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Emerging Trends in Solar PV Performance Enhancement: Cooling, Concentration, Spectral Splitting, and Tracking Techniques

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Abstract: The worldwide need for clean sustainable energy has boosted research on solar photovoltaic (PV) systems to enhance their productivity, dependability, and flexibility. Despite major breakthroughs in materials and manufacturing, PV modules suffer significant performance drops under real-world conditions due to higher cell temperatures uneven sunlight, and off-center sun angles. This article gives updates on new trends and technologies that aim to boost PV performance focusing on four key areas: cooling methods concentrated photovoltaic (CPV) systems solar trackers, and their benefits and drawbacks. The first part of the article looks at the development of both passive and active cooling techniques. These include air and liquid cooling methods, phase change materials (PCM), and hybrid PV/T cooling systems. These approaches help reduce temperature-related degradation and increase energy output. The second part explores CPV technologies that use optical concentration such as Fresnel lenses parabolic reflectors, and cold mirrors. These technologies can deliver more sunlight through a smaller PV surface area and/or with less heat on the PV module. The third section looks into how tracking technologies have evolved from single-axis to more complex dual-axis systems, and their impact on boosting solar exposure while cutting down on shade-related losses. The article explores the main possibilities and hurdles linked to bringing in these technologies focusing on what's technically and doable as well as eco-friendly answers. To wrap up, the paper shows that innovations in solar cooling, concentration, and tracking made possible by cutting-edge control algorithms and modular designs offer a promising way to push forward PV systems that can handle climate changes and deliver top-notch performance.

Keywords: Solar Radiation; Ambient Temperature; Atmospheric Conditions; Extreme Weather Events; PV System Performance.

1. Introduction

Recent data on global energy shows that worldwide energy demand increased by 2.2% in 2024 surpassing the typical growth rates of the last ten years [1-5]. The increase spread across all key fuels and energy technologies, with the power sector leading the charge. Worldwide electricity use grew 4.3% far outstripping global GDP growth of 3.2% [6-9]. This stems from harsh weather events, a quickening shift to electrify end-use sectors, and the swift digitization of industrial and home systems [10-14]. Looking at new supply, growth in renewables made up the biggest part of total growth, at 38% followed by natural gas (28%), coal (15%), oil (11%), and nuclear (8%) [15-17].

The advancement of photovoltaic (PV) technology has shifted research focus from material optimization at the cell level to system-level performance enhancement through thermal and optical and mechanical system integration [18-23]. The combination of nanofluids for heat transfer and phase change materials and hybrid PV/T systems shows promising results for extending efficiency degradation times caused by high temperatures [24-27]. The development of concentrated photovoltaic (CPV) systems with low-cost Fresnel lenses and compound parabolic concentrators (CPCs) and multi-junction cells has led to improved conversion efficiency under high direct-normal-irradiance (DNI) conditions [28-29]. Advances in spectral splitting and filtering technology to manage heat loads have also fundamentally changed the way thermal loads are perceived, from post-absorption thermal management to pre-absorption temperature control, ultimately allowing more efficient use of wavelengths and permitting less thermal loading of PV cells [30-34].

The literature contains a several number of studies on solar PV performance Enhancement, and there are several key contributions. For example, it was reported [35] that the use of back-side cooling can reduce PV system cell temperature by 57.8% and increase electrical efficiency and thermal efficiency by 82.6% and 97.75%, respectively. One study investigated [36] both electrical efficiency and thermal management of PV panels while also reducing the side effects of dust deposition. A paraffin-based spectral filter (RT25) placed above the glass surface of the panel serves as a thermal management layer. In [37], the authors developed a new spectral-splitting CPV/T prototype that was integrated with a truncated compound parabolic concentrator (CPC) and validated it experimentally. A radiative transfer model was proposed to couple the concentrator geometry to the spectral filter characteristics, which predict optical performance accurately. The authors proposed a fluid-based spectral splitting method to enhance PVT collector performance through better solar energy management. The authors of [38] verified that the spectral filter's optical lower-bound determines how solar energy distributes between electrical and thermal domains while showing that the best optical filter depends on the system's thermal energy ratio.

