

Innovative Strategies for Enhancing Solar Energy Efficiency in Power Plants: A Comprehensive Review

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Publishing Date: 15/10/2025

Abstract

Solar energy has emerged as a vital component of the global renewable energy landscape due to its sustainability and abundance. Nevertheless, the conversion efficiency of solar power plants has been relatively low which has been a major barrier to widespread adoption. In this review, current strategies and emerging technologies that improve solar energy efficiency are synthesised. Advanced photovoltaic materials, solar tracking systems, hybrid solar integration, thermal energy storage, concentrated solar power (CSP) systems and AI based optimization are some of the topics. It is also discussed in terms of economic viability and environmental impacts. In this paper we give an overview of the technological advancements that will drive the future of efficient solar power generation.

I. INTRODUCTION

The energy landscape worldwide is being revolutionised by the dual need to satisfy increasing energy demand and minimise environmental damage from fossil fuel consumption. Solar energy is one of the most promising among array of renewable energy sources because it is abundant, scalable and has zero greenhouse gas emissions during its operation. Over the last two decades deployment of solar technologies has accelerated dramatically, from residential rooftops to utility scale solar farms. Despite huge investments and technological progress, however, one of the most significant problems associated with solar energy utilisation is that the efficiency of energy conversion in solar power plants is still relatively low (Hassan et al., 2024).

The term efficiency of a solar power plant means how much incident solar irradiance can be converted to useful electrical energy. This efficiency is dependent upon multiple factors such as material and structural limitations of photovoltaic (PV) cells, suboptimal design and orientation of solar panels, thermal losses, dust and debris accumulation and most importantly, the fact that solar energy is intermittent and varies daily and seasonally in sunlight. Besides limiting the output of solar energy, these limitations also affect the economic viability and

reliability of solar as a major power source in the national and global energy grids (Kumba et al., 2024).

Intense efforts have recently been devoted in addressing these challenges with multi-disciplinary innovations. It comprises the development of new photovoltaic materials such as perovskites and multi junction cells, intelligent solar tracking, integration with wind and battery storage and thermal energy storage (TES) to extend operational hours. Moreover, the use of concentrated solar power (CSP) technologies and artificial intelligence (AI) and machine learning (ML) in system optimization is a transformative tool to raise the overall plant efficiency (Firoozi et al., 2025).

Here, current advances and emerging strategies that are enabling the efficiency of solar power generation to increase are synthesised. This paper analyses the range of technological, environmental and economic perspectives that provide a comprehensive understanding of the converging innovations across domains from the technological, environmental and economic perspectives. The solar energy systems will play an important role in this transition to a decarbonized future and efficiency of the systems will be critical.

II. UNDERSTANDING SOLAR ENERGY EFFICIENCY

The efficiency of solar power system to convert the sunlight into usable electrical energy is determined by a critical parameter. It is most often defined as the ratio of electrical output of a system to the total incident solar energy. But the concept which seems so simple, is determined by a complex interplay of technological, environmental and design factors. As solar energy systems become a larger proportion of the global energy mix, it is crucial to understand the efficiency determinants so that performance can be optimised, costs reduced and long-term sustainability guaranteed.

➤ *Photovoltaic Cell Efficiency:*

Photovoltaic (PV) cell is the core of any solar energy system as it directly converts solar radiation into electricity by the photovoltaic effect. PV cell efficiency is the term used to describe the ratio of solar energy that can be converted into electrical energy by a PV cell. However, typical silicon based solar cells have efficiency of 15–22% and newer technologies such as multi junction and perovskite cells have demonstrated much higher performance. Properties of the semiconductor material, cell architecture, ability to absorb light and losses from reflection or recombination affect PV efficiency (Husain et al., 2018).

