

# Advanced Materials for Solar Photovoltaic Cells: Recent Developments and Future Prospects

Neeraj Pandey<sup>1,\*</sup>, Amit Shrivastava<sup>2</sup>

## Abstract

*Solar energy is becoming a key component of renewable energy systems due to the global shift to sustainable energy sources. Recent developments in solar photovoltaic (PV) cell materials have resulted in notable gains in scalability, cost-effectiveness, and efficiency. With an emphasis on inorganic, organic, hybrid, and developing materials, this review looks at the most recent advancements in materials for photovoltaic technology. Notably, organic photovoltaics offer benefits in flexibility and inexpensive production costs, whereas perovskite solar cells have attracted a lot of attention because of their high efficiency and simplicity of construction. Furthermore, new developments in quantum dot technologies, tandem solar cells, and transparent conductive materials are emphasized. Along with discussing issues including material stability, scalability, and environmental impact, the study also suggests potential avenues of inquiry for the development of next-generation solar systems.*

**Keywords:** Solar photovoltaic cells, advanced materials, perovskite solar cells, organic photo voltaic, quantum dots, tandem cells, material stability, energy efficiency, renewable energy

## INTRODUCTION

In recent years, the development of advanced materials for solar photovoltaic (PV) cells has emerged as a central focus of energy research, driven by the need to improve the efficiency, scalability, and cost-effectiveness of solar power. Traditional silicon-based solar cells have dominated the market for decades; however, alternative materials and novel architectures have garnered significant attention due to their potential to surpass the limitations of silicon. This review aims to provide an overview of the latest developments in solar cell materials, particularly focusing on III-V multijunction, perovskites, quantum dots, organic photovoltaics (OPVs), two-dimensional (2D) materials, and their future prospects. Additionally, advancements in the design and manufacturing techniques, such as flexible and lightweight

cells, energy payback times, and recycling strategies, are explored. The concept of energy efficiency refers to the ability to get the best results in any given activity by utilizing the least amount of energy resources possible. It enables us to reduce the consumption of any type of energy including the associated environmental impacts. This is applicable from production to consumption of energy.

## III-V MULTIJUNCTION SOLAR CELLS: FLEXIBLE AND HIGH-POWER DENSITIES

III-V semiconductors, such as gallium arsenide (GaAs), indium phosphide (InP), and their alloys, have long been recognized for their high efficiency in photovoltaic applications. The use of multiple junctions in these cells allows for the absorption of

### \*Author for Correspondence

Neeraj Pandey

E-mail: [neerajpandey.ee@itmuniversity.ac.in](mailto:neerajpandey.ee@itmuniversity.ac.in)

<sup>1</sup>Assistant Professor, Department of Electrical Engineering, School of Engineering and Technology, Institute of Technology and Management (ITM) University, Gwalior, Madhya Pradesh, India

<sup>2</sup>Assistant Professor, Department of Electrical Engineering, Institute of Professional Studies (IPS) College of Technology & Management, Gwalior, Madhya Pradesh, India

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a broader spectrum of sunlight, significantly improving their power conversion efficiency (PCE). Algora *et al.* have provided significant insights into the development of flexible and lightweight III-V multijunction solar cells [1]. Their study emphasizes how these cells, which have been traditionally used in space applications, can now be adapted for terrestrial use. The main advantage of these cells lies in their high efficiency at concentrated power densities, making them ideal for niche markets such as space and mobile applications. However, despite their high performance, the cost of production remains high, limiting their widespread use in everyday solar energy applications. Recent research focuses on reducing costs while maintaining the high efficiency and flexibility of these cells.

### **DUAL-AXIS SOLAR TRACKERS: ENHANCING EFFICIENCY FOR CONCENTRATED PV APPLICATIONS**

A crucial aspect of increasing the efficiency of concentrated photovoltaic (CPV) systems, which often use III-V multijunction cells, is the precise alignment of the solar panel with the sun. Elgeziry and Hatem designed a dual-axis open-loop solar tracker specifically for CPV applications [2]. This tracker improves the overall performance by keeping the solar cell at the optimal angle throughout the day. By incorporating such technologies into CPV systems, it is possible to extract more energy from the same surface area, thus increasing the overall efficiency of the system. The integration of advanced tracking systems with flexible, lightweight III-V multijunction cells could significantly improve the cost-efficiency of solar power generation. A dual-axis solar tracker significantly enhances efficiency in concentrated photovoltaic (CPV) applications by allowing solar panels to precisely follow the sun's movement in both horizontal (east-west) and vertical (elevation) directions, maximizing the amount of sunlight captured and converting it into electricity compared to fixed or single-axis tracking systems [3]; this is particularly crucial for CPV systems due to their high concentration of sunlight on a smaller receiver area, requiring precise alignment to optimize energy production.

