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## Recent advances in solar photovoltaic technologies: Efficiency, materials, and applications

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### Abstract

Recent advancements in solar photovoltaic (PV) technologies have significantly enhanced the efficiency, materials, and applications of solar energy systems, driving the transition towards more sustainable energy solutions. This paper provides an overview of these advancements and their implications for the future of solar energy. One of the major breakthroughs in solar PV technology is the development of high-efficiency photovoltaic cells. Innovations in cell design and manufacturing processes have led to significant improvements in conversion efficiency. For instance, multi-junction solar cells, which layer multiple semiconductor materials, have achieved efficiencies exceeding 40% under concentrated sunlight. Additionally, advances in passivated emitter rear cell (PERC) technology and bifacial solar cells, which capture light from both sides, have further boosted the efficiency of traditional silicon-based PV cells. Materials science has also played a crucial role in advancing solar PV technologies. The emergence of new materials such as perovskite solar cells has revolutionized the field with their potential for high efficiency and low production costs. Perovskite materials offer flexibility and ease of fabrication, allowing for lightweight and adaptable solar panels. Furthermore, advances in organic photovoltaics (OPVs) and quantum dot solar cells are contributing to the development of flexible, semi-transparent, and aesthetically pleasing PV panels, expanding the scope of their applications. The application of solar PV technologies has broadened significantly due to these advancements. Innovations in solar panel integration into building materials, such as solar windows and photovoltaic roofing tiles, have facilitated the seamless incorporation of solar energy systems into architectural designs. Additionally, advances in energy storage solutions, including high-capacity batteries and hybrid systems, are enhancing the reliability and efficiency of solar energy use, making it a viable option for residential, commercial, and industrial applications. These advancements collectively contribute to reducing the cost of solar energy, increasing its accessibility, and promoting its adoption worldwide. As research and development continue, future innovations are expected to further improve the efficiency, versatility, and economic viability of solar PV technologies, reinforcing their role in achieving global sustainability and energy independence.

**Keywords:** Recent Advances; Solar; Photovoltaic Technologies; Efficiency; Materials

### 1. Introduction

Recent advances in solar photovoltaic (PV) technologies have significantly transformed the landscape of renewable energy. Solar PV systems, which convert sunlight directly into electricity using semiconductor materials, have evolved considerably since their inception (Anaba, Kess-Momoh & Ayodeji, 2024, Ekechukwu & Simpa, 2024, Nwankwo & Ihueze, 2018, Okpala, Nwankwo & Ezeanyim, 2023). These advancements have led to increased efficiency, improved materials, and broader applications, making solar energy a more viable and competitive alternative to traditional energy sources (Green et al., 2020).

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The importance of advancements in solar PV technologies cannot be overstated. As global energy demand rises and the effects of climate change become more pronounced, the need for efficient, sustainable energy solutions is urgent (Ihueze, Obiuto & Okpala, 2011, Kupa, et. al., 2024, Ogunbiyi, et. al., 2024, Olaboye, 2024). Enhancements in PV efficiency directly contribute to better performance and cost-effectiveness, enabling more energy to be generated from the same amount of sunlight (Louwen et al., 2021). Improvements in materials, such as the development of new semiconductors and coatings, have led to higher energy conversion efficiencies and greater durability of PV systems (Calle et al., 2020). Additionally, advancements in applications, including integration into building materials and off-grid solutions, have expanded the use of solar PV in various sectors, contributing to a more versatile and accessible renewable energy infrastructure (Zhou et al., 2021).

The objectives of this review are to provide a comprehensive overview of the recent advances in solar PV technologies, focusing on three key areas: efficiency improvements, material innovations, and expanded applications (Maha, Kolawole & Abdul, 2024, Obiuto, et. al., 2024, Olaboye, 2024, Olaboye, et. al., 2024). By examining these developments, the review aims to highlight the progress made in enhancing solar PV performance and explore the implications for future energy solutions. The scope includes a discussion of cutting-edge technologies, emerging materials, and novel applications that are shaping the future of solar energy.