The research contributes to PV system optimization through its comprehensive analysis of new technologies which enhance operational efficiency and dependability and versatility in actual deployment settings. The research investigates three core areas of cooling and concentration and solar tracking systems which serve as fundamental elements to boost PV system performance. The paper organizes cooling methods into two categories of passive and active systems which include air cooling and liquid cooling and phase change material cooling and hybrid PV/T systems that show effectiveness in reducing temperature effects and boosting power output. The research investigates CPV technologies which use Fresnel lenses and parabolic reflectors and cold mirrors to boost solar power while keeping thermal effects under control. The research investigates the evolution of tracking systems from single-axis to dual-axis systems which demonstrate their ability to minimize shading and solar incidence.

2. Cooling Techniques

Although incident solar radiation is converted into electrical energy by photovoltaic (PV) panels, excessive heat accumulation is still a major problem that negatively impacts conversion efficiency and system longevity [39-41]. According to empirical data, the rate of performance degradation roughly doubles for every 10 °C increase in the module's operating temperature. An integrated design concept called the photovoltaic/thermal (PV/T) system was created to address this thermal constraint. In this system, a heat sink that serves as a heat exchanger is thermally coupled to the PV module [42-44].

Additionally, through the utilization of a variety of cooling media, this configuration allows for the simultaneous generation of electricity and the recovery of thermal energy [45-47]. To further demonstrate, the impact of these media and the structural differences of the thermal collector can be thoroughly investigated in the following section dependent on the cooling technique used [48-50]. As identified in Figure 1, these cooling techniques can be broadly divided into two groups.

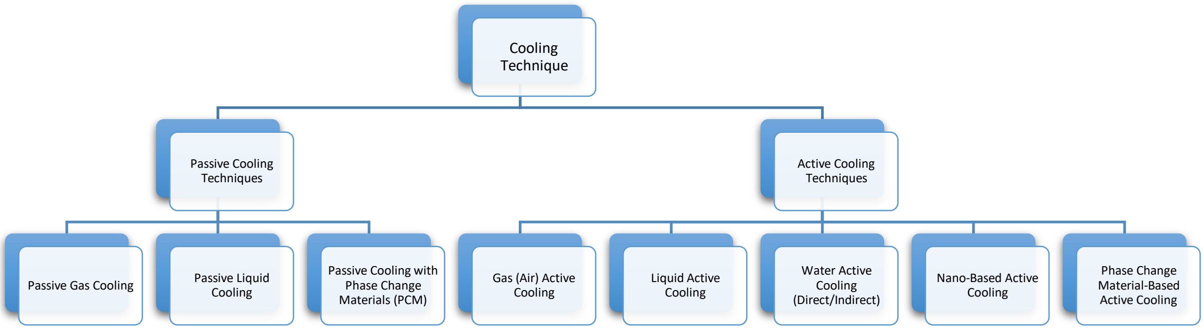

Figure 1. Cooling techniques

Table 1 provides a compared evaluation of the main cooling techniques employed with PV panels and outlines the benefits, drawbacks, and practical uses of each technique. The evaluation indicates that passive cooling techniques like phase change materials (PCM), liquid conduction, and natural air convection are structurally simple and financially viable means of effectively controlling module temperature without the need for external energy. The above techniques are effective most effectively in locations with moderate solar intensity and in installations that are small to medium in size.

Table 1. Summary of cooling techniques for photovoltaic (PV) panels [51-60].

Category	Cooling Technique	Working Principle	Key Advantages	Limitations / Challenges	Typical Applications
Passive Cooling Techniques	Passive Gas Cooling	Utilizes natural air convection around or beneath the PV module to dissipate heat without external energy input.	Simple, low-cost, maintenance-free, suitable for remote areas.	Limited cooling capacity in low-wind conditions; effectiveness decreases in dense arrays.	Rooftop PV, small-scale systems, desert and rural installations.
	Passive Liquid Cooling	Employs a closed-loop or static liquid layer beneath the PV panel; heat dissipates through natural convection in the liquid.	Higher heat transfer rate than air; improves electrical efficiency modestly.	Risk of leakage or corrosion; requires careful material selection.	Building-integrated PV/T systems (BIPVT) with minimal flow requirements.
	Passive Cooling with Phase Change Materials (PCM)	Integrates PCM behind the PV cell to absorb excess heat through latent heat during melting; solidifies at night.	Stabilizes module temperature; extends lifespan; no power input needed.	Limited by PCM thermal conductivity; cyclic degradation over time.	Urban rooftops, façades, hybrid PV/T systems with day–night temperature swings.
Active Cooling Techniques	Gas (Air) Active Cooling	Uses forced airflow via fans or blowers beneath or across the PV surface to enhance convective heat removal.	Cost-effective; easy to retrofit; moderate temperature reduction (8–15 °C).	Parasitic power consumption; dust accumulation; noise.	Utility-scale PV plants in arid climates with high ambient temperatures.
	Liquid Active Cooling	Circulates water or coolant through a heat exchanger attached to the PV	High heat removal efficiency; supports	Requires pumps and maintenance; potential leakage and fouling.	PV/T water-heating systems, industrial or

