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Performance of solar concentrated PV systems: A review

Jean Pierre Shumbusho[1*], Omer Eisa Babiker[2], Saadelnour Abdueljabbar Adam[3], Yinka Sanusi[4], Onep Samuel George[5]

[1,2,3,4,5]Department of Mechanical Engineering, Kampala International University, Uganda.

Corresponding author: Jean Pierre Shumbusho (*Email: shumbushojp2024@gmail.com*)

Abstract

The increasing global demand for energy and the crucial need for sustainable solutions have led to innovations in photovoltaic (PV) technology. Concentrated photovoltaic (CPV) systems, which utilize optical components to focus sunlight onto high-efficiency solar cells, present a promising alternative to conventional PV systems. This work provides a comprehensive review of CPV system performance by focusing on efficiency, reliability, and economic viability. The research analyzes a range of optical concentration methods, including Fresnel lenses, parabolic mirrors, and dielectric concentrators, by assessing their energy conversion efficiency impacts. It also explores the role of multi-junction (MJ) solar cells, solar tracking systems, and thermal management strategies essential for optimizing CPV performance. The findings of this article show that CPV systems offer notable advantages, including higher efficiency and reduced material usage compared to traditional PV systems. Current technological advancements, including improved cooling systems and more precise tracking, have resulted in efficiency improvements of 10 to 15% and cost reductions of up to 20%. However, CPV's dependence on direct normal irradiance (DNI) limits its deployment to high-sunlight regions. In conclusion, CPV systems hold significant potential for large-scale implementation in regions with higher solar irradiation. While certain limitations persist, ongoing innovations continue to enhance their technical and economic viability, making them a competitive option for future energy systems.

Keywords: Concentrated PV, Energy efficiency, Performance analysis, Solar energy, Solar irradiation.

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1. Introduction

Renewable energy sources have gained attention over the past few years as global efforts to meet sustainable energy demand increase. Among various renewable energy sources, solar energy remains the most promising solution due to its environmental friendliness, abundance, and potential to reduce dependency on fossil fuels [1]. Solar PV technologies have gained substantial attention in the research and industrial sectors [2]. Regarding sustainable energy solutions, PV systems are an excellent choice due to their non-polluting nature, quiet operation, and easy installation. Their long-term sustainability and environmental benefits make them a valuable asset for a cleaner future energy source [3]. Nowadays, hybrid systems integrating both PV and CPV systems are increasing to improve energy conversion efficiency compared to traditional PV systems [4, 5].

The global increase in energy consumption, combined with the urgent need for environmentally sustainable energy sources, has intensified research into renewable energy technologies. Among these, photovoltaic (PV) systems have emerged as a leading solution for harnessing solar energy. However, conventional PV technologies are often limited by issues related to efficiency, material usage, and economic viability in large-scale deployments [6]. In response, concentrated photovoltaic (CPV) systems have been developed, which use optical concentrators such as Fresnel lenses and parabolic mirrors to direct sunlight onto high-efficiency solar cells, notably multi-junction (MJ) cells [7]. These systems offer an innovative approach to maximizing solar energy conversion, particularly in regions with high levels of direct normal irradiance (DNI) [8]. This research aims to provide a comprehensive review and performance analysis of CPV systems, focusing on: (i) evaluating different optical concentration methods and their efficiency, (ii) assessing the contributions of MJ solar cells, solar tracking, and thermal management to overall CPV system performance, and (iii) analyzing the economic feasibility of CPV systems in comparison to traditional PV technologies.

Despite their promising performance in ideal conditions, CPV systems have not achieved widespread adoption. Their reliance on DNI, higher initial setup complexity, and maintenance demands have limited deployment primarily to specific geographic regions. There remains a need for systematic evaluation of CPV subsystems and their integration to identify whether ongoing technological improvements can overcome these limitations and make CPV a viable alternative for large-scale solar power generation. While existing studies have addressed various aspects of CPV technologies, such as individual optical components or MJ cell performance, there is a lack of holistic reviews that integrate technical performance, reliability, and economic analysis across different system configurations, referred to as a research gap in this work. Furthermore, recent advancements in cooling systems and solar tracking technologies have not been thoroughly evaluated within a unified framework [9]. This research addresses this gap by compiling and analyzing recent innovations and assessing their cumulative impact on CPV viability.

To guide the analysis, this study seeks to answer the following questions: (i) What are the comparative advantages of CPV systems over conventional PV in terms of efficiency and material use? (ii) How do various optical concentration methods affect the overall energy conversion efficiency of CPV systems? (iii) What roles do MJ cells, tracking systems, and thermal management strategies play in improving CPV performance? (iv) To what extent have recent technological advancements reduced costs and increased reliability in CPV systems? (v) What are the primary barriers to the wider adoption of CPV technology? To address the research questions, this study conducts an extensive literature review of CPV technologies, focusing on publications from the past decade. The review examines the performance of different concentrator designs (e.g., Fresnel lenses, parabolic mirrors), evaluates MJ solar cell efficiency under concentrated light, and analyzes the impact of solar tracking and thermal regulation strategies. Cost and economic trends are also investigated to determine viability. Findings are synthesized to identify future development opportunities and assess the potential of CPV systems in global energy markets.

2. Literature Review

2.1. Conventional PV Technology and PV Panels Classification

The current section will discuss the ways in which semiconductor materials and solar PV technologies can convert sunlight into electrical energy [10]. A solar PV system consists of an interconnection of MSC to generate maximum output power [11]. Traditional PV modules, including monocrystalline and polycrystalline silicon cells, have been widely used in residential, commercial, and industrial applications [10]. Figure 1 shows the categorization of solar PV technologies.