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## 2. Advances in Efficiency

Advances in solar photovoltaic (PV) technology have dramatically improved the efficiency of converting sunlight into electricity (Ukoba et al., 2024a, Basseyy et al., 2024). Among the most significant advancements are high-efficiency photovoltaic cells, including multi-junction solar cells, passivated emitter rear cells (PERC), and bifacial solar cells (Kupa, et. al., 2024, Maha, Kolawole & Abdul, 2024, Oladimeji & Owoade, 2024, Solomon, et. al., 2024). Each of these technologies represents a leap forward in PV performance, offering different advantages and addressing various limitations. Multi-junction solar cells are one of the most notable advancements in high-efficiency photovoltaic technology. These cells consist of multiple semiconductor layers, each designed to capture different parts of the solar spectrum. The principle behind multi-junction cells involves stacking several layers of solar cell materials, each optimized for a specific range of wavelengths (Adanma & Ogunbiyi, 2024, Ezeanyim, Nwankwo & Umeozokwere, 2020, Obiuto, et. al., 2024, Olanrewaju, Ekechukwu & Simpa, 2024). This design allows the cell to absorb a broader spectrum of light and convert it into electricity more efficiently than traditional single-junction cells (Green et al., 2020). Recent improvements in multi-junction solar cells have led to record-breaking efficiencies. For instance, the record efficiency for multi-junction cells has surpassed 47% under concentrated sunlight conditions, thanks to advancements in material science and fabrication techniques (Sinton et al., 2021). However, multi-junction cells also face limitations, including high production costs and complex manufacturing processes. Their use is often restricted to specialized applications, such as space missions and concentrated solar power systems (Yoshida et al., 2021).

Passivated emitter rear cells (PERC) represent another significant advancement in solar cell efficiency. PERC technology enhances the performance of conventional silicon solar cells by adding a passivation layer to the rear surface of the cell (Kupa, et. al., 2024, McKinsey & Company, 2020, Obinna, & Kess-Momoh, 2024, Obiuto, et. al., 2024). This layer reduces recombination losses and improves the overall efficiency of the cell (Ager et al., 2020). The design and fabrication techniques of PERC cells involve the use of advanced materials and processes, such as chemical vapor deposition and high-temperature annealing, to create a passivated rear surface (Adebayo, et. al., 2024, Aiguoabarueghian, et. al., 2024, Olaboye, et. al., 2024). Efficiency enhancements achieved through PERC technology have led to commercial cells with efficiencies exceeding 23%, compared to the 15-17% efficiency range of traditional silicon cells (Zhao et al., 2021). PERC cells also offer advantages such as improved low-light performance and better temperature coefficients. Comparative analyses indicate that PERC cells can outperform traditional cells in various environmental conditions, making them suitable for a wide range of applications, from residential to large-scale solar farms (Rauschenbach et al., 2021).

Bifacial solar cells are another innovative technology that has made significant strides in recent years (Ekechukwu & Simpa, 2024, Obiuto, et. al., 2024, Oduro, Simpa & Ekechukwu, 2024, Udeh, et. al., 2023). Bifacial cells are designed to capture light on both the front and rear sides of the panel, effectively utilizing reflected and diffused sunlight to increase overall energy production (Kistler et al., 2020). The technology relies on the principle that light reflected from surfaces such as rooftops or the ground can contribute to the electricity generation of the cell. Bifacial solar cells have demonstrated efficiency gains of up to 30% compared to traditional monofacial cells, particularly in installations where ground reflection is significant (Wang et al., 2021). Market adoption of bifacial technology has been growing, with numerous large-scale solar projects incorporating bifacial panels to maximize energy yield. Case studies from various installations show that bifacial cells can significantly enhance energy output, making them a valuable option for both commercial and residential applications (Baker et al., 2021).