➤ *System Design Parameters:*

Operational efficiency of a solar power plant is very much dependent on its design and physical layout. The key design elements are the tilt angle of the panels, the azimuth orientation, spacing and the overall array configuration. Incorrect orientation or suboptimal spacing may lead to shading losses, less exposure to the sun, and, in turn, reduced energy output. Moreover, tracking systems that follow the sun's movement can be integrated to increase the exposure and increase the efficiency by up to 25–30%. Fixed mount, single axis or dual axis trackers are an efficiency vs. installation and maintenance cost trade off (Marwan et al., 2024).

➤ *Environmental Conditions:*

Solar system efficiency is very much affected by environmental factors. Due to the high ambient temperatures, PV cells can produce less voltage and thus lower performance of the system. Energy losses can also be contributed to by dust accumulation, soiling, cloud cover or shading from vegetation or nearby structures. These issues can be mitigated through regular maintenance, cleaning protocols and choice of site with the best solar irradiance. Additionally, IoT and AI based tools for real time monitoring systems and predictive maintenance can assist to keep the optimal operating conditions (Bamisile et al., 2025).

➤ *Balance of System (BoS) Efficiency*

While the solar panels themselves are one part of the system, the other parts include inverters, wiring, transformers and energy storage components. Losses in these components can have a big impact on the net

efficiency of the system. For example, inverter efficiency is how well DC power produced by PV modules is converted to usable AC power. BoS losses can be reduced and the total system efficiency improved by proper sizing, quality components and smart grid integration (Osmani et al., 2023).

These interdependent factors need to be understood and addressed in order to maximise solar energy performance. With the progress of technologies, system level integration, environmental adaptation and intelligent design will be more and more critical in realising higher efficiencies and more resilient solar power infrastructure.

III. TECHNOLOGICAL INTERVENTIONS TO IMPROVE SOLAR EFFICIENCY

To deal with solar energy's natural drawbacks and the fact that it is intermittent, many technological solutions have been created. The goal is to increase the quality of photovoltaic materials and also to improve the design, storage, delivery, and dependability of the system. This part of the report lists important actions that are improving the effectiveness and profitability of solar power plants.

➤ *Advanced Photovoltaic Technologies*

The development of novel photovoltaic (PV) materials and architectures have yielded significant gains in efficiency.

Perovskite Solar Cells are a promising next generation PV technology owing to their low production cost, tunable bandgap and power conversion efficiencies in excess of 25%. However, despite their current stability and scalability issues, perovskite based modules are the focus of intensive research in order to commercialise them for large scale deployment (Shah and Meyer, 2025).

Multi-junction Solar Cells, used in space applications and high-performance concentrator systems, layer multiple semiconductors with varying band gaps to capture a broader range of the solar spectrum. These cells have demonstrated laboratory efficiencies surpassing 40%, although their high cost currently limits widespread terrestrial use (Raisa et al., 2025).

Thin-film Solar Technologies, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), offer lightweight, flexible, and cost-effective alternatives to traditional silicon-based cells. While typically less efficient (10–15%), advancements in deposition techniques and materials engineering are steadily narrowing the performance gap (Wijewardane and Kazmerski, 2023).

➤ *Solar Tracking Systems*

Solar tracking systems enhance efficiency by maintaining optimal alignment between the solar panels and the sun throughout the day

Single-Axis Trackers rotate along a horizontal axis (typically east–west), increasing energy capture by

approximately 15–20% compared to fixed-tilt systems (Azad et al., 2025).

Dual-Axis Trackers adjust panel orientation on both the horizontal and vertical planes, enabling more precise solar alignment and boosting output by up to 25–30%. However, these systems involve higher installation, maintenance, and land use costs (Paliyal et al., 2024).

➤ *Hybrid Solar Power Systems*

Hybridization improves reliability and overall system efficiency by integrating solar with complementary technologies:

Solar–Wind Hybrid Systems capitalize on the complementary nature of solar and wind patterns—solar energy peaks during the day, while wind energy is often available at night or during cloudy conditions (Hassan et al., 2023).

Solar–Thermal Hybrid Systems pair PV or CSP plants with conventional thermal power sources (e.g., biomass or fossil fuels) to enhance baseload supply and dispatchability (Mills, 2018).