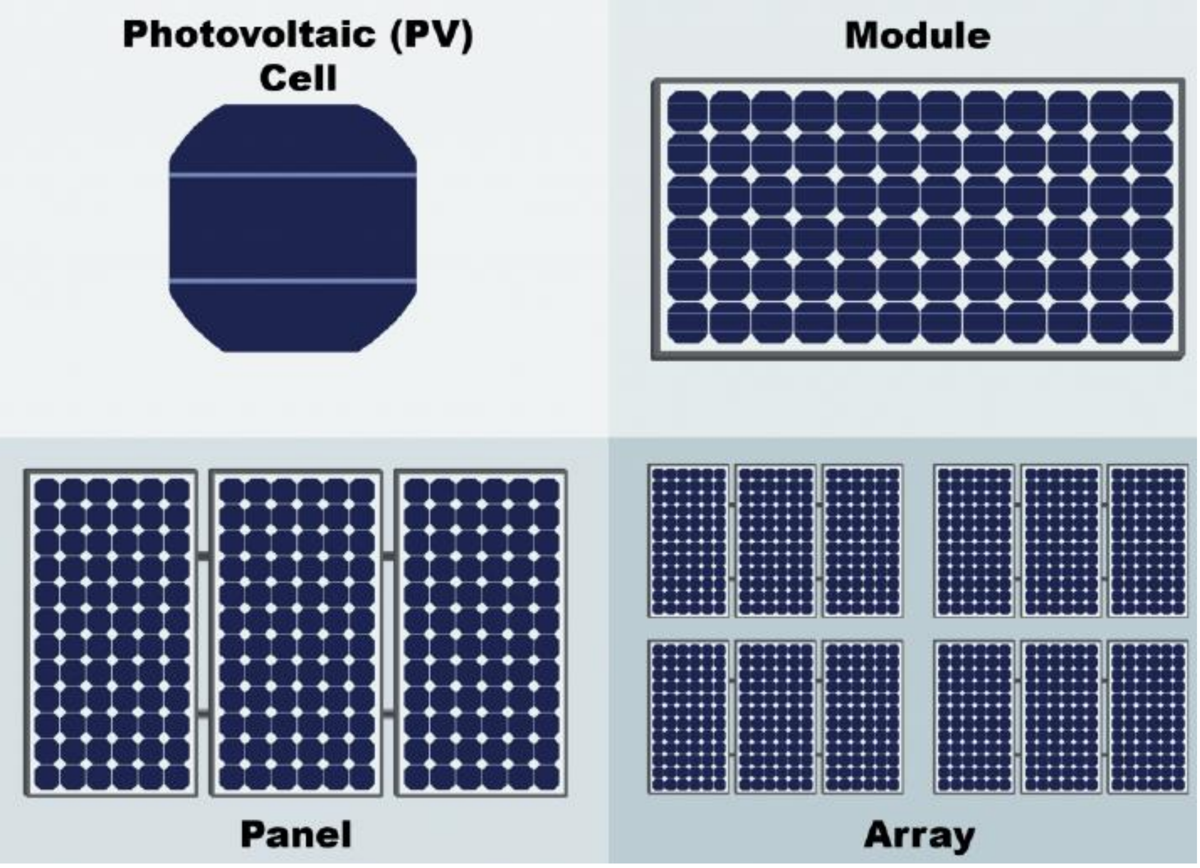

Figure 1.
Categorization of solar PV technologies, Olayiwola, et al. [11].

However, one of the critical limitations of conventional PV systems is their relatively low efficiency, typically ranging between 15 and 22%, leading to larger space requirements for significant power generation [12]. The solar cell equivalent circuit and calculations are illustrated in Kali et al. [13], while the parameters of a typical PV characteristic or I-V curve are provided in Olayiwola, et al. [11]. The solar PV panels can be arranged into three main generations: 1) the first, the second, and the third generations refer to Figure *2*. The first generation of solar cells (1st G) consists of i) monocrystalline, ii) polycrystalline, and iii) amorphous panels. Introduced first in 1954, these PV cells have become the leading choice for domestic applications, accounting for approximately 80% of the market [13].

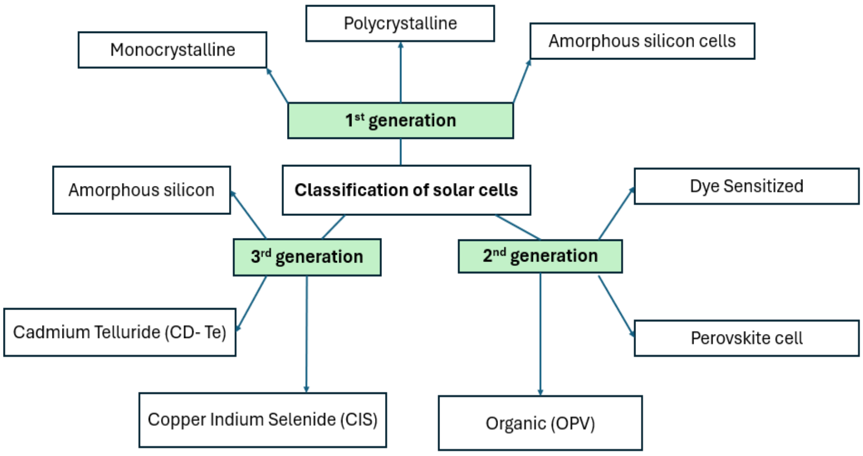

Figure 2.
Classification of photovoltaic technologies Ibrahim, et al. [13] and Lazaroiu, et al. [14].

Monocrystalline panels possess notable efficiencies of up to 26%, while polycrystalline panels achieve around 21%. These cells, made from silicon, feature a bandgap of 1.1 eV, demonstrating their high efficiency in harnessing solar energy [13]. The third generation (3rd G) includes emerging technologies, such as organic photovoltaics (OPVs), perovskite solar cells, multi-junction cells, and quantum dot solar cells. This generation offers an emerging response in efficiency and material limitations compared to other technologies [13, 14].

Table 1.
Assessment of solar PV technologies.

Solar panel type	Power output (W)	Efficiency (%)	Lifespan (years)	Typical applications
Monocrystalline	300- 450	17- 22	25 -30	Residential rooftops, commercial installations
Polycrystalline	250- 400	13- 17	25- 30	Residential and commercial installations
Thin-Film	100- 300	10- 18	10- 20	Metal roofs, portable applications
Crystalline silicon	250- 450	15- 22	25- 30	Residential and commercial
Amorphous silicon	50-150	7- 10	20- 25	Calculators and small devices
Organic photovoltaics	10–100	3–11	15- 20	building-integrated photovoltaics

Source: Lazaroiu, et al. [14], Enasel [15], Machín and Márquez [16] and Chen, et al. [17]

The National Renewable Energy Laboratory (NREL) oversees a comprehensive chart shown in Elibrahimi, et al. [18] to highlight different efficiencies for various types of solar cells, which remains the most reliable source of information on solar cell efficiency [18]. The latest data from the NREL efficiency, the confirmed highest efficiency values for various types of solar cells are as follows [14]. Multijunction solar cells have an efficiency of 47.1% (research grade), concentrator solar cells achieve 46.1% (research grade), tandem perovskite/silicon solar cells reach 29.5% (research grade), silicon solar cells (single-junction) attain 27.6% (commercial grade), and organic solar cells have an efficiency of 18.9% (research grade). The highest research cell efficiency reported by NREL is provided in Lazaroiu, et al. [14] and represents cutting-edge performance achieved in laboratory settings under optimal conditions. While they highlight the potential of current solar technology, it is essential to consider that these efficiencies may not reflect the performance of products available on the market.

2.2. Concentrated Photovoltaic Technology

Several PV technologies have been developed to overcome efficiency constraints. These include thin-film PV, tandem solar cells, and CPV. To enhance energy yield, CPV technology employs optical components that concentrate sunlight into small solar cells of high efficiency [10]. CPV and CSP are of higher research interest due to their higher electrical efficiency compared to conventional PV systems [19]. CPV systems leverage optical concentration techniques to intensify solar irradiance onto high-performance multi-junction solar cells. Unlike flat-panel PV systems, CPV modules operate with tracking systems that allow them to follow the sun's trajectory, ensuring maximum light absorption throughout the day [10]. By utilizing concentrator optics, CPV systems can achieve efficiency levels exceeding 40%, significantly outperforming conventional PV technologies. The typical models of CPV systems are shown in Figure 3.

The performance of the CPV system generally depends on equivalent irradiance, which can be enhanced through the design of various optical elements. The uneven distribution of irradiance causes hotspots on the solar cell, increasing its temperature and consequently reducing efficiency. In Wang, et al. [20] linear Fresnel reflectors were preferred over parabolic troughs to achieve a uniform irradiance distribution pattern, referring to Figure 4. Figure 4 (b) shows the comparison of simulation and experimental results of solar concentrating performance on the solar receiver surface.