	rear surface, transferring heat by forced convection.	cogeneration (PV/T).		residential co-generation.
Water Active Cooling (Direct/Indirect)	Sprays or flows water over PV surfaces or through back channels for evaporative or conductive cooling.	Achieves large ΔT reduction (up to 25 °C); simple and effective in high-solar regions.	Water consumption, scaling, and electrical safety issues.	High-DNI zones, experimental solar farms, coastal or desert sites.
Nano-Based Active Cooling	Employs nanofluids (e.g., Al_2O_3, CuO, TiO_2 in base fluids) to enhance thermal conductivity and convective heat transfer.	Superior heat transfer performance; enhances PV/T efficiency up to 10–20%.	Nanoparticle agglomeration, cost, and potential erosion or toxicity.	Research-oriented PV/T systems, advanced solar cooling prototypes.
Phase Change Material-Based Active Cooling	Combines PCM with active circulation (e.g., forced fluid or air movement) to enhance PCM solidification and continuous heat extraction.	Hybrid advantage: passive latent storage with controlled active removal; maintains uniform cell temperature.	System complexity; additional energy demand for circulation.	Hybrid PV/T modules requiring stable operation under fluctuating irradiance.

The table 1 provides a structured synthesis of photovoltaic (PV) cooling strategies, categorizing them into passive and active techniques while highlighting their operational principles, advantages, limitations, and application domains. A critical examination reveals clear trade-offs between system simplicity, thermal performance, cost, and operational complexity. From a thermodynamic and system design perspective, passive cooling techniques offer notable advantages in terms of reliability and sustainability. Methods such as passive gas cooling and passive liquid cooling rely on natural convection mechanisms, eliminating the need for external energy input. This makes them particularly suitable for remote or off-grid installations where energy efficiency and low maintenance are priorities. However, their cooling capacity is inherently limited, especially under high irradiance or densely packed PV arrays, where natural convection alone cannot adequately dissipate accumulated heat. The integration of phase change materials (PCM) represents a more advanced passive approach, as it leverages latent heat storage to stabilize module temperature. While PCM improves thermal regulation and extends module lifespan, its effectiveness is constrained by low thermal conductivity and long-term material degradation, which may reduce performance over repeated thermal cycles.

In contrast, active cooling techniques demonstrate significantly higher thermal management capability, driven by forced convection or fluid circulation. Air-based active cooling systems are economically attractive and relatively easy to retrofit into existing PV installations. Liquid-based active cooling methods, including direct and indirect water cooling, provide superior heat removal efficiency due to the higher thermal capacity of liquids. These systems are particularly advantageous in hybrid photovoltaic/thermal (PV/T) applications, where recovered heat can be utilized for secondary energy purposes. However, they introduce engineering challenges, including system complexity, risk of leakage, scaling, and increased maintenance requirements. Water consumption and electrical safety concerns further restrict their deployment in water-scarce or high-risk environments.

Emerging technologies such as nano-fluid cooling and PCM-assisted active systems aim to bridge the gap between performance and efficiency. Nano-fluids enhance thermal conductivity and convective heat transfer, leading to measurable improvements in PV efficiency. Yet, issues related to nanoparticle stability, cost, and potential environmental or health risks remain unresolved. Similarly, hybrid PCM-active systems offer enhanced thermal regulation by combining latent heat storage with continuous heat extraction, but at the expense of increased system complexity and energy demand.

Overall, the table underscores that no single cooling technique is universally optimal. The selection of an appropriate method depends on application-specific constraints, including climatic conditions, system scale, economic considerations, and maintenance capabilities. Passive techniques are preferable for low-cost, low-maintenance scenarios, whereas active and hybrid systems are more suitable for high-performance applications where efficiency gains justify additional complexity.

3. Concentrated photovoltaic (CPV) technologies

CPV technologies have emerged as a promising means of increasing the electrical efficiency of PV systems by increasing the intensity of incident solar radiation on the cell surface. The primary goal of a concentrated photovoltaic system (CPVS) is to reduce the total cost of materials and system footprint by increasing power output with fewer PV cells [61,62]. According to their optical concentration ratio, CPV configurations are typically divided into low-concentration (LCPV), medium-concentration (MCPV), and high-concentration (HCPV) systems, as illustrated in Figure 2. These components encompass different optical geometries and cooling requires. Technical summary of CPV is illustrated in Table 2.