Solar + Battery Storage Systems utilize lithium-ion or other advanced batteries to store excess solar energy for use during periods of low irradiance or peak demand, ensuring grid stability and enabling time-shifted power delivery (Enasel and Dumitrascu, 2025).

➤ *Thermal Energy Storage (TES)*

TES systems are pivotal in concentrated solar applications, enabling electricity generation even after sunset:

Molten Salt Storage involves heating salts to high temperatures during the day and storing the thermal energy in insulated tanks. This heat is later used to generate steam for power production during non-sunny periods (Rahbari et al., 2024).

Phase Change Materials (PCMs) absorb and release thermal energy as they change states (e.g., solid to liquid), offering compact and efficient solutions for thermal buffering in solar thermal applications (Yang et al., 2021).

➤ *Concentrated Solar Power (CSP) Systems*

Unlike conventional PV systems, CSP plants use reflective surfaces to concentrate sunlight for thermal energy production:

Parabolic Troughs concentrate sunlight onto linear receivers containing heat transfer fluids, which produce steam to drive turbines (González-Mora et al., 2024).

Solar Towers use large arrays of heliostats to direct sunlight onto a central receiver mounted on a tower. Such systems can operate at higher operating temperatures and higher efficiencies in areas with high DNI (Hussaini et al., 2020).

➤ *Cooling Techniques and Heat Harvesting*

Excessive heat reduces PV efficiency, making thermal management essential:

Active Cooling systems employ water, air, and refrigerants to reduce the temperature of PV panels. They are effective but make operations more complex and consume more water (Dwivedi et al., 2020).

Natural airflow or high thermal conductivity materials are used to dissipate heat in Passive Cooling designs without consuming additional energy (Dwivedi et al., 2020).

Heat Harvesting Devices (HHDs), which turn excess panel heat into supplementary electricity or utilise it within a combined heat and power (CHP) application, increase overall system efficiency (Dobre et al., 2024).

➤ *AI and Optimization Algorithms*

Artificial intelligence (AI) and data-driven tools are being revolutionised with each other.

Solar irradiance can be accurately predicted by AI and Machine Learning Algorithms, and system diagnostics can be automated and energy dispatch optimised with respect to real-time demand and supply conditions (Shahverdi et al., 2025).

Geographic Information Systems (GIS) and simulation software are used to select the site and layout design to reduce shading and optimise panel orientation and thereby optimise the energy output (Kucuksari et al., 20214).

These technological advancements are being combined to modify the solar energy sector and improve the sector to be more efficient, resilient and cost effective for power generation systems. Innovation and integration of these domains will continue and accelerate the global transition to renewable energy.

IV. ECONOMIC FEASIBILITY OF EFFICIENCY IMPROVEMENTS

The economic viability of solar energy is closely related to the technological advancement that improves system efficiency. In this context, the most important metric is the Levelized Cost of Electricity (LCOE) which is the average cost of a kilowatt hour (kWh) of electricity produced over the life of a solar power plant. As solar conversion efficiency improves, solar energy becomes more competitive with conventional energy sources and therefore has a lower LCOE because of higher energy output per unit of installed capacity (Kabeyi and Olanrewaju, 2023).

These advanced technologies are costly to implement—multi-junction solar cells, dual-axis tracking systems, thermal energy storage and AI-based optimization tools all cost a lot of money. Although, they can be a barrier to adoption especially in developing

countries or regions where there is no strong policy in support. Although the initial costs of such measures can be potentially high, the long term economic benefits such as higher energy output, lower operating costs and longer system life are often justified (Choudhary et al., 2019).

The trends of recent years in which the cost of solar energy is plummeting are explained by advances in PV materials, scale economies and automation in manufacturing and system integration. For instance, the global average LCOE of utility-scale solar PV has fallen more than 80% between 2010 and 2020 and it is expected to continue to decline as the next generation of technologies matures and becomes commercially available (Khare et al., 2023).