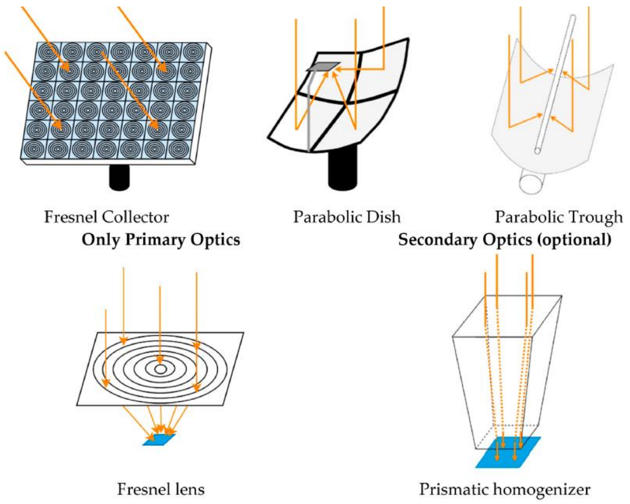

Figure 3.
Concepts of concentrator photovoltaic (CPV) systems, Iqbal et al. [22].

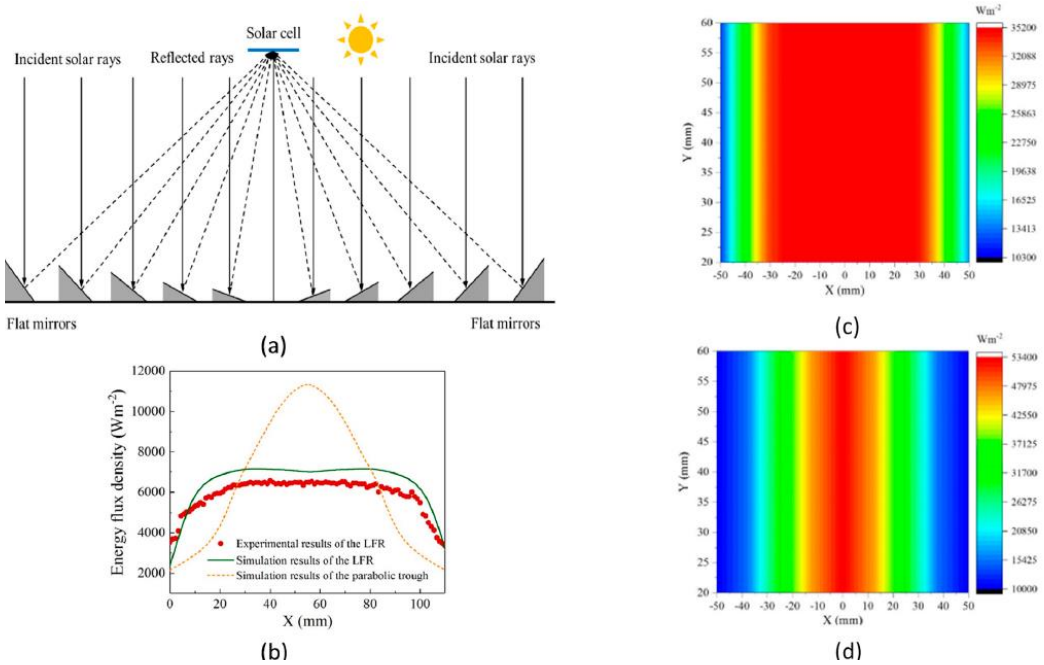

Figure 4.
Parabolic trough and Fresnel reflector comparison : (a) linear Fresnel reflector, (b) simulation results of the two systems together, (c) distribution of irradiance over the solar cell through the linear Fresnel reflector, and (d) distribution of nonuniform irradiance through the use of the parabolic trough concentrator Masood et al [1].

Figure 4 shows that the simulation and test results agree on energy flux distribution, showing improved solar uniformity over traditional troughs, enhancing CPV efficiency [1]. The simulation results of Figure 4 (c) show a reasonably high uniformity of solar concentration on solar cells of the CPV device. For a comparative analysis, a simulation model of a parabolic trough concentrator has been established, and its solar concentration process has also been simulated. The theoretical geometric concentration ratio of the parabolic trough concentrator is 31.31, which is consistent with the proposed LFR concentrator, as shown in the simulation results Figure 4 (d), [20].

2.2.1. The CPV Components

The three main CPV systems components are optical concentrators, high-efficiency solar cells, and tracking systems. In this section, these components are discussed.

2.2.2. Optical Concentrators

These concentrators typically use lenses or mirrors to gather and focus on sunlight. There are various types of concentrators [21, 22]. Large-scale concentrated solar power (CSP) plants are particularly effective in regions with high direct solar radiation and ample available land. To focus on these optimal locations, the efficiency and impact of solar energy generation can be maximized. The comparison of different concentrators based on application field, advantages, and disadvantages is shown in Table 1.

Table 1.
Comparison of different concentrators based on application field, advantages, and disadvantages [22] [23].

Criteria	**Fresnel Lenses**	**Parabolic Mirrors**	**Compound Parabolic Concentrators (CPCs)**
1. Application Field	- Solar thermal collectors - Optical and cooking systems	- CPV installation -Solar power plants	- Daylighting systems -Solar thermal collectors
2. Advantages	- Cost-effective - Easy for fabrication	- Accurate focusing - In large-scale CSP	- Ideal for diffuse radiation - No need for a tracking system
3. Disadvantages	- Less durable - Tracking requirements	- Bulky and heavy - Requires tracking	- Larger size - Lower concentration ratio

Source: El Himer, et al. [21] and Tien and Shin [22]

2.2.3. High-Efficiency Solar Cells

A high-efficiency solar cell is at the core of a CPV system. Unlike conventional solar cells made from silicon, CPV systems often utilize multi-junction (MJ) solar cells. These cells consist of multiple layers of different semiconductor materials, with each layer absorbing a specific part of the solar spectrum. The most common materials used in CPV systems are gallium arsenide G_aA_s and its compounds. MJ cells can achieve efficiencies exceeding 40%, compared to approximately 15-20% for conventional silicon solar cells [23, 24]. The G_aA_s solar cells offer various advantages over crystalline silicon solar cells, including high-efficiency potential, the ability to produce thin films, a favorable temperature coefficient, radiation resistance, and the potential for multi-junction applications [23].

2.2.4. Tracking Systems

Since sunlight is not constant throughout the day and varies based on location and time, CPV systems use tracking mechanisms to keep the optical concentrators aligned with the sun. The main objective of tracking systems is to improve energy yield, ranging between 22% and 56% in comparison with fixed solar systems [25]. These tracking systems can be Single-axis trackers and dual-axis trackers, as shown in Figure 5 [26]. Solar energy implementation can be promoted through subsidies, examination, and sun-tracking solar systems to increase efficiency [27]. The block diagram of a dual-axis tracking system is shown in Figure 6.