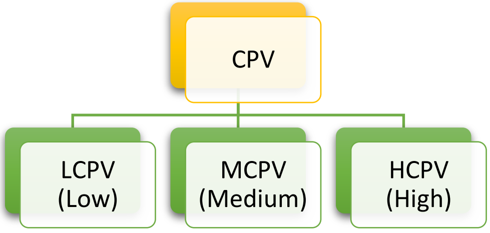

Figure 2. Classification of CPV8

Table 2. Technical Summary Of Concentrated CPV Technologies [63-66].

Class	Typical Concentration Ratio (C, ×)	Primary Optics	Receiver / Cell Type	Cell Eff. Range (%)	Tracking Requirement	Thermal Heat Flux on Cell (W/cm^2)
LCPV (Low)	2 – 10	CPCs, shallow Fresnel lenses, simple reflectors	c-Si (mono), Si heterojunction; sometimes a-Si tandem	20 – 26	Single-axis (preferred) or fixed with seasonal tilt	1 – 10
MCPV (Medium)	10 – 100	Fresnel lenses, parabolic troughs/dishes (small), multi-facet reflectors	High-efficiency c-Si or III–V (dual/triple junction) at upper C	24 – 35 (Si) / 35 – 42 (III–V)	Dual-axis recommended	10 – 50
HCPV (High)	300 – 1000 (up to ~1500 in research)	High-precision Fresnel or reflective dishes/heliostats	III–V multijunction (GaInP/GaAs/Ge, 3J–6J) on tiny cells	38 – 45 (cell)	Dual-axis mandatory	50 – 200

The concentration ratio (C) fundamentally dictates the architectural complexity of CPV systems. In LCPV configurations (2–10×), relatively simple optical components such as compound parabolic concentrators (CPCs) and shallow Fresnel lenses are sufficient due to the low level of solar flux concentration. As the system transitions to MCPV (10–100×), more advanced optical designs, such as parabolic dishes and multi-faceted reflectors, become necessary to maintain efficient light focusing. In HCPV systems (300–1000×), the requirement for highly precise optical alignment becomes critical, necessitating the use of high-accuracy Fresnel lenses or heliostat-based reflectors. This progression illustrates that higher concentration ratios inherently increase system complexity, precision requirements, and sensitivity to optical losses.

The type of photovoltaic cell employed evolves significantly with increasing concentration levels. LCPV systems typically utilize conventional crystalline silicon (c-Si) cells, including mono-crystalline and heterojunction variants, due to their cost-effectiveness and adequate performance under low concentration. In MCPV systems, there is a transition toward higher-efficiency silicon cells and the introduction of III–V semiconductor materials, especially under higher concentration conditions. HCPV systems, however, rely almost exclusively on III–V multijunction cells such as GaInP/GaAs/Ge, which are specifically engineered to operate efficiently under extreme irradiance. This progression reflects the increasing demand for materials with superior spectral absorption, lower thermal sensitivity, and higher conversion efficiency.

A clear performance enhancement is observed as concentration increases across CPV classes. LCPV systems exhibit cell efficiencies in the range of 20–26% and module efficiencies of 16–22%, which are comparable to conventional PV systems. MCPV systems achieve moderate improvements, with module efficiencies rising to 20–30% due to better light utilization and improved cell technologies. HCPV systems demonstrate the highest efficiencies, with cell efficiencies reaching up to 45% and module efficiencies between 28–38%. Despite these gains, a persistent gap exists between cell and module efficiencies, primarily due to optical losses, thermal effects, and system-level inefficiencies, which become more noticeable at higher concentration levels.

Tracking requirements become increasingly stringent with higher concentration ratios. LCPV systems can operate effectively with single-axis tracking or even fixed installations with seasonal tilt adjustments, owing to their wider acceptance angle. MCPV systems typically require dual-axis tracking to maintain optimal solar alignment and maximize energy capture. In HCPV systems, dual-axis tracking is mandatory due to the extremely narrow acceptance angle of high-concentration optics. This introduces additional mechanical complexity, higher installation and maintenance costs, and increased susceptibility to alignment errors, making tracking a critical component of overall system performance.