High efficiency systems are strongly dependent on government policies that incentivize high efficiency systems such as tax credits, feed in tariffs and subsidies that offset initial costs. These measures reduce the risk of investment and, for this reason, enhance the financial attractiveness of solar projects for public and private stakeholders.

One of the promising technologies is Concentrated Solar Power (CSP) because it can be scaled and stored. The International Energy Agency (IEA) and Greenpeace said CSP could supply 3–3.6% of global electricity by 2030, rising to 8–11.8% by 2050. CSP is also expected to cost \$0.05 per kWh by 2025 which is very competitive compared to fossil fuels in sun rich areas (Wang et al., 2017).

Future attempts to make the solar sector sustainable economic growth should be focused on CAPEX reduction, energy efficiency increase, and cost-effective supporting infrastructure development, such as smart grids and energy storage systems. The future for solar energy is bright, with continued innovation and supportive policy frameworks, and it will be a leading force in the world's move toward a clean, resilient energy economy.

V. ENVIRONMENTAL AND SUSTAINABILITY CONSIDERATIONS

It is well known that solar energy can reduce greenhouse gas emissions and thereby help mitigate climate change. Unlike fossil fuels, solar power generation does not emit air pollutants or carbon emissions during operation and is a cornerstone of global sustainability efforts. The environmental benefits of solar energy are significant; however, there are significant sustainability challenges related to its lifecycle, including manufacturing and installation, decommissioning, and waste management (Hassan et al., 2023).

One of the biggest concerns is electronic waste (e-waste) generation. As the first generation of large scale solar installations reach the end of their service life larger volumes of decommissioned solar panels will enter the waste stream. However, if there is no proper recycling infrastructure, then these panels could become a burden in

landfills and a depleted resource. In order to remedy this problem, we must develop effective and scalable recycling programmes that would enable us to recover valuable materials such as silicon, glass and metals from old panels (Preet and Smith, 2024).

Another environmental challenge is created by hazardous substances used in manufacturing. Certain types of thin film solar panels such as cadmium telluride (CdTe) solar panels, contain toxic elements that are harmful to human health and the environment if improperly disposed. Safety measures are very rigidly followed in manufacturing facilities and end of life panels are handled with care to avoid environmental contamination (Ramos-Ruiz et al., 2017).

In order to increase its sustainability, research and innovation in solar technology continues. They involve the creation of nontoxic, lead free perovskite material, designing panels to improve disassembly and recycling and enhancing non hazardous and abundant resources in the process of solar cell manufacturing. The solar business is being investigated for the ideas of the circular economy to improve reuse, refurbishing and recycling (Jindal et al., 2024).

Calculating the true environmental impact of solar technologies requires significant use of the tool of lifecycle analysis (LCA). LCA evaluates energy inputs, emissions and material use to the solar system over the life cycle of the system, from raw material extraction to end of life disposal. This analysis helps decision makers to decide on policy, regulatory framework and technology development for more sustainable outcomes (Cellura et al., 2024).

After all, solar energy is cleaner than fossil fuels by its nature, but only if the material sourcing, the waste management and the design are done responsibly. In this transition, the solar systems must be carbon free and environmentally and socially responsible and this necessitates considering the entire lifecycle of solar systems.

VI. CONCLUSION AND FUTURE PERSPECTIVES

Solar power plant efficiency is a multi-disciplinary problem involving materials science and engineering, electrical and mechanical engineering, environmental science, and data analytics. With growing energy demands and escalating concerns over climate change, solar energy has become a key solution to provide affordable, clean, and renewable power. But additional innovation and strategic implementation of efficiency-enhancing technologies are still needed to unlock its full potential.

On the basis of this review, a variety of interventions (advanced photovoltaic materials, solar tracking systems, thermal energy storage, hybrid configurations, and AI-based optimization) are highlighted that are challenging

the performance limits of solar energy. Not only do these technological advancements increase energy output, but they do so in a way that improves grid reliability, lowers costs, and extends the operational flexibility of solar power plants.