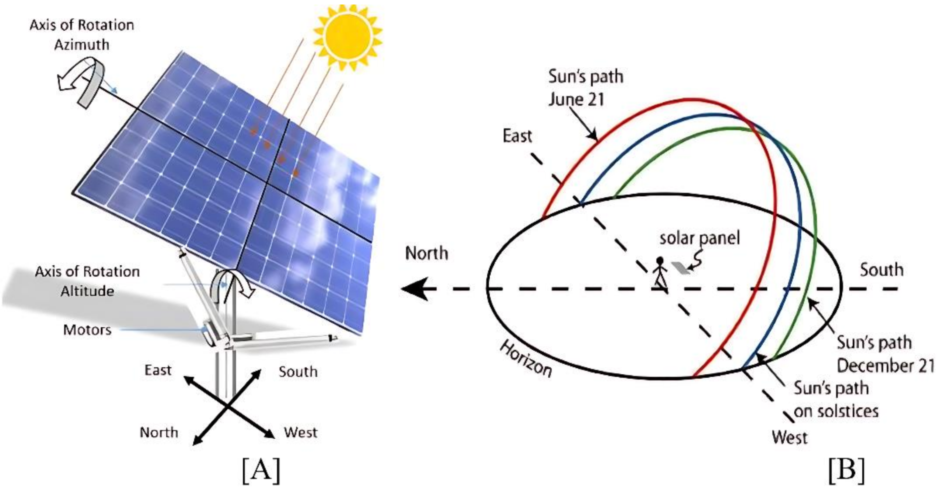

Figure 5.
(A) Dual-axis solar tracker, (B) Cyclical movement of the sun concerning the Earth, El Himer, et al. [7]

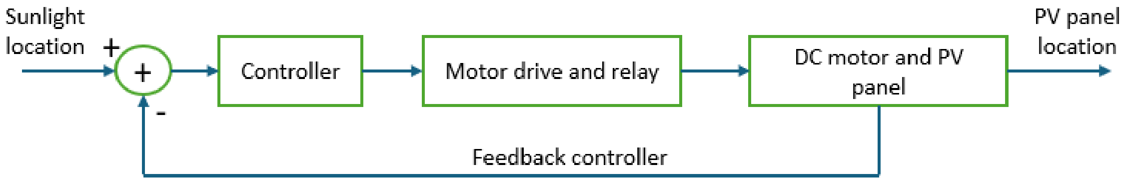

Figure 6.
Dual-axis for solar tracking system Seme, et al. [27].

Here, it is crucial to consider the sun's movement in the sky throughout the year. A dual-axis solar tracking system uses a block-based structure to maximize sunlight capture. First, the sunlight's location is detected using light sensors that track the sun's position in real-time. This data is sent to the controller, which processes the information and determines the required movement angles. The controller then activates the motor driver and **relay**, which supply appropriate power signals to the DC motors. These motors are mechanically connected to the PV panel, adjusting its location on both horizontal (azimuth) and vertical (elevation) axes to align with the sun. A feedback controller continuously monitors the panel's orientation and sensor data, ensuring accurate positioning by correcting deviations. This closed-loop system ensures optimal solar exposure throughout the day for maximum energy generation [27].

2.2.5. Traditional PV vs Concentrated PV Systems

The difference between traditional PV and concentrated PV (CPV) Systems is shown in Table 2. Traditional photovoltaic (PV) systems use flat-plate, silicon-based solar panels that convert both direct and diffuse sunlight into electricity without optical concentration. In contrast, CPV systems use optical components such as lenses or mirrors to focus direct sunlight onto high-efficiency MJ solar cells [28]. The CPV systems can attain efficiencies exceeding 40%, compared with 15-22% for traditional photovoltaic (PV) systems. While traditional PV typically uses monocrystalline or polycrystalline silicon, CPV utilizes III-V semiconductor materials, for example, Gallium Arsenide (GaAs), because of their superior performance under concentrated light. CPV systems rely on direct sunlight and require precise dual-axis tracking, unlike traditional PV systems, which can operate without tracking or may use simpler single-axis tracking systems [29]. CPV systems require advanced thermal management to effectively dissipate heat from concentrated light, while traditional PV systems manage lower thermal loads. Consequently, CPV systems provide higher efficiency but are more complex and costly.

Table 2.
Comparison of traditional PV with CPV systems.

Characteristic	Traditional PV Systems	CPV Systems
Technology	Uses flat solar cells	Uses optical concentrators
Efficiency	15-22% for silicon-based cells.	30-40% or higher with MJ cells.
Solar cell material	Monocrystalline, polycrystalline, or thin-film silicon.	High-efficiency MJ cells.
Energy conversion mechanism	Direct sunlight strikes the surface of the solar cells.	Concentrated sunlight is focused on small, high-efficiency cells.
Tracking systems	no tracking or single-axis tracking.	Requires single-axis or dual-axis tracking systems.
Thermal management	Low thermal load and minimal cooling required.	Thermal load requires cooling systems to prevent overheating.

Source: Vu, et al. [28].

2.2.6. Classification of CPV Systems Based on Concentration Ratios

Based on concentration ratios, CPV systems are classified into three main types: low, medium, and high-concentration photovoltaics (LCPV, MCPV, and HCPV), respectively [30] as shown in Table 4. The choice of an HCPV system relies on different factors, including geographic location, space availability, and economic considerations. Higher concentration systems offer greater efficiencies but come with increased complexity and costs [30]. However, these systems necessitate precise sun-tracking mechanisms and advanced thermal management strategies to mitigate heat dissipation issues [31]. Four classes of CPV systems are shown in Table 3.

Table 3.
Four classes of CPV systems and their requirements.

	Low concentration	Medium concentration	High concentration
Cooling	Not applicable	Passive cooling	Active cooling
Tracking	Not applicable	1-tracking axis	2- tracking axis
Concentration ratio	2 to 10	10 to100	100 to 400 (and beyond)
PV materials	Si	Si, C_d , T_e, etc.	MJ cells

Source: Xiao, et al. [31].

CPV systems are composed of four key components: concentrators, solar cells, tracking systems, and cooling mechanisms. The concentrators, typically Fresnel lenses or parabolic mirrors, focus sunlight onto a small area of highly efficient solar cells, usually made of multi-junction materials [30, 32].

2.2.7. CPV Operating Principles

The operating principle of CPV involves concentrating sunlight using optical devices, encompassing the following stages: concentration of sunlight, focusing light onto the solar cell, generation of electrical power, and tracking and cooling.

2.2.7.1. Sunlight concentration technology

The first step in CPV operation is the concentration of sunlight using parabolic mirrors or Fresnel lenses, gathering sunlight on a large scale and focusing it onto a small scale. For example, a Fresnel lens may concentrate sunlight 500 to 1000 times, meaning it collects sunlight from a surface 500 to 1000 times larger than the surface of the solar cell itself. Higher concentration ratios typically lead to better efficiency, but they also require more precise tracking and cooling systems to avoid damaging the solar cells due to excessive heat [33].

After the sunlight is concentrated by the optical concentrators, it is focused on a small, high-efficiency solar cell. These cells are typically MJ cells that are designed to absorb a wider range of the solar spectrum and are found in [34, 35]. The MJ cells are more efficient compared to single-junction cells because they can capture energy from different wavelengths of light, each of which is absorbed by a different layer in the cell [35, 36]. In a typical MJ solar cell, each layer is made from a material with a specific bandgap. The top layer is designed to absorb high-energy (blue) light, whereas the bottom layer absorbs lower-energy (red) light. By using multiple layers with various bandgaps, a cell can capture a larger part of the energy from the sun to increase its efficiency [35, 36]. The efficiency of an MJ solar cell structure varies depending on how each sub-cell absorbs part of the solar spectrum. MJ solar cells consist of multiple layers (junctions), individually designed to absorb specific ranges of wavelengths from the solar spectrum. They are typically stacked with materials of decreasing bandgap energy from top to bottom.

2.2.7.2. Generation of Electrical Power

Once the concentrated sunlight strikes the solar cell, it generates electricity. The photons from the sunlight excite the electrons in a semiconductor material, producing electron-hole pairs. These pairs are then split by the electric field within the solar cell, generating a flow of electricity. The efficiency of the cell is shown in El-Gahouchi, et al. [37] and Khanam and Foo [38] and determines how well it can convert the energy from incoming photons into electrical energy. Multi-junction cells have high efficiencies because each layer is optimized for different wavelengths of light, leading to better overall performance compared to traditional silicon-based cells [37, 38].

