receiver. To compare the theoretical and experimental results, the authors employed the parameters of the elements used in the experimental study, expecting a theoretical coupling η of 49%. In the proof-of-concept configuration, the maximum diameter of the generated bubble reaches 370 μm due to the limited available power of the IR light source. Focusing on a specific case with a bubble diameter of 300 μm, the minimum light transmission through the sample was determined to be 17%, which closely matched the expected value from the simulation, with a small margin of error. When calculating the coupled light based on the minimum power reaching the detector, the coupling η achieved was 40%, a value slightly below the theoretically expected maximum of 49%, as not all of the light was effectively coupled to the waveguide. Figure 8c shows this type of self-tracking.

Although this internal tracker approach has the disadvantage of the need to account for wind loading due to a fixed inclined position, it also offers significant advantages. Because the tracker is located inside the module, it is protected from inclement weather, which can mean increased durability and tracking that requires minimal mechanical movement to adjust the cell. In the case of the waveguide, lateral displacement or a change of medium would suffice.

2.2.4. Hybrid Tracking System

Mainly, the literature on tracking-integrated systems primarily addresses single-stage tracking, wherein tracking takes place at a specific moment and is executed by one of the elements in the module. As shown earlier, this occurs either through the primary optics or, depending on whether it is an external or internal tracker, with respect to the POE. However, a special case of two-stage tracking is also encountered. It involves a two-shell spherical lens array, each layer with a different refractive index, along with a solar cell. In this design, the lenses move vertically while the cells move laterally. It is therefore a more complex design as it involves all of its components in tracking the displacement of the Sun. Solar radiation is concentrated within a maximum incidence angular range of $\pm 44^{\circ}$ [61]. In addition, the simulated η_{opt} achieved was 76% for a system with a C_g of 100x. A schematic of this system is presented in Figure 9.

2.3. Summary of Integrated Tracking Literature Review

As a summary of the detailed review, tracking-integrated CPV systems fall mainly into three categories: tracking concentrator elements, external trackers, and internal trackers. In general, tracking-integrated systems seek to align system components with the Sun's path, either by moving optical elements, using external devices to collimate radiation, etc., to achieve the optimal concentration of solar radiation and avoid the need for conventional solar trackers. These approaches offer innovative solutions to improve the performance and η of CPV systems.

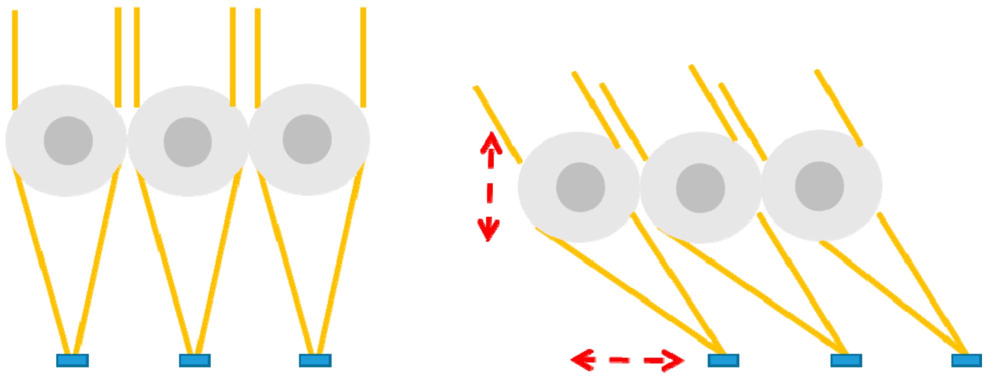

Figure 9. Two-state tracking system; the primary optics describes a first vertical movement. After radiation concentration, the solar cell array moves laterally to follow the displacement of the focal point.

Tracking concentrator elements present an approach where the POE that is part of the CPV system is moved to follow the Sun's path by mechanical displacements of refractive lenses. Some variants include the use of electrically controlled liquid lenses. This approach allows for high concentrations and improves system performance.

If the POE is held fixed, tracking can be performed externally or internally. On the one hand, the external tracker allows the traditional CPV module (consisting of a lens and solar receiver) to be held fixed, with tracking taking place before light concentration occurs. Additional external devices such as mirrors, prisms, or lens systems redirect the incident light beam to collimate the rays that are directed toward the POE. On the other hand, the internal tracker is used after beam focusing. Fixed point-focusing lenses are used to concentrate the incident solar radiation at a point that is the focal point of the POE. Once the radiation is concentrated at a point, tracking can be performed either by moving the solar cell itself or by using an optical waveguide through which the total internal reflection directs the radiation toward the solar cell.

Although these are the main categories, a hybrid tracking system that combines vertical and lateral movements of the lenses and solar cells to achieve higher concentration η has also been discussed.

In the studied technologies, heat removal methods are employed to prevent its detrimental impact on both the overall module efficiency and the electrical efficiency or lifetime of the solar cells. Typically, passive cooling plates integrated on the rear side of the module or attached to the receivers are utilized. There are also cases where an optimal arrangement of solar cell distribution improves the heat sink and thermal management. Furthermore, by reducing their size and employing micro-solar cells, it is expected to mitigate the thermal load by effectively distributing heat throughout the module.