### **PEROVSKITE SOLAR CELLS: EFFICIENCY GAINS AND ENVIRONMENTAL CONSIDERATIONS**

Perovskite solar cells (PSCs) have made a significant leap in terms of efficiency, rivaling traditional silicon-based solar cells. One key advantage of perovskites is their ease of fabrication at low temperatures, which reduces manufacturing costs compared to silicon. Additionally, the wide tunability of the perovskite bandgap allows for the optimization of light absorption and the creation of tandem structures that further improve efficiency. Celik *et al.* analyzed the energy payback time (EPBT) and energy return on energy invested (EROI) for perovskite tandem solar cells [4]. Their findings show that these cells are not only efficient in energy conversion but also have a favorable energy payback ratio, making them a sustainable option for large-scale deployment. Perovskite solar cells (PSCs) are a promising photovoltaic (PV) technology that can be more efficient than silicon solar cells. However, they also contain lead, which can be toxic to humans and the environment. Despite impressive progress, several challenges remain [5]. The long-term stability of perovskite solar cells, particularly in outdoor environments, is a critical barrier to their commercialization. Christians *et al.* highlighted the sensitivity of perovskites to moisture, oxygen, and UV radiation [6]. The use of lead in many perovskite formulations is another significant concern, which has led to extensive research into lead-free alternatives. Sharma *et al.* explored lead-free double halide perovskite solar cells, aiming to mitigate the environmental risks while retaining the high efficiency of traditional perovskites [7].

Moreover, stability improvements have been realized through interface engineering. Prasanna *et al.* demonstrated that better interface management can significantly enhance the stability and performance of perovskite tandem solar cells [8].

### **QUANTUM DOT SOLAR CELLS: BOOSTING EFFICIENCY THROUGH NANOTECHNOLOGY**

Quantum dots (QDs) have become a promising candidate for next-generation solar cells due to their unique optical properties, such as size-tunable bandgaps and the ability to generate multiple excitons

from a single photon, enhancing efficiency [9]. Bedi and Singh provided a comprehensive review of quantum dot solar cells (QDSCs), pointing out the advantages and challenges of using quantum dots as the primary absorbing material [10]. One of the key challenges in QDSCs is maintaining the stability and uniformity of the quantum dots, which can affect the device's overall performance. Recent advancements in material synthesis and device architecture, however, have mitigated some of these issues. Quantum dot solar cells (QDSCs) utilize nanotechnology by incorporating tiny semiconductor particles called "quantum dots" to significantly enhance the efficiency of solar energy conversion by allowing for better light absorption across a wider spectrum due to their size-dependent bandgap properties, potentially generating multiple electron-hole pairs from a single photon, leading to higher energy output compared to traditional solar cells.

Further, Christians *et al.* proposed the use of perovskite quantum dots in tandem solar cells, showing how these materials can be used to improve the light absorption in the top cell of a tandem configuration [6]. The use of perovskite quantum dots in tandem structures has been particularly promising, as it combines the high efficiency of perovskites with the unique properties of quantum dots, creating a pathway to even higher efficiency solar cells [11]. They explored the potential of integrating quantum dots with other materials, such as CdTe quantum dots embedded in GaAs quantum wells, to further increase the efficiency of solar cells. This integration holds promise for future multi-junction solar cells that could outperform current technologies in terms of efficiency.