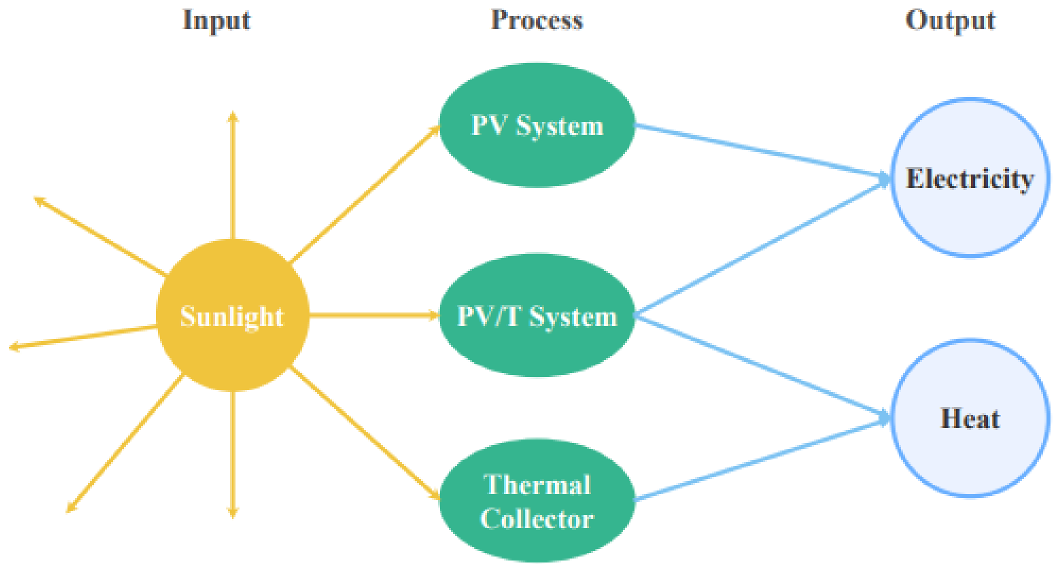

Figure 7.
Generated heat and electricity from PV, PV/T, compared to solar thermal systems, Hamid, et al. [39].

Referring to the network with sunlight, the PV system can be used to generate electricity, the thermal collector can be used to generate heat, while the PV/T (PV thermal) system can generate both electricity and heat. In this work, our solar PV system will be improved using CPV to produce more electricity with a small-scale solar PV system. The solar PV/T is a merged hybrid PV and thermal collector system, as shown in Figure 7.

Table 4.
Comparison of PV, CPV, and PVT systems.

	CPV system	**PV system**	**PVT system**
Efficiency	Optical concentrators enable 40% efficiency for multi-junction cells in high-DNI.	Silicon modules achieve 15-22% efficiency, performing well in diffuse sunlight.	PV-thermal systems exceed 70% efficiency in harvesting electricity and heat.
Cost	High initial costs, but competitive LCOE in high-DNI regions.	Most cost-effective solar technology; widespread adoption with significant cost reductions.	Costlier than standard PV; justified when >70% of electricity and heat needed.
Thermal management	Thermal management is crucial in CPV; cooling maintains performance under high heat.	Standard PV systems use passive cooling; high temperatures reduce approximately 15-22% in efficiency.	PVT systems actively extract heat, boosting efficiency beyond 70% overall.
Environmental impact	Concentrators require more materials, but higher efficiency reduces land footprint.	Low environmental impact, with concerns about material lifecycle and recycling.	PVT systems reduce carbon emissions by combining electricity and heat generation.

Source: Cancro, et al. [40].

2.2.8. Cooling of CPV

CPV systems rely on tracking systems to concentrate the sunlight received by the system, thereby maximizing overall energy generation. However, as sunlight is concentrated on the solar cells, they generate significant amounts of heat. High temperatures can decrease the solar cells' efficiency and even destroy them over time. To address this, CPV systems often include cooling systems to maintain the solar cells' optimal operating temperatures. These cooling systems can be passive, using heat sinks or radiators, or active, using liquid cooling systems. Effective cooling is crucial to maintain the efficiency and longevity of CPV systems [41].

2.2.8.1. Cooling techniques for CPV systems

Effective cooling methods are essential to mitigate thermal effects and sustain high efficiency. CPV cooling techniques are categorized into passive and active cooling schemes. The flow chart illustrating various PV system cooling methods is presented in Figure 8.

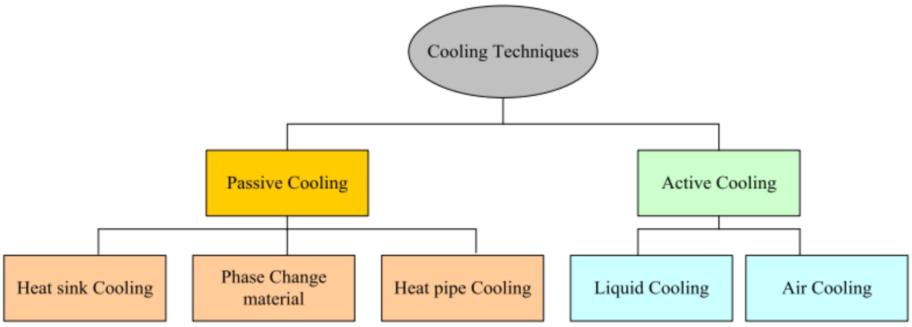

Figure 8.
Flowchart of different cooling techniques, Alaas [42].

2.2.8.1.1. Passive Cooling Techniques

Passive cooling methods leverage natural heat dissipation mechanisms such as convection, radiation, and conduction, making them both cost-effective and energy-efficient. However, these methods may not always be sufficient for high-concentration CPV (Concentrated Photovoltaic) systems [31].

1. Heat sinks: Heat sinks, often made of aluminium or copper, improve cooling by increasing surface area, aiding CPV systems with concentration ratios of up to 10,000 suns for temperature control [31, 43].

2. Phase change materials (PCMs): PCMs absorb and collect surplus thermal energy through phase transitions, stabilizing temperature fluctuations in CPV systems [44, 45].

3. Heat pipe cooling (HPC) is a promising technology for cooling solar panels. Traditional columnar heat pipes and flat solar panels have a high thermal contact resistance [46], which results in inefficient heat transfer. Figure 9 shows the cell temperature differential.

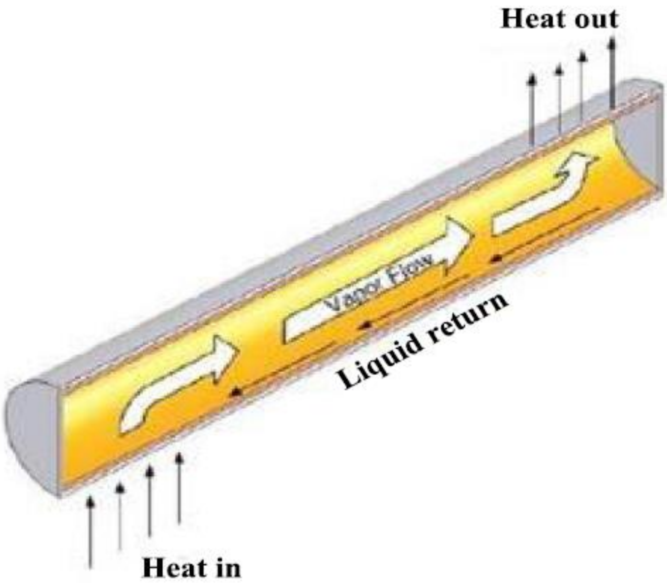

Figure 9.
Mechanism of the heat pipe, Alaas [42].