Thermal management becomes a dominant design constraint as concentration increases. In LCPV systems, the thermal heat flux ranges from 1–10 W/cm², which can generally be managed through passive cooling techniques. MCPV systems experience higher heat flux levels (10–50 W/cm²), requiring enhanced cooling strategies such as forced air or basic liquid cooling. In HCPV systems, the heat flux can reach 50–200 W/cm², necessitating advanced active cooling solutions, including liquid cooling and heat exchangers. Ineffective heat dissipation at these levels can lead to significant efficiency losses, accelerated material degradation, and reduced system lifespan.

Each CPV class reflects a different balance between performance, cost, and operational complexity. LCPV systems are well-suited for applications where simplicity, low cost, and minimal maintenance are priorities, even if efficiency gains are modest. MCPV systems offer a balanced compromise, delivering improved efficiency without excessive system complexity. HCPV systems are designed for maximum energy conversion efficiency, particularly in regions with high direct normal irradiance (DNI), but require substantial investment, precise tracking, and advanced thermal management. Therefore, the selection of a CPV system must align with site-specific conditions, economic considerations, and performance objectives.

The overarching insight from the table is that increasing the concentration ratio enhances energy conversion efficiency but introduces disproportionate increases in system complexity, cost, and engineering challenges. Higher concentration demands greater optical precision, more advanced materials, stricter tracking requirements, and more robust thermal management systems. Consequently, the benefits of higher efficiency must be carefully weighed against these added complexities to determine the most practical and economically viable CPV configuration for a given application.

4. Spectral Splitting and Filtering

Due to each type of photovoltaic (PV) cell is designed to operate in a particular region of the solar spectrum, PV cells have the potential to convert energy based on wavelength. Therefore, the majority of commercial solar cells, such as crystalline silicon, have an effective spectral response that is restricted to a small range of wavelengths within the larger spectrum of solar radiation [67,68]. The excess energy is mostly lost as heat when exposed to photons outside of this ideal range, especially in the infrared (IR) and ultraviolet (UV) spectrums, which raises cell temperatures and lowers electrical conversion efficiency.

Traditional thermal management techniques use post-absorption cooling, which removes the excess heat after the module has already absorbed it. By filtering or rerouting unwanted spectral components before they reach the PV surface, the spectral splitting technique, on the other hand, is a pre-absorption thermal mitigation strategy. Two fundamental optical configurations exist for the operation of spectral splitting and filtering [69,70]:

- Reflective (Interference) Method - relies on thin-film dielectric along with wave-interference filters to reflect undesirable wavelengths whereas transmitting the target range to the PV cell.
- Absorptive (Selective Absorber) Method - involves spectrally selective materials or coatings that capture specific wavelength bands and convert them into suitable heat energy.

The setup used for the experiment involved a Fresnel lens, a cold mirror for spectral splitting, a cooling unit utilizing phase change material (PCM), and a two-dimensional solar tracking mechanism. Receiving solar radiation was directed onto the photovoltaic receiver through a Fresnel lens, in addition a cold mirror transmitted the visible spectrum that was optimized for electrical conversion and specifically reflected infrared wavelengths to prevent overheating of the photovoltaic cell. The PCM-based cooling system absorbed excess heat during peak irradiance, thus attaining thermal equilibrium, enhancing energy conversion efficiency, and maintain stable temperatures during operation [70-72].

5. Tracking Systems

Solar tracking systems, by consistently orienting PV modules to the sun's apparent trajectory during the day, exemplify advanced technologies aimed at optimizing solar energy collection. In order to maximize the effective irradiance received and overall electrical yield, the basic idea behind these systems is to dynamically adjust the panel orientation, both azimuth and elevation angles, so that incident solar rays maintain as perpendicular to the active surface as possible [73-76]. Partial shading, which can drastically lower array efficiency and result in power mismatch losses across series-connected modules, is one of the main operational issues with stationary PV installations. Solar tracking system offers a mechanical and predictive solution, even though conventional electrical configurations like bypass diodes and optimized string connections can somewhat reduce shading effects. Tracking Types can be illustrated in Figure 4. A comparison of fixed, single-axis, and dual-axis solar tracking systems is given in Table 3, which also highlights the systems' tracking axes & motion, typical orientation, tracking range, maintenance level, benefits, drawbacks, and appropriate uses.