## **ORGANIC PHOTOVOLTAICS: RECENT DEVELOPMENTS AND EFFICIENCY IMPROVEMENTS**

Organic photovoltaics (OPVs) have garnered attention due to their potential for flexible, lightweight, and low-cost solar cells. Chen and Cao provided a detailed overview of OPVs, focusing on the materials, devices, and strategies for improving efficiency [12]. They noted that the development of non-fullerene acceptors has led to significant improvements in efficiency and stability. These new acceptors are less susceptible to degradation compared to traditional fullerene-based materials, which has been a major limitation in the commercial viability of OPVs. The efficiency of OPV cells has reached up to 20% which is relatively higher than the early stage. The development of new materials such as perovskite, fullerene derivatives, and new device architecture such as tandem cells have contributed to this improvement.

The main challenge for OPVs remains the relatively low efficiency compared to silicon and other technologies. Additionally, Yuan *et al.* reported significant progress in overcoming carrier transport losses, which have been a critical bottleneck in OPV efficiency [13]. These advances in device engineering suggest that OPVs may soon become a viable competitor to traditional solar cell technologies, especially in niche applications such as wearable electronics or portable solar solutions. They also explored the use of 2D materials in tandem solar cells, noting their potential to absorb light more efficiently and improve carrier mobility. The integration of 2D materials with traditional photovoltaic technologies could pave the way for new, highly efficient devices with excellent mechanical flexibility and scalability.

## **GRAPHENE AND 2D MATERIALS: ROLE IN ENHANCING PHOTOVOLTAIC PERFORMANCE**

Graphene and other two-dimensional (2D) materials, such as transition metal dichalcogenides (TMDs), have shown great potential for improving the performance of solar cells. Guo *et al.* highlighted the role of 2D materials in enhancing charge transport and light absorption in solar cells [14]. Graphene, for instance, can be used as a transparent electrode material in perovskite solar cells, which improves the overall efficiency by reducing resistive losses and enhancing charge collection. Notably, graphene's 2D internal architecture emerges as a protector for photovoltaic devices, guaranteeing long-term stability against various environmental challenges. It acts as a transportation facilitator and charge extractor to the electrodes in photovoltaic cells.

Zhuang *et al.* also conducted research into the use of graphene-based transparent electrodes for flexible perovskite solar cells, showing that this combination improves efficiency by reducing series resistance [15].

While 2D materials hold great promise, their large-scale production and integration into commercial devices remain challenging. Researchers are focused on developing scalable methods for synthesizing high-quality 2D materials and integrating them into solar cell architectures.

### **RECYCLING OF SOLAR CELLS: ADVANCED METHODS AND SUSTAINABILITY**

As the demand for solar energy grows, the recycling of photovoltaic cells has become an important area of research. Sprague *et al.* investigated the implementation of artificial intelligence (AI) in the recycling of perovskite solar cells, proposing that AI could optimize the recycling process and improve the efficiency of material recovery [16]. Given the environmental concerns associated with some of the materials used in solar cells, such as lead in perovskites, improving recycling methods is critical for the sustainability of solar energy technologies. In this study, chemical etching or leaching methods are chosen for silicon recovery, with a primary emphasis on cell recycling [16]. The initial phase of solar cell recycling involves the collection and transportation of used panels to recycling facilities.

### **FUTURE PROSPECTS AND CHALLENGES IN SOLAR ENERGY TECHNOLOGIES**

The future of solar photovoltaics lies in the integration of multiple advanced materials to form tandem solar cells with enhanced efficiencies. Green *et al.* [17] and NREL [18] have provided insights into the ongoing advancements in solar cell efficiencies, highlighting the role of next-generation materials like perovskites and quantum dots in achieving higher PCE. Future developments will likely focus on hybrid solar cells that combine the best features of organic, inorganic, and quantum dot materials. The future of solar energy technologies is promising, but it faces challenges such as high upfront costs, a lack of skilled labor, and administrative issues [19, 20]. Additionally, Zhuang *et al.* [15] and Mathews *et al.* [19] emphasize the importance of developing scalable manufacturing processes and improving the stability of emerging materials to ensure that they can be deployed on a large scale.

### **CONCLUSION**

The field of solar photovoltaics is undergoing a revolution, driven by the development of advanced materials that promise to overcome the limitations of traditional silicon-based solar cells. From III-V multijunction to perovskites, quantum dots, organic photovoltaics, and 2D materials, a variety of new materials and technologies are being explored to enhance the efficiency, stability, and cost-effectiveness of solar cells. As research continues, these advancements will help shape the future of solar energy, enabling broader adoption and contributing to global sustainability goals.

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