These key features are compiled in Table 1, and a summary of the results obtained from the articles analyzed is presented. The "Category" column indicates the group in which each of the systems is classified, as shown in Figure 2. The "No. of movements" column indicates whether a single-direction (x1) or dual-direction (x2) movement is required to achieve solar tracking. This information is crucial for understanding the complexity and practical viability of the examined tracking-integrated systems.

The "No. of mobile elements" column highlights whether a single component (1) or two components (2) are used for tracking, providing essential insights into the configuration and design of CPV systems. Additionally, the "Mobile element" column specifies the type of component used such as a lens, solar cell, waveguide, or any other specific element responsible for carrying out the tracking.

Table 1. Summary of the key features of tracking-integrated systems found in the literature.

Category	No. of Movements	No. of Mobile Elements	Mobile Element	Control	Tracking-Integrated	Other Data	Refs.
Tracking concentrator element	x1	2	Lenses	Mechanic	Concentrator element	Theoretical	[19,20]
Tracking concentrator element	x2	1	GRIN lens	Micro-mechanic	Concentrator element	Theoretical	[26]
Tracking concentrator element	x1	1	Liquid crystal	Electrode	Concentrator element	Theoretical	[27]
External tracker	x2	2	Prism	Mechanic	Before concentrator element	Theoretical	[31]
External tracker	x2	1	Micro-heliostat	Mechanic	Before concentrator element	Theoretical	[32]
External tracker	x2	2	BSLA	Mechanic	Before concentrator element	Theoretical/ Experimental	[33–35]
External tracker	x1	2	Liquid crystal	Electrowetting	Before concentrator element	Theoretical	[36,37]
Internal tracker	x2	1	Cell	Mechanic	After concentrator element	Theoretical/ Experimental	[41,43]
Internal tracker	x1	1	Cell	Mechanic	After concentrator element	Theoretical/ Experimental	[46,47]
Internal tracker	x1	1	Waveguide	Mechanic	After concentrator element	Theoretical/ Experimental	[48,49]
Internal tracker	x1	2	Lenses and waveguide	Mechanic	After concentrator element	Theoretical	[50]
Internal tracker	x1	1	Membrane	Material property	After concentrator element	Theoretical/ Experimental	[52]
Internal tracker	x1	1	Smart light coating	Material property	After concentrator element	Theoretical	[54]
Internal tracker	x1	1	Switchable transparency	Material Property	After concentrator element	Theoretical	[55,57]
Internal tracker	x1	1	IR absorber	Material property	After concentrator element	Theoretical/ Experimental	[59]
Hybrid tracker	x2	2	Two-shell spherical lens and cell	Mechanic	Hybrid	Theoretical	[61]

The “Control” column describes the method employed to control the movements of the tracking system, which may include mechanical approaches, changes in the material properties, or any other relevant control mechanism investigated in the reviewed studies. The “Tracking-integrated” column provides information on whether solar tracking occurs before concentration, or once concentration has taken place. The “Other data” column indicates whether the analyzed studies are of a theoretical nature or also include experimental aspects, enabling us to understand the scope and limitations of the findings presented in the reviewed articles. Finally, the “Refs.” column includes the bibliographic references of each article to facilitate further consultation.

This data synthesis forms a solid foundation for the analysis and detailed discussion of the results, facilitating the identification of emerging trends and the evaluation of implications for the design and optimization of CPV systems.

3. Conclusions

In conclusion, this comprehensive review provides valuable insight into the research and technologies of CPV tracking-integrated systems. The expanded classification of sunlight tracking methods presented here offers a deeper understanding of the different approaches that have been investigated to integrate tracking into the CPV module.

Based on the information and data obtained from this review, it can be considered that among the different categories of integrated tracking systems, modules with internal trackers are the most developed. Among the internal trackers, various systems utilize different approaches for tracking including the use of the solar cell itself or the incorporation of optical components like waveguides. The key factor is that the fewer optical stages the solar beam has to pass through and the shorter the optical path of the rays to the cell, a reduction in losses can occur within the system. The design that holds the greatest potential and could be implemented more easily is the one where the solar cell itself moves to track the Sun’s movement. This line of thought aligns with the commercial module developed by the startup Insolight. Manufactured with industry-standard dimensions, it has been experimentally tested and achieved an efficiency of 29%.

The potential of tracking-integrated CPV systems to expand into previously untapped markets is significant. By enabling the deployment of CPV in areas where conventional CPV solar trackers is not feasible such as on building rooftops or in agricultural applications, this technology holds promise for broader adoption and increased energy production. The use of different materials has emerged as a crucial factor for improving current systems and inspiring future innovative designs. Furthermore, future studies focusing on designs optimization, manufacturing cost analysis, and energy production will be essential to fully realize the potential of this type of technology and its impact on the CPV industry.

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Nomenclature

PV	Photovoltaic
CPV	Concentrator photovoltaic
LCPV	Low concentrator photovoltaic
MCPV	Medium concentrator photovoltaic
HCPV	High concentrator photovoltaic
DNI	Direct normal irradiance (W/m^2)
APV	Agrivoltaics
AOI	Angle of incidence (°)
POE	Primary optical element
GRIN	GRadient-INdex
LC	Liquid lens
BSLA	Beam-steering lens arrays
PDMS	Polydimethylsiloxane
CPC	Compound parabolic concentrator
IR	Infrared
Symbols	
η	Efficiency (%)
η_{opt}	Optical efficiency (%)
C_g	Geometrical concentration (x)
C_{eff}	Effective concentration (suns)

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