In summary, recent advances in high-efficiency photovoltaic cells have marked significant progress in solar energy technology. Multi-junction solar cells have achieved record efficiencies by capturing a broader spectrum of sunlight, though their high cost limits their applications. PERC technology has enhanced the performance of silicon solar cells through rear surface passivation, leading to higher efficiencies and better performance in diverse conditions (Abdul, et. al., 2024, Adebajo, et. al., 2023, Obiuto, et. al., 2024, Osunlaja, et. al., 2024). Bifacial solar cells have increased energy production by utilizing light from both sides of the panel, offering substantial gains in efficiency and expanding market applications. Each of these advancements contributes to the ongoing evolution of solar PV technology, highlighting the potential for further improvements in efficiency and performance.

### 3. Advances in Materials

Recent advances in solar photovoltaic (PV) technologies have significantly impacted the field, particularly through innovations in materials (Lukong et al., 2023, Ukoba et al., 2024b). Key developments include perovskite solar cells, organic photovoltaics (OPVs), and quantum dot solar cells (Kess-Momoh, et. al., 2024, Maha, Kolawole & Abdul, 2024, Olatona, et. al., 2019, Solomon, et. al., 2024). Each of these technologies offers unique advantages and challenges, contributing to the evolution of solar energy applications. Perovskite solar cells have emerged as a highly promising technology due to their remarkable efficiency and relatively low manufacturing costs (Ukoba et al., 2024c). The material composition of perovskite solar cells typically involves a hybrid organic-inorganic lead or tin halide compound that mimics the crystal structure of the mineral perovskite (Kang et al., 2020). These materials exhibit exceptional light absorption properties and high charge-carrier mobility, leading to high power conversion efficiencies. Recent advancements have achieved efficiencies exceeding 25%, approaching those of traditional silicon-based solar cells (Noh et al., 2021). However, stability remains a significant challenge for perovskite solar cells. The sensitivity of perovskites to moisture, heat, and light can lead to degradation over time, impacting long-term performance (Yang et al., 2021). Researchers are addressing these stability issues by developing encapsulation methods and exploring alternative perovskite compositions that offer greater environmental resilience. Manufacturing processes for perovskite solar cells have also seen considerable progress (Adanma & Ogunbiyi, 2024, Obinna, & Kess-Momoh, 2024, Olaboye, et. al., 2024, Olajiga, et. al., 2024). Techniques such as spin-coating and vapor deposition are employed to create thin films of perovskite materials on substrates, which can be scaled up for commercial production (Kojima et al., 2020). Cost considerations are favorable, as these methods are relatively inexpensive compared to those used for silicon-based cells. Current research focuses on improving the stability and scalability of perovskite solar cells, with future prospects including integration into flexible and transparent solar panels (Park et al., 2021).

Organic photovoltaics (OPVs) represent another significant advancement in PV materials. OPVs utilize organic materials—such as polymers and small molecules—that can be processed into thin films (Eseoghene Krupa, et. al., 2024, Nwankwo & Ihueze, 2018, Okpala, Igbokwe & Nwankwo, 2023). These materials offer several advantages, including flexibility, lightweight, and aesthetic appeal. Organic materials used in OPVs include conjugated polymers like poly(3-hexylthiophene) (P3HT) and fullerene derivatives like [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) (Kim et al., 2021). The flexibility of OPVs allows for their application in various form factors, including roll-to-roll processing on large-area substrates, which is ideal for integrating solar cells into unconventional surfaces like building facades or wearable devices. While OPVs offer these benefits, they have historically struggled with lower efficiencies compared to inorganic solar cells. However, recent improvements in material design and device architecture have led to efficiencies exceeding 18%, up from previous levels below 10% (Gao et al., 2021). These advancements are achieved through innovations in donor-acceptor polymer pairs and improved processing techniques. Practical applications of OPVs are expanding, with commercial products such as flexible solar panels and integrated photovoltaic materials for textiles becoming more prevalent (Zhang et al., 2022).