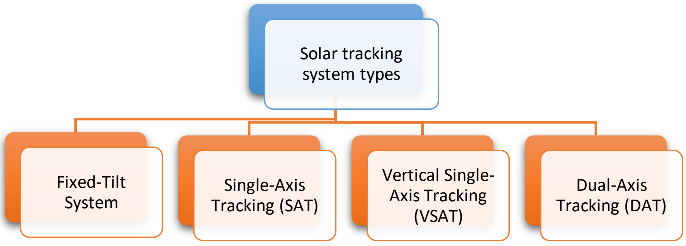

Figure 4. Solar tracking system types.

The most common and affordable configuration is represented by fixed-tilt systems. They are mechanically immobile, and in order to optimize yearly radiation, the module tilt angle is usually set to roughly correspond with the local latitude. Although they are very dependable and require little upkeep, their lower energy harvest efficiency is caused by their incapacity to adjust to the sun's seasonal and diurnal motion.

Table 3. Comparative Summary of Solar Tracking System Configurations [77-85]

Tracking Type	Tracking Axes & Motion	Typical Orientation / Geometry	Control Mechanism	Advantages	Limitations / Challenges	Suitable Applications / Climate Conditions
Fixed-Tilt System	None (Static Installation)	Tilt angle ≈ latitude ±10°	None (static mount)	Simple, low-cost, reliable; minimal maintenance; suitable for rooftops and small systems.	Inefficient at off-peak angles; limited solar capture; affected by shading geometry.	Residential rooftops, low-maintenance sites, cloudy or high-diffuse regions.
Single-Axis Tracking (SAT)	One axis (azimuth or altitude)	East–West (horizontal) or North–South (tilted)	Sensor-based, astronomical, or hybrid	Increases annual yield; reduces shading loss; cost-effective compromise between fixed and dual-axis.	Requires larger land area; increased O&M; less efficient in cloudy climates.	Utility-scale PV farms in mid- to low-latitude zones; high-DNI or mixed irradiance sites.
Vertical Single-Axis Tracking (VSAT)	Vertical rotation (azimuth only)	Panels rotate around vertical axis; often bifacial	Motorized with solar position algorithm	Suited for bifacial modules; compact design; high albedo utilization.	Reduced efficiency at high latitudes; susceptible to wind load.	Bifacial ground-mount systems; desert or bright-ground regions.
Dual-Axis Tracking (DAT)	Two axes (azimuth + elevation)	Follows solar altitude and azimuth continuously	Closed-loop or predictive astronomical control	Maximizes irradiance capture; maintains optimal tilt year-round; ideal for CPV systems.	Higher CAPEX and O&M; complex mechanics; wind stability concerns.	Concentrated PV (CPV) and high-DNI regions (≥5.5 kWh/m^2·day); research and hybrid systems.

As a result, fixed systems are a suitable option for low-maintenance applications, residential rooftops, and areas with high diffuse radiation where tracking offers minimal advantage. Utilizing rotating about a single axis, either horizontally or stiltedly, single-axis tracking systems (SAT) provide dynamic adaptability by allowing the modules to follow the east-west path of the sun. Compared to fixed installations, this configuration usually increases annual energy output by 15–25%. The system is a technically and financially feasible option for utility-scale PV plants in areas with high direct-normal-irradiance (DNI) levels due to its moderate tracking precision (1–3°) and comparatively low energy consumption (approximately 0.3–0.6% of output power). It worthy to mention that, Dual-axis systems have been connected to higher capital expenditures (CAPEX), more operation and maintenance (O&M) demands along with potential structural vulnerabilities in strong wind conditions, despite their superior efficiency.

In a comparable scenario, local operational, climatic, and economic considerations ought to influence the selection of a suitable tracking configuration. Fixed systems prove to be the least expensive option in high-latitude or diffuse-light areas. Meanwhile, dual-axis tracking has the greatest potential for concentrated solar installations, investigations, and regions with frequently elevated DNI values (≥5.5 kWh/m^2·day). Single-axis tracking, on the other hand, supplies an outstanding price-to-performance ratio for massive solar power plants in sunny climates.

6. Opportunities and Challenges

This section of the article offers compelling opportunities to increase energy yield, stabilize module temperature, and bring down LCOE. Moreover, Passive/active thermal management may eliminate heat-induced efficiency losses alongside accelerate reliability; concentrator designs demonstrate higher flux on smaller cell areas; spectral splitting more effectively matches photon energies to cell bandgaps; and modern single-/dual-axis trackers increase capture according to variable sky atmospheric conditions. Yet each pathway presents different challenges: additionally, optical and mechanical degree of complexity, parasitic power and O&M burdens, sensitivity to soiling and misalignment, durability of fluids and phase-change materials, and bankability risks tied to uncertain long-term reliability.