Heat pipe cooling is an effective passive thermal management technique for CPV systems, addressing the high thermal loads caused by sunlight concentration. It improves system reliability, efficiency, and lifespan without adding energy consumption or mechanical complexity [47].

2.2.8.1.2. Active Cooling Techniques

Active cooling methods utilize mechanical components to dissipate excess heat, resulting in higher efficiency at the expense of increased power consumption [48]: (i) Forced air cooling: Fans or blowers are employed to enhance convective heat transfer, effectively reducing CPV module temperatures. (ii) Liquid cooling: Water or dielectric fluids circulate through channels integrated within the CPV modules to absorb and efficiently dissipate heat. Figure 10 shows the PV module linked with the cooling system.

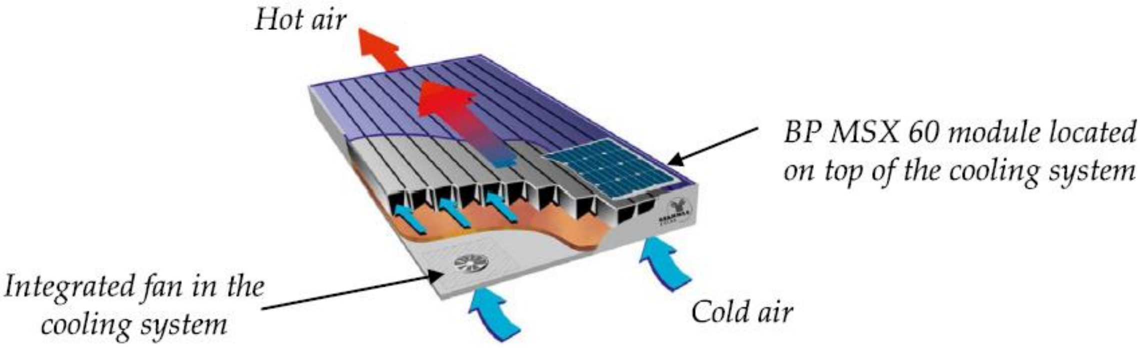

Figure 10.
PV module linked with the cooling system, Bel Hadj Brahim Kechiche and Hamza [49].

To improve the electrical efficiency of a solar PV module, a numerical solution that maintains the operating temperature close to the ambient temperature must be developed. This is directly linked to the properties of the PV cells and warrants further investigation. Additionally, integrating a cooling system with a heat exchanger beneath the solar PV module will yield significant benefits. It was found that the cooling system would reach and maintain an operating temperature of C during a rise in the concentration ratio [49].

2.3. Thermal Management of CPV Systems

Thermal effects present significant challenges to CPV performance, requiring innovative cooling techniques and system optimization strategies to maintain efficiency. Passive and active cooling methods provide viable solutions, while advanced materials, optical design improvements, and hybrid energy integration offer promising avenues for future research. As CPV technology continues to advance, effective thermal management will be essential in realizing its full potential for sustainable and high-efficiency solar energy generation. Balancing heat management with efficiency optimization requires a multi-faceted approach integrating material selection, system design, and cooling techniques.

2.3.1. Advanced Materials and Coatings

It was found that coatings with high thermal conductivity can help minimize heat-induced degradation, promoting the longevity and consistency of solar panels. There are two types of them: high-temperature tolerant solar cells [50] and anti-reflective and thermally conductive coatings [51, 52].

2.3.2. Optical Design Considerations

In the optical design of CPV systems, several considerations are crucial for enhancing performance. The following design strategies contribute to the advancement of CPV technology by improving efficiency and thermal management: reduction in the concentration of CPV [53] and spectrum splitting optics [54, 55].

2.3.2.1. Advantages Of CPV Systems

The CPV systems offer several advantages over traditional flat-plate PV systems, notably their higher efficiency. Recent advancements have resulted in MJ solar cells used in CPV systems achieving efficiencies exceeding 40% in laboratory settings [56]. The enhanced efficiency of CPV systems translates to greater output power per unit area, enabling them to be suitable for installations in areas with limited space. This efficiency becomes high compared to traditional silicon-based PV cells, ranging from 15% to 22%. Additionally, CPV systems have the advantage of minimizing system costs due to the use of tracking systems, concentrators, and cooling. Furthermore, CPV systems reduce the amount of material required for the same power output compared to traditional PV systems. CPV systems are also well-suited for areas with higher direct normal irradiance (DNI) [57, 58].

2.3.2.2. Challenges Facing CPV Systems

Despite their advantages, CPV systems present several challenges that hinder widespread adoption. These include the requirement for high direct normal irradiance (DNI), which limits effective deployment to regions with abundant direct sunlight. In areas with frequent cloud cover or low DNI, CPV performance can be significantly reduced, making them less attractive compared to traditional PV systems. The complexity of CPV systems introduces additional challenges, such as the need for precise optical alignment, dual-axis tracking, and effective cooling solutions [59]. Moreover, the cooling requirements of CPV systems present challenges in design and material selection, as the cooling system must be both efficient and cost-effective to maintain overall economic viability [31]. To address these challenges, advancements in CPV systems are essential. Manufacturing advancements in MJ solar cells have enabled the addition of more layers to enhance efficiency; 4-junction and 6-junction solar cells have achieved optical efficiencies of 46% to 50%.

3. Results and Discussions

3.1. Performance of CPV Systems

The performance of the CPV system can be influenced by several factors, including the concentrator's optical efficiency, the solar cells' efficiency, the cooling system's effectiveness, and the tracking system's accuracy. These factors are interdependent, and optimizing each component is essential for achieving high overall system performance. CPV system performance depends on optical efficiency, temperature, and sun-tracking accuracy but is limited by reliance on direct sunlight, spectral changes, misalignment, and long-term material degradation [60]. Effective thermal management is vital for CPV systems to prevent overheating and efficiency loss [61]. CPV systems require economic and lifecycle evaluations; despite high efficiency, cost-effectiveness, and hybrid integration such as CPV/T, they are key for large-scale adoption and energy maximization [62].

3.1.1. Concentrator PV Design

Concentrator Photovoltaics (CPV) is an advanced solar power technology that enhances the efficiency of photovoltaic (PV) cells by concentrating sunlight onto a smaller, high-efficiency PV surface. This paper explores the design principles, modeling, and calculations of five types of CPV systems, including parabolic troughs, Fresnel lenses, compound parabolic concentrator (CPC) PV, dish concentrator CPV, and holographic CPV. Through analytical and numerical methods, we examine the optical concentration ratios, geometric design parameters, and energy conversion efficiencies [63]. These types are found in Figure 3. Fresnel lenses offer lightweight, low-cost concentration, enhancing PV performance. Dish concentrators achieve very high concentration ratios and tracking accuracy, making them ideal for CPV systems. Compound parabolic concentrators (CPCs) are non-imaging optics that accept wide angles of sunlight, thereby reducing tracking needs. Holographic CPV employs wavelength-selective concentration, enabling multi-junction cell efficiency with minimal material use, which promotes sustainability [64].