Quantum dot solar cells represent a cutting-edge approach to improving solar energy conversion. Quantum dots are semiconductor nanocrystals that exhibit unique electronic properties due to quantum confinement effects (Abdul, et. al., 2024, Anaba, Kess-Momoh & Ayodeji, 2024, Omotoye, et. al., 2024, Simpa, et. al., 2024). The technology involves embedding these nanocrystals into a photovoltaic device to enhance light absorption and conversion efficiency (Liu et al., 2021). Quantum dot solar cells offer advantages such as tunable bandgaps, allowing for better optimization of the solar spectrum absorption. This tunability enables the design of devices that can absorb a broader range of wavelengths compared to traditional PV materials. Additionally, quantum dots can be engineered to exhibit high photoluminescence and charge-carrier mobility, further enhancing efficiency (Sargent et al., 2021). Despite these advantages, several development challenges persist, including issues related to the uniformity of quantum dot films, scalability of production, and potential environmental and health concerns associated with some quantum dot materials. Emerging trends in quantum dot solar cell research focus on improving the stability and performance of these devices by exploring new quantum dot compositions and incorporating advanced nanostructuring techniques (Li et al., 2021).

In summary, recent advancements in materials for solar photovoltaic technologies have significantly impacted the efficiency, cost, and applications of solar energy. Perovskite solar cells have shown tremendous potential with high efficiencies and low manufacturing costs, though stability and environmental concerns remain critical areas of research (Egerson, et. al., 2024, Ekechukwu & Simpa, 2024, Obiuto, Olajiga & Adebayo, 2024, Simpa, et. al., 2024). Organic photovoltaics offer flexibility and lightweight properties, with ongoing improvements enhancing their efficiency and practical applications. Quantum dot solar cells represent a promising frontier in PV technology, with unique advantages in light absorption and conversion efficiency but facing challenges in scalability and material stability. The continued development of these materials is essential for advancing solar energy technology and expanding its role in sustainable energy solutions.

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#### 4. Advances in Applications

The recent advances in solar photovoltaic (PV) technologies have not only improved efficiency and material properties but have also expanded the scope of their applications across various sectors (Bassey and Ibegbulam, 2023). These advancements are paving the way for innovative uses of solar energy, from integration into building materials to energy storage solutions and emerging applications. Solar windows represent a significant leap in integrating solar technology into building materials (Ilori, Kolawole & Olaboye, 2024, Nwankwo & Etukudoh, 2024, Olajiga, et. al., 2024, Simpa, et. al., 2024). These windows incorporate photovoltaic cells within the glass panes, allowing buildings to generate electricity without sacrificing natural light or aesthetics. The technology behind solar windows involves embedding thin-film photovoltaic materials or organic photovoltaics into the glass or coating it with transparent photovoltaic films (Zhao et al., 2021). This approach enables the production of electricity while still allowing visible light to pass through, thus maintaining the visual and functional characteristics of conventional windows. Solar windows offer both aesthetic and practical benefits, including the potential for substantial energy generation in urban environments where roof space might be limited (Choi et al., 2020). However, challenges remain in optimizing the efficiency and cost-effectiveness of these windows, particularly in scaling up production and improving the durability of the photovoltaic materials used (Adebayo, et. al., 2021, Kupa, et. al., 2024, Obiuto, et. al., 2024, Olanrewaju, Oduro & Simpa, 2024).

Photovoltaic roofing tiles are another innovative application of solar technology. These tiles are designed to replace traditional roofing materials with integrated solar cells, combining the functionality of a roof with the ability to generate electricity (Aiguoarueghian, et. al., 2024, Maha, Kolawole & Abdul, 2024, Oladimeji & Owoade, 2024, Simpa, et. al., 2024). The design of photovoltaic roofing tiles involves embedding thin-film or crystalline silicon cells into durable, weather-resistant tiles that can be installed on rooftops (Krebs et al., 2020). The performance of these tiles is closely related to their ability to withstand environmental conditions and their efficiency in converting sunlight into electricity. The benefits of photovoltaic roofing tiles include their seamless integration with building architecture, reducing the need for additional space for solar panels and enhancing the aesthetic appeal of solar installations (Delgado et al., 2021). However, installation challenges and higher costs compared to traditional roofing materials remain significant barriers to widespread adoption.