A. Opportunities

1) Higher energy yield and performance ratio (PR) uplift

The integration of thermal management (PV/T), optical concentration (CPV), and dual-axis tracking (DAT) directly enhances the incident irradiance utilization and reduces temperature-induced efficiency degradation. From a performance modeling standpoint, module efficiency typically decreases by ~0.3–0.5%/°C for silicon-based PV; therefore, active or hybrid cooling stabilizes operating temperature, maintaining voltage (Voc) and improving fill factor. Simultaneously, CPV optics increase the effective irradiance on the cell, while DAT ensures near-normal solar incidence throughout the day, minimizing cosine losses. The combined effect can yield 15–40% annual energy gains, particularly in high-DNI regions. Additionally, spectral pre-filtering reduces sub-bandgap photon absorption (which otherwise manifests as heat), improving electrical conversion efficiency and mitigating thermal drift, thus enhancing long-term PR stability.

2) Hybrid co-generation and exergy utilization

PV/T systems represent a shift from purely electrical generation toward multi-output energy systems, enabling simultaneous electricity and thermal energy production. From an exergy perspective, conventional PV dissipates a large portion of absorbed solar energy as low-grade heat; PV/T systems recover this thermal component (typically 40–70 °C) for domestic hot water, space heating, or industrial preheating. The integration of liquid cooling loops and phase change materials (PCM) enhances heat capture and temporal storage, smoothing thermal output. This dual-use significantly improves overall system exergy efficiency, which is otherwise limited in standalone PV systems. Economically, this translates into reduced Levelized Cost of Energy (LCOE) through revenue stacking, electricity sales combined with displaced thermal energy costs, making such systems particularly attractive in energy-intensive facilities.

3) Material and optical innovations

Recent advances in photonic and thermal materials provide new degrees of freedom in solar energy harvesting. Radiative cooling films, engineered with high emissivity in the atmospheric window (8–13 μm), enable passive heat rejection to the sky, reducing module temperature without energy input. Similarly, spectrally selective dielectric stacks (cold mirrors) allow wavelength-specific reflection/transmission, enabling spectral splitting architectures that direct high-energy photons to PV cells while diverting infrared (IR) to thermal collectors. Optical components such as Fresnel lenses and compound parabolic concentrators (CPCs) are being optimized for higher optical efficiency, lower aberration, and improved durability. These innovations collectively enable pre-absorption thermal control, improved photon management, and enhanced overall system efficiency.

4) Land use and CAPEX efficiency in high-DNI regions

In regions with high Direct Normal Irradiance (DNI), CPV systems combined with tracking significantly increase power density (W/m^2). This allows for reduced land footprint or higher energy yield per unit area, which is particularly valuable in land-constrained or high-cost locations. Additionally, repowering existing PV sites with CPV or hybrid systems can enhance output without expanding physical infrastructure. Spectral splitting further enables integrated energy systems, where IR radiation is diverted to thermal loads (e.g., industrial process heat), improving internal rate of return (IRR). These configurations are especially advantageous in industrial campuses where both electricity and heat demand coexist, enabling more efficient resource utilization.

B. Challenges

1) Thermal–mechanical complexity and reliability

The integration of cooling systems, tracking mechanisms, and optical concentrators introduces significant system complexity. Components such as pumps, valves, actuators, seals, and precision optics increase the number of potential failure modes. From a reliability engineering perspective, maintaining tracking accuracy (≤1° for DAT and ≤0.2° for HCPV) under dynamic conditions (wind loads, thermal expansion, dust accumulation) is particularly challenging. Misalignment directly reduces optical efficiency and can cause non-uniform flux, leading to localized overheating (hot spots). Moreover, increased operation and maintenance (O&M) requirements elevate lifecycle costs and may offset performance gains if not properly managed.

2) Environmental exposure and soiling effects

Optical and thermal components, such as mirrors, lenses, interference filters, and radiative coatings, are highly sensitive to environmental degradation. Factors such as ultraviolet (UV) radiation, humidity, sand abrasion, and particulate deposition can degrade optical transmittance and reflectivity over time. Soiling losses are particularly critical in arid, high-DNI regions where CPV systems are most viable. Even minor contamination can significantly reduce optical efficiency due to the multiple nature of optical losses. Maintaining performance requires regular cleaning protocols, anti-soiling coatings, and materials validated for long-term durability (>20–25 years), which remains an ongoing challenge in field deployments.