3.2. The Comparison of CPV System Designs Based on Optical Components

The CPV systems utilize optical components to focus sunlight on high-efficiency solar cells, enhancing energy capture. The performance of these systems varies significantly under different solar irradiance conditions, particularly direct normal irradiance (DNI). This discussion compares five CPV optical designs: (i) Fresnel lens CPV, (ii) Parabolic dish CPV, (iii) Parabolic trough CPV, (iv) Compound parabolic, and (v) Holographic CPV (HCPV), focusing on their efficiencies under high and low DNI scenarios as shown in Figure 11. The performance of CPV systems is heavily influenced by their optical design and the DNI levels at which they operate [64]. Parabolic dish CPV systems are highly efficient in high DNI conditions, achieving efficiency rates of up to 40%. However, their efficiency drops below 5% in low DNI conditions. Similarly, Fresnel lens CPV systems perform well in high DNI situations but face comparable limitations when DNI is low.

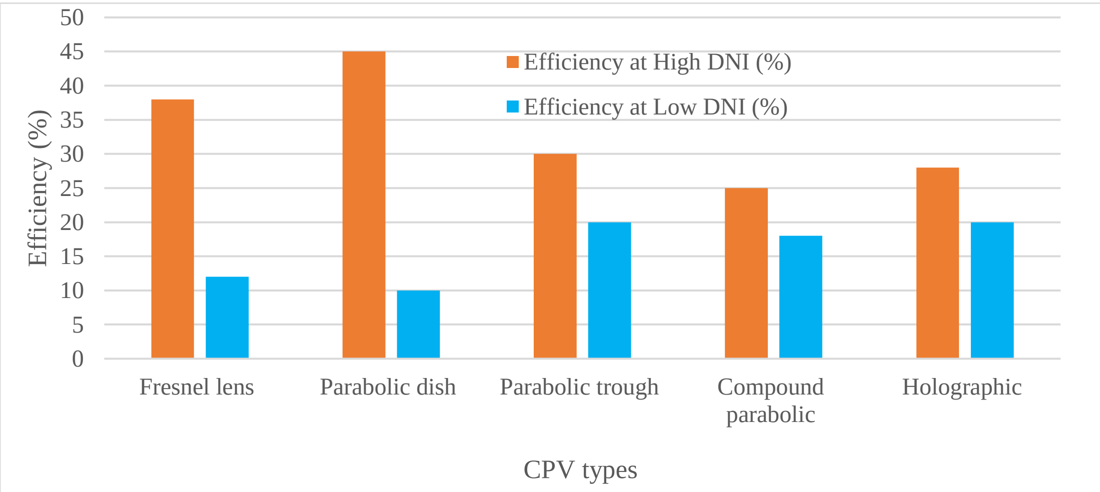

Figure 11.
The comparison of CPV system designs based on optical components, Zhang, et al. [65].

Comparing efficiency at high DNI and efficiency at low DNI for Fresnel lens CPV systems, parabolic trough CPV systems effectively balance performance in both high and low DNI conditions. In contrast, CPC systems and holographic CPV systems are more suitable for areas with fluctuating or lower DNI levels, as they excel at capturing diffuse sunlight. Each type of system has its advantages, depending on the specific application and environmental conditions [66].

3.2.1. Thermal Effects on the Performance of Concentrator Photovoltaics (CPV)

The CPV system introduces significant thermal challenges. Excessive heating leads to performance degradation, thermal stress, and material fatigue in CPV cells. Effective thermal management is, therefore, critical to maintaining high efficiency and longevity. Recent studies have highlighted that CPV cells' efficient cooling is essential to inhibit thermal degradation and guarantee optimal performance [13]. These effects include *Temperature-dependent efficiency loss* [67, 68], *impact on electrical performance* [42], *thermal stress and material degradation* [69].

These effects highlight the need for efficient heat dissipation techniques in CPV systems. Different cooling techniques have been investigated to alleviate overheating in CPV systems, including integrating thermoelectric generators to convert excess heat into electrical power [70]. More research into modern cooling techniques and system integrations continues to enhance the efficiency and viability of CPV systems.

3.3. Factors Affecting the Performance of CPV Panels

CPV technologies rely heavily on DNI, necessitating precise solar tracking mechanisms. Environmental variables, particularly solar irradiance and temperature, significantly impact CPV system output. This section explores the key environmental and operational parameters that affect CPV performance and compares the efficiency of various CPV configurations under different irradiance and thermal conditions [71-73].

3.3.1. Solar irradiance

The performance of CPV systems is closely tied to the intensity of solar irradiance they receive. CPV systems are particularly efficient under high levels of DNI, as they depend on the focused concentration of direct sunlight onto photovoltaic cells [74]. The CPV system's performance is highly affected by solar irradiance, where during higher irradiance levels, more electrical power is generated. However, the system faces thermal management challenges when irradiance exceeds optimal levels. The excessive heat generated can lead to elevated temperatures in the photovoltaic cell, which adversely affect its efficiency and overall performance. This phenomenon results in thermal degradation of the system, reducing its long-term power output [75].

3.3.2. Temperature

Temperature plays an important role in the performance of CPV systems. As the temperature increases, the efficiency of the solar cells decreases due to the negative temperature coefficient of the semiconductor materials used. In other words, the voltage output decreases as the temperature rises [76]. Key temperature-related impacts on CPV systems include thermal management, decreases in cell efficiency, and cooling solutions [76]. The comparison of the CPV systems' efficiencies is illustrated in Table 5 based on the tracking type, description, and efficiency improvement over fixed systems.

Table 5.
CPV systems' efficiency comparison.

Tracking Type	**Description**	**Efficiency improvement** over fixed systems **(%)**
Fixed Tilt	No tracking: panels are stationary.	Baseline
Single-Axis	Follows the daily movement of the sun (east-west).	20% - 35
Dual-Axis	Adjusts for both daily and seasonal sun movement.	35% - 50

The efficiency improvement over fixed systems refers to the enhanced power generation compared to traditional flat-panel solar systems [77, 78]. Concentrated Photovoltaic (CPV) systems are categorized based on their concentration ratios, which significantly influence their efficiency and thermal performance [31]. CPV systems with advanced thermal management and tracking achieve high efficiency. However, temperature rise control becomes a primary challenge, limiting long-term reliability and overall performance in CPV technology.

3.4. Role of CPV In Microgrid and Grid-Connected Systems

Despite the benefits of the CPV system, CPV technology encounters various challenges, particularly regarding its economic viability, cost-effectiveness, and the necessity for substantial subsidies and incentives to remain competitive with other energy sources [79]. In this paper, the roles of CPV in microgrid and grid-connected systems are classified according to cost-benefit analysis, economic feasibility, and incentives. CPV systems play a crucial role in off-grid or remote microgrid installations, especially in areas with high solar insolation.

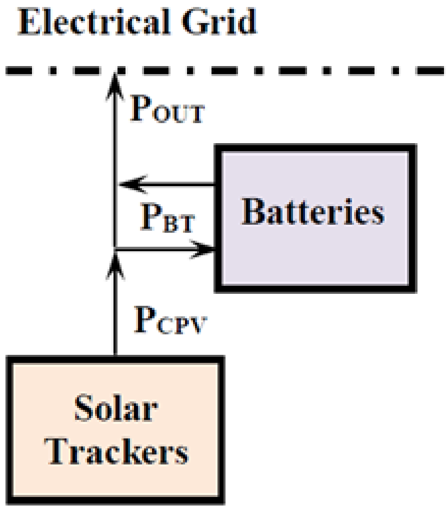

Figure 12.
Simplified structure of the CPV integrated solar PV power plant (modified) Cau, et al. [80].