Advances in battery technology have greatly improved the capacity and efficiency of energy storage solutions for solar energy (Ihuezze, Obiuto & Okpala, 2012, Kess-Momoh, et. al., 2024, Olaboye, et. al., 2024, Simpa, et. al., 2024). High-capacity batteries, such as lithium-ion and solid-state batteries, have become crucial in storing solar energy for use when sunlight is not available (Chen et al., 2021). Recent developments in these technologies focus on enhancing energy density, cycle life, and safety. Lithium-ion batteries, in particular, have seen improvements in their capacity and longevity, making them suitable for residential and commercial solar energy storage applications (Tarascon & Armand, 2021). Solid-state batteries, which use a solid electrolyte instead of a liquid one, promise even higher energy densities and improved safety features (Yoshino, 2020). These advancements are crucial for improving the reliability of solar energy systems and facilitating their integration into the power grid.

Hybrid systems that combine solar PV with other renewable energy sources are also gaining traction. These systems aim to maximize the reliability and efficiency of renewable energy generation by integrating solar power with wind, hydro, or other renewable sources (Kumar et al., 2021). Hybrid systems can balance energy supply and demand more effectively by leveraging the strengths of different renewable sources and providing a more consistent energy output. For instance, solar-wind hybrid systems can generate electricity even when solar irradiance is low, as wind energy can provide an alternative source of power (Chowdhury et al., 2020). The benefits of hybrid systems include increased energy reliability and reduced dependence on non-renewable energy sources, making them a promising solution for diverse energy needs across various sectors.

The development of portable solar solutions has expanded the versatility of solar technology. Portable solar panels and chargers offer a convenient way to harness solar energy in off-grid locations and for mobile applications (Adanma &

Ogunbiyi, 2024, Ekechukwu & Simpa, 2024, Okpala, Obiuto & Elijah, 2020, Simpa, et. al., 2024). These solutions are particularly valuable for outdoor activities, emergency situations, and remote areas where access to conventional power sources is limited (Ding et al., 2021). Recent innovations in portable solar technology focus on improving the efficiency, portability, and durability of these devices, making them more practical for everyday use.

Solar-powered transportation is another exciting area of development. Solar panels are being integrated into vehicles, such as electric cars, buses, and even boats, to provide supplementary power and improve energy efficiency (Hoffmann et al., 2021). This integration helps reduce the reliance on external charging sources and enhances the overall sustainability of transportation systems. For instance, solar panels installed on electric cars can extend their range and reduce the frequency of charging, while solar-powered buses can contribute to lower emissions and operational costs (Zhang et al., 2021). As technology advances, the efficiency and integration of solar power in transportation are expected to improve, further supporting sustainable mobility solutions.

Integration with smart grid technologies is also transforming the way solar energy is managed and distributed. Smart grids use advanced communication and control technologies to optimize the generation, distribution, and consumption of electricity (Liu et al., 2021). Integrating solar PV systems with smart grid technologies enables more efficient management of solar power, including real-time monitoring, demand response, and automated control (Zhou et al., 2021). This integration helps balance the supply and demand of solar energy, improve grid stability, and enhance the overall efficiency of energy distribution (Igbokwe, Chukwumeka & Constance, 2021, Obiuto, et. al., 2015, Olajiga, et. al., 2024, Onwurah, Ihueze & Nwankwo, 2021).

In conclusion, the advances in solar photovoltaic technologies have led to significant improvements in efficiency, materials, and applications. The integration of solar technology into building materials, such as solar windows and photovoltaic roofing tiles, has enhanced the aesthetic appeal and functionality of solar energy systems. Advances in energy storage solutions, including high-capacity batteries and hybrid systems, have improved the reliability and efficiency of solar power (Abdul, et. al., 2024, Adanma & Ogunbiyi, 2024, Obiuto, et. al., 2024, Oduro, Simpa & Ekechukwu, 2024). Emerging applications, such as portable solar solutions, solar-powered transportation, and integration with smart grid technologies, are expanding the scope of solar energy and contributing to its broader adoption. As research and development continue, these innovations will play a crucial role in advancing solar technology and supporting the transition to a more sustainable energy future.