➤ *Looking Ahead, Several Critical Areas of Focus Must Guide Future Research and Deployment Strategies:*

- *Long-Term Stability of High-Efficiency Materials:*

While perovskite and multi-junction solar cells offer record-breaking efficiencies, their long-term durability and environmental stability must be improved for widespread adoption in large-scale applications.

- *Scalable and Cost-Effective Storage Solutions:*

Energy storage technologies such as advanced batteries, molten salt, and phase change materials must be developed further to address the intermittency of solar energy and support 24/7 power availability.

- *Smart Grid Integration and AI-Driven Operation:*

Intelligent energy management systems using artificial intelligence and machine learning can significantly enhance system efficiency, predict energy output, and streamline grid operations in real time.

- *Sustainable Manufacturing and End-of-Life Strategies:*

The environmental footprint of solar technologies must be minimized through eco-friendly materials, recyclable panel designs, and robust waste management systems to ensure solar energy remains a truly sustainable option.

To summarize, solar energy has a promising path forward, but there are obstacles to overcome. If we maintain investment in research, have supportive policy frameworks, and commit to sustainability, solar energy will be the foundation of a carbon-neutral global energy system. With efficient use of materials and integration into the grid at every step, solar power can not only meet today's energy needs but also be the catalyst for a cleaner, more resilient energy future.

REFERENCES

- [1]. Hassan Q, Algburi S, Sameen AZ, Al-Musawi TJ, Al-Jiboory AK, Salman HM, Ali BM, Jaszczur M. A comprehensive review of international renewable energy growth. *Energy and built environment*. 2024 Jan 9.
- [2]. Kumba K, Upender P, Buduma P, Sarkar M, Simon SP, Gundu V. Solar tracking systems: Advancements, challenges, and future directions: A review. *Energy Reports*. 2024 Dec 1; 12:3566-83.
- [3]. Firoozi AA, Firoozi AA, Maghami MR. Harnessing photovoltaic innovation: Advancements, challenges, and strategic pathways for sustainable global development. *Energy Conversion and Management: X*. 2025 May 16:101058.
- [4]. Husain AA, Hasan WZ, Shafie S, Hamidon MN, Pandey SS. A review of transparent solar photovoltaic technologies. *Renewable and sustainable energy reviews*. 2018 Oct 1; 94:779-91.
- [5]. Marwan MD, Suhono S, Subekti L. The potential of shading to optimize the performance ratio of a solar power system. *E-Prime-Advances in Electrical Engineering, Electronics and Energy*. 2024 Dec 1; 10:100768.
- [6]. Bamisile O, Acen C, Cai D, Huang Q, Staffell I. The environmental factors affecting solar photovoltaic output. *Renewable and Sustainable Energy Reviews*. 2025 Feb 1; 208:115073.
- [7]. Osmani K, Haddad A, Lemenand T, Castanier B, Alkhedher M, Ramadan M. A critical review of PV systems' faults with the relevant detection methods. *Energy nexus*. 2023 Dec 1;12:100257.
- [8]. Shah AU, Meyer EL. Perovskite-based solar cells in photovoltaics for commercial scalability: Current progress, challenges, mitigations and future prospectus. *Solar Energy*. 2025 Jan 15;286:113172.
- [9]. Raisa AT, Sakib SN, Hossain MJ, Rocky KA, Kowsar A. Advances in multijunction solar cells: an overview. *Solar Energy Advances*. 2025 Mar 23:100105.
- [10]. Wijewardane S, Kazmerski LL. Inventions, innovations, and new technologies: Flexible and lightweight thin-film solar PV based on CIGS, CdTe, and a-Si: H. *Solar Compass*. 2023 Sep 1;7:100053.
- [11]. Azad AA, Bhuiya KM, Shoshi SR, Jamal JR, Udoy SA, Zilani S, Hawlather A, Hasan M, Azad TR. Harnessing the sun: Framework for development and performance evaluation of AI-driven solar tracker for optimal energy harvesting. *Energy Conversion and Management: X*. 2025 Apr 1;26:100990.
- [12]. Paliyal PS, Mondal S, Layek S, Kuchhal P, Pandey JK. Automatic solar tracking system: a review pertaining to advancements and challenges in the current scenario. *Clean Energy*. 2024 Dec;8(6):237-62.
- [13]. Hassan Q, Algburi S, Sameen AZ, Salman HM, Jaszczur M. A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in engineering*. 2023 Dec 1;20:101621.
- [14]. Mills S. Combining solar power with coal-fired power plants, or cofiring natural gas. *Clean Energy*. 2018 Jun;2(1):1-9.
- [15]. Enasel E, Dumitrascu G. Storage solutions for renewable energy: A Review. *Energy Nexus*. 2025 Feb 10:100391.
- [16]. Rahbari HR, Mandø M, Arabkoohsar A. Real-time modeling and optimization of molten salt storage with supercritical steam cycle for sustainable power generation and grid support. *Process Safety and Environmental Protection*. 2024 Feb 1;182:866-79.
- [17]. Yang T, King WP, Miljkovic N. Phase change material-based thermal energy storage. *Cell Reports Physical Science*. 2021 Aug 18;2(8).