The simplified structure of the CPV integrated solar PV power plant with battery storage system is shown in Figure 12. Thus, the roles of CPV in microgrid and grid-connected systems are: high efficiency in space-constrained environments, energy storage integration, peak shaving and grid stability, and integration with smart grids [79-81].

3.4.1. Cost-Benefit and Economic Feasibility of CPV Systems

Deploying CPV systems generally incurs higher costs compared to traditional flat-plate PV systems, primarily due to the requirement for advanced optical components, cooling mechanisms, and tracking systems. As technology advances and production scales up, the currently high costs are predicted to decline over time, making the technology more affordable and accessible globally [82-85]. CPV systems are economically viable in high-DNI regions, offering benefits over PV systems. Advancements and cost competitiveness enhance their appeal as long-term investments [86]. CPV systems are highly adaptable for remote, off-grid areas lacking infrastructure. They reduce power generation and transmission costs, promoting economic development and sustainability. As technology advances, CPV systems become more cost-effective, offering competitive, reliable energy solutions [87-89].

3.4.2. Incentives and Subsidies for CPV Systems

In this paper, the following incentives and subsidies for CPV systems are discussed. To foster the widespread adoption of CPV systems, financial incentives are offered by various governments across the globe. These include tax credits, rebates, and grants, which significantly reduce the initial installation costs. Some of the prominent incentives are discussed here:

1. Investment tax credit (ITC): This financial incentive improves the economic feasibility of CPV installations, increasing their appeal to investors and businesses [90, 91].
2. Subsidies and grants: CPV systems in remote areas often receive government subsidies, aiding installation costs and promoting clean energy adoption in underserved or developing regions through microgrid solutions [92].
3. Subsidies for research and development: Governments and private entities fund CPV R&D to improve efficiency, increase innovation, encourage global adoption, and reduce costs [93, 94].

3.4.3. Comparison between CPV and traditional PV systems

CPV systems contribute substantially to shaping the future of global energy solutions, especially in microgrid and grid-connected systems. Despite their higher initial costs, CPV systems offer significant potential for efficiency gains, particularly in high DNI regions, and can contribute to both energy independence and grid stability.

Table 6 shows the comparison between traditional PV and CPV systems. The economic feasibility of CPV improves as technology matures and with supportive government incentives and subsidies. As a result, CPV systems are poised to become a key player in the renewable energy market, particularly in regions where space is limited and solar resources are abundant [95-97].

Table 6.
Comparison between CPV and traditional PV systems.

System Type	Capital cost (USD/kW)	Efficiency (%)	Incentives
CPV (high concentration)	Higher (2.5-3.0)	35 - 45	Tax Credits, Feed in Tariffs, R&D grants
Traditional PV (flat plate)	Lower (1.0-1.5)	15- 20	Tax Credits, Subsidies, FiTs

Source: Sarwar, et al. [61]

3.4.4. Challenges for the Extensive Adoption of CPV

CPV offers the promise of significantly higher efficiency, exceeding 40% in some multi-junction cell configurations [98, 99]. However, despite its theoretical advantages, CPV has seen limited commercial deployment compared to conventional PV technologies. The primary barriers to widespread adoption fall into two broad categories: technical challenges and cost-related constraints.

3.4.5. The technical challenges

The technical challenges are: dependence on direct normal irradiance (DNI), complex tracking systems, thermal management, optical and alignment sensitivities, and limited standardization as discussed in

Table 7 [100, 101].

Table 7.
Technical challenges of CPV based on design, operational and installation.

Challenge	Design	Operational	Installation
1. Dependence on DNI	CPV systems require DNI > 6 kWh/m²/day.	Output drops drastically in cloudy or hazy conditions	-Requires high-DNI locations. - Increases logistics costs
2. Complex Tracking Systems	Dual-axis tracking systems increase capital cost	Mechanical failures	Trackers of high precision.
3. Thermal Management	High-concentration ratio.	Poor thermal dissipation can degrade cell efficiency.	Incorporating heat sinks or fluid cooling increases material cost
4. Optical and Alignment Sensitivities	Optical concentrators must be precisely designed.	Misalignment leads to up to 60% loss in light concentration.	High-precision alignment tools are needed during assembly.
5. Limited Standardization	Few industry-wide design norms	Difficult to source replacement parts.	Increased training for specialized installation teams.

Source: Elgeziry and Hatem [100] and Emam and Ahmed [101].

3.4.6. The Cost Challenges

The cost challenges identified include high capital expenditure (CapEx), operational and maintenance costs (OpEx), lack of economies of scale, and investment risk and financing, which are discussed below:

- High Capital Expenditure (CapEx): CPV faces limited adoption due to high capital costs, complex components, and expensive infrastructure, unlike cheaper, simpler flat-plate PV systems that enable faster, more economical, and modular solar energy deployment [102].
- Operational and maintenance costs (OpEx): CPV systems require intensive maintenance due to moving parts, frequent cleaning of optics, and thermal management needs, leading to higher operational costs compared to traditional PV, especially in dusty environments [103].
- Lack of economies of scale: Flat-plate PV benefits from mass production and low costs, while CPV remains niche, with high costs, limited manufacturers, and slow innovation, making it less competitive without large-scale deployment [103].

Investment risk and financing: CPV technology offers strong investment potential despite limited data and complexity. Although traditional PV systems are more established, CPV's advantages and high rewards make it appealing, especially when managed by experienced teams navigating development and reliability challenges [102].

4. Conclusion and Future Research Direction

4.1. Conclusion

Considering escalating global energy demands and the pressing need for sustainable energy solutions, this study explores the potential of CPV systems as a high-efficiency alternative to traditional PV technologies. Utilizing advanced optical elements, including parabolic mirrors, Fresnel lenses, and dielectric concentrators, CPV systems concentrate sunlight onto MJ solar cells, achieving superior energy conversion. Enhanced performance is further supported by precise solar tracking and improved thermal management. The review highlighted the key advantages, including reduced material use, higher efficiency, and lower lifecycle costs. Technological advancements have led to efficiency gains of 10 to 15% and cost reductions of up to 20%, increasing CPV's competitiveness in the renewable energy sector. However, dependence on DNI limits deployment to high-irradiance regions. Despite this, nonstop improvements in system design and integration are expanding CPV's viability. With focused research and innovation, CPV systems hold strong promises for driving future clean energy transitions.

4.2. Future Directions of the Research

Over the past decade, advances in silicon PV technologies include: 1. PERC (or passivated emitter and rear cell) technology is a modification to conventional solar cell design that improves energy conversion efficiency by reducing recombination losses and enhancing light reflection. 2. Bifacial solar cells are photovoltaic (PV) cells that can generate electricity when illuminated from both their front and back sides. 3. Tandem cells are intended to increase efficiency by absorbing a broader solar spectrum. These types of solar cells have boosted efficiencies above 25% while lowering costs, reducing the appeal of CPV. Flat-plate PV systems are more versatile, easier to install, and better suited for diverse applications, making them the preferred option for developers. Although CPV offers high theoretical efficiency, especially in sunny regions, it faces challenges such as dependence on direct sunlight, complex tracking systems, and high costs. For CPV to compete, innovations in optics, tracking, and hybrid integration are needed to overcome current limitations and achieve broader market adoption [104]. The future directions of this research are based on design and simulation, tracking systems, integration systems, cooling systems, and efficiency improvements.

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