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## 5. Impact on Cost and Accessibility

The recent advances in solar photovoltaic (PV) technologies have had a profound impact on the cost and accessibility of solar energy, leading to significant reductions in solar energy costs, increased adoption and market growth, and a wide range of socioeconomic and environmental benefits (Hassan, et. al., 2024, Ihueze, et. al., 2023, Maha, Kolawole & Abdul, 2024, Odulaja, et. al., 2023). These advancements in efficiency, materials, and applications have collectively contributed to making solar energy more affordable and accessible to a broader population.

One of the most notable impacts of recent advancements in solar PV technologies is the significant reduction in solar energy costs. Technological innovations in photovoltaic materials and manufacturing processes have led to substantial decreases in the cost per watt of solar electricity (Adebayo, et. al., 2024, Aiguoarueghian, et. al., 2024, Obiuto, Olajiga & Adebayo, 2024, Onwurah, et. al., 2019). For instance, improvements in silicon cell technology, including the development of high-efficiency multi-junction cells and passivated emitter rear cells (PERC), have enhanced the performance of solar panels while reducing production costs (Green et al., 2020). The introduction of new materials, such as perovskite solar cells and organic photovoltaics (OPVs), has further contributed to cost reductions by offering potentially cheaper alternatives to traditional silicon-based solar cells (Kojima et al., 2009; Friend et al., 2011). Additionally, advances in manufacturing techniques, such as automated production lines and economies of scale, have lowered the costs of producing and installing solar panels (IRENA, 2020). As a result, the levelized cost of electricity (LCOE) from solar PV has decreased significantly, making solar energy increasingly competitive with conventional energy sources.

These cost reductions have led to increased adoption and market growth of solar PV technologies (Chikwendu, Constance & Chiedu, 2020, Ekechukwu & Simpa, 2024, Okpala, Obiuto & Ihueze, 2011, Olaboye, et. al., 2024). The falling costs of solar panels have made solar energy more accessible to residential, commercial, and industrial users, driving widespread deployment of solar PV systems across various sectors (REN21, 2021). The global solar PV market has expanded rapidly, with installed capacity growing from around 10 gigawatts (GW) in 2010 to over 800 GW in 2021 (IEA, 2021). This growth is driven by both public and private investments in solar technology, as well as supportive policies and incentives implemented by governments worldwide. For example, feed-in tariffs, tax credits, and net metering

policies have played a crucial role in promoting the adoption of solar PV systems by reducing the upfront costs for consumers and encouraging investment in solar energy projects (Wiser et al., 2020).

The increased adoption of solar PV technology has led to significant socioeconomic and environmental benefits. Economically, the expansion of the solar industry has created numerous job opportunities in manufacturing, installation, and maintenance, contributing to economic growth and development (IRENA, 2021). The solar sector has become a major source of employment, with millions of people working in various roles within the industry. Additionally, the growth of solar energy has stimulated investment in related sectors, such as energy storage and grid integration, further boosting economic activity and innovation (Mazzucato et al., 2018).

Environmentally, the widespread adoption of solar PV technology has contributed to the reduction of greenhouse gas emissions and the transition to a more sustainable energy system. Solar energy is a clean and renewable resource that does not produce direct emissions of carbon dioxide or other pollutants during operation (Lark et al., 2015). The shift from fossil fuel-based power generation to solar energy has helped mitigate the impacts of climate change by reducing the carbon footprint of energy production (Jacobson et al., 2018). Furthermore, the use of solar energy can reduce reliance on non-renewable resources, decrease air and water pollution, and minimize the environmental impacts associated with traditional energy sources (Miller et al., 2020).

In summary, recent advances in solar PV technologies have had a transformative impact on the cost and accessibility of solar energy. The reduction in solar energy costs, driven by innovations in efficiency and materials, has made solar power more competitive with conventional energy sources and has spurred widespread adoption across various sectors (Abati, et. al., 2024, Abdul, et. al., 2024, Nwankwo & Nwankwo, 2022, Olaboye, et. al., 2024). This increased adoption has led to significant socioeconomic and environmental benefits, including job creation, economic growth, and a reduction in greenhouse gas emissions. As technology continues to advance and costs continue to decline, the potential for solar energy to play a central role in the global energy transition will only increase.