- [18]. González-Mora E, Durán-García MD. Assessing parabolic trough collectors and linear Fresnel reflectors direct steam generation solar power plants in Northwest México. *Renewable Energy*. 2024 Jul 1;228:120375.
- [19]. Hussaini ZA, King P, Sansom C. Numerical simulation and design of multi-tower concentrated solar power fields. *Sustainability*. 2020 Mar 19;12(6):2402.
- [20]. Dwivedi P, Sudhakar K, Soni A, Solomin E, Kirpichnikova I. Advanced cooling techniques of PV modules: A state of art. *Case studies in thermal engineering*. 2020 Oct 1;21:100674.
- [21]. Dobre C, Costin M, Constantin M. A review of available solutions for implementation of small–medium combined heat and power (CHP) systems. *Inventions*. 2024 Jul 19;9(4):82.
- [22]. Shahverdi N, Saffari A, Amiri B. A systematic review of artificial intelligence and machine learning in energy sustainability: Research topics and trends. *Energy Reports*. 2025 Jun 1;13:5551-78.
- [23]. Kucuksari S, Khaleghi AM, Hamidi M, Zhang Y, Szidarovszky F, Bayraksan G, Son YJ. An Integrated GIS, optimization and simulation framework for optimal PV size and location in campus area environments. *Applied Energy*. 2014 Jan 1;113:1601-13.
- [24]. Kabeyi MJ, Olanrewaju OA. The levelized cost of energy and modifications for use in electricity generation planning. *Energy Reports*. 2023 Sep 1;9:495-534.
- [25]. Choudhary P, Srivastava RK. Sustainability perspectives-a review for solar photovoltaic trends and growth opportunities. *Journal of Cleaner Production*. 2019 Aug 1;227:589-612.
- [26]. Khare V, Chaturvedi P, Mishra M. Solar energy system concept change from trending technology: A comprehensive review. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*. 2023 Jun 1;4:100183.
- [27]. Wang J, Yang S, Jiang C, Zhang Y, Lund PD. Status and future strategies for Concentrating Solar Power in China. *Energy Science & Engineering*. 2017 Apr;5(2):100-9.
- [28]. Preet S, Smith ST. A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook. *Journal of Cleaner Production*. 2024 Mar 8:141661.
- [29]. Ramos-Ruiz A, Wilkening JV, Field JA, Sierra-Alvarez R. Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions. *Journal of hazardous materials*. 2017 Aug 15;336:57-64.
- [30]. Jindal R, Tripathi A, Mohan C, Garg A, Varma RS. Lead-free halide double perovskites for sustainable environmental applications. *Chemical Physics Impact*. 2024 Dec 1;9:100770.
- [31]. Cellura M, Luu LQ, Guarino F, Longo S. A review on life cycle environmental impacts of emerging solar cells. *Science of the total environment*. 2024 Jan 15;908:168019.