3) Water, fluid, and material sustainability

Active cooling strategies, especially those involving water spraying, evaporative cooling, nanofluids, or PCM, introduce sustainability concerns. Water-based systems may face constraints in arid regions, while nanofluids can present issues related to stability, agglomeration, and potential environmental toxicity. Likewise, phase change materials may suffer from leakage, phase segregation, or degradation over repeated cycles. From an ESG (Environmental, Social, and Governance) standpoint, lifecycle impacts, including material sourcing, operational consumption, and end-of-life disposal, must be carefully evaluated. Therefore, there is a strong need for closed-loop systems, non-toxic materials, and recyclable components to ensure long-term sustainability and regulatory compliance.

4) Site dependence and resource mismatch

The performance of CPV and advanced tracking systems is highly dependent on solar resource characteristics, particularly DNI. In regions dominated by diffuse irradiance (e.g., cloudy or humid climates), CPV systems underperform relative to conventional flat-plate PV. Similarly, the effectiveness of spectral splitting depends on precise alignment between the incident solar spectrum and the external quantum efficiency (EQE) of the PV cells. Any mismatch leads to optical losses that can negate theoretical efficiency gains. This introduces a strong site-specific optimization requirement, where system design must be tailored to local atmospheric conditions, spectral distribution, and load profiles to achieve optimal performance.

Overall, the opportunities highlight a pathway toward high-efficiency, multi-functional solar energy systems, while the challenges emphasize the need for robust engineering, material durability, and site-specific optimization. The transition from conventional PV to integrated CPV/PV-T systems is not merely incremental but represents a shift toward complex energy systems engineering, where performance gains must be balanced against reliability, cost, and sustainability constraints.

7. Conclusion

This section provides an in-depth and integrated assessment of advanced strategies for enhancing solar photovoltaic (PV) performance, emphasizing the synergistic roles of thermal management, optical concentration, spectral control, and solar tracking. The analysis confirms that concentrator designs (e.g., Fresnel lenses, CPCs, and heliostat-based systems) can substantially increase incident solar flux on reduced cell areas, enabling the use of high-efficiency materials and improving overall power density. In parallel, spectral splitting techniques, through wavelength-selective filters and dielectric stacks**,** facilitate a more precise alignment between the solar spectrum and photovoltaic cell bandgaps, thereby minimizing thermalization losses and improving conversion efficiency. Additionally, the integration of single- and dual-axis tracking systems enhances solar capture by maintaining near-optimal incidence angles under varying atmospheric and diurnal conditions, reducing cosine losses and increasing annual energy yield.

Equally important, passive and active thermal management approaches, including radiative cooling, forced convection, liquid cooling, and phase-change materials (PCM), play a critical role in stabilizing module temperature. By mitigating heat-induced efficiency degradation, particularly the temperature dependence of open-circuit voltage, these methods not only improve instantaneous performance but also contribute to long-term reliability and slower material degradation rates. When combined within hybrid configurations such as PV/T or CPV systems, these technologies offer a pathway toward multi-functional energy generation, higher performance ratios (PR), and reduced levelized cost of energy (LCOE).

However, the deployment of these advanced solutions introduces a set of interrelated technical and economic challenges. The incorporation of high-precision optics, tracking mechanisms, pumps, and thermal control systems increases overall system complexity, leading to a higher likelihood of component failure and greater demands on operation and maintenance (O&M). Parasitic power consumption, particularly in active cooling and tracking systems, can partially offset net energy gains if not carefully optimized. Moreover, system performance is highly sensitive to optical misalignment and environmental factors such as soiling, dust accumulation, and UV-induced material degradation, all of which can significantly reduce optical efficiency over time.

Material durability also presents a critical constraint; working fluids, nanofluids, and PCM may suffer from degradation, leakage, fouling, or phase instability under prolonged thermal cycling, raising concerns about lifecycle performance and maintenance costs. From a techno-economic perspective, these uncertainties translate into bankability risks, as investors and stakeholders require robust evidence of long-term reliability (20–25 years or more) and predictable performance. In summary, while the discussed technologies offer substantial opportunities for efficiency enhancement, energy yield improvement, and system optimization, their successful implementation depends on achieving a careful balance between performance gains and system robustness. Future progress will rely on advances in durable materials, low-loss optical designs, intelligent control systems, and site-specific optimization frameworks, ensuring that high-performance PV systems remain both technically viable and economically competitive over their operational lifetime.

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