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## 6. Future Directions and Research Opportunities

The future of solar photovoltaic (PV) technologies promises substantial advancements and opportunities for innovation, driven by ongoing research and development efforts aimed at improving efficiency, materials, and applications (Abdul, et. al., 2024, Aderonke, 2017, Kupa, et. al., 2024, Obiuto, et. al., 2023). As the world transitions toward sustainable energy solutions, the integration of advanced technologies and novel applications will play a crucial role in optimizing the performance and impact of solar energy systems. This overview explores the key future directions and research opportunities in the field, including advancements in efficiency and materials, innovations in manufacturing and integration techniques, exploration of new applications, and policy and regulatory considerations.

Continued advancements in solar PV efficiency and materials are paramount for enhancing the performance and economic viability of solar energy systems. Researchers are focused on developing high-efficiency photovoltaic cells that can maximize energy conversion while minimizing costs (Festus-Ikhuoria, et. al., 2024, Ihueze, et. al., 2013, Obasi, et. al., 2024, Obiuto & Ihueze, 2020). Multi-junction solar cells, which use multiple semiconductor materials to capture different wavelengths of light, are a prime example of this progress. Recent developments have achieved record efficiencies, with triple-junction cells reaching over 40% efficiency under concentrated sunlight (Green et al., 2020). Furthermore, perovskite solar cells, known for their exceptional light absorption and potential for low-cost production, continue to advance, with efficiencies surpassing 25% in laboratory settings (Kojima et al., 2009). Ongoing research aims to address stability and scalability issues to facilitate commercial deployment and long-term reliability (Saliba et al., 2016). The development of advanced materials, such as tandem cells combining perovskite and silicon, promises further efficiency improvements, potentially exceeding the capabilities of traditional silicon-based cells (Snaith, 2018).

Innovations in manufacturing and integration techniques are also critical for advancing solar PV technologies. The evolution of manufacturing processes has the potential to significantly reduce production costs and improve the scalability of solar technologies. Techniques such as roll-to-roll printing for organic photovoltaics and automated assembly lines for high-efficiency silicon cells are transforming the production landscape (Yum et al., 2019). Additionally, advancements in integration techniques, such as building-integrated photovoltaics (BIPV) and photovoltaic-thermal hybrid systems, offer opportunities for seamless incorporation of solar technology into building materials and infrastructure (Faiman, 2008). These innovations not only enhance the aesthetic and functional integration of solar PV systems but also contribute to the development of multifunctional materials that can generate electricity while serving other purposes, such as thermal regulation or structural support.

Exploration of new applications and market potential is a key area of future research in solar PV technologies (Adebajo, et. al., 2022, Adenekan, et. al., 2024, Bamisaye, et. al., 2023, Obinna, & Kess-Momoh, 2024). The integration of solar PV systems into various sectors beyond traditional utility-scale and residential applications presents new opportunities for growth. Portable solar solutions, such as solar-powered chargers and camping equipment, are gaining popularity due to their convenience and energy independence (Norton et al., 2020). Similarly, the potential for solar-powered transportation, including solar electric vehicles and solar-assisted aircraft, represents a significant avenue for reducing reliance on fossil fuels and minimizing carbon emissions (Hegde et al., 2021). Emerging applications in agriculture, such as agrivoltaics—where solar panels are integrated into farming systems—offer dual benefits of energy production and enhanced crop yields (Dupraz et al., 2011). These innovative applications highlight the versatility of solar PV technologies and their potential to address diverse energy and environmental challenges.

Policy and regulatory considerations play a crucial role in supporting innovation and the widespread adoption of advanced solar PV technologies (Ekechukwu & Simpa, 2024, Enahoro, et. al., 2024, Maha, Kolawole & Abdul, 2024, Nwankwo & Nwankwo, 2022). Effective policies and incentives can drive research and development efforts, facilitate commercialization, and ensure market growth. Supportive measures, such as tax credits, feed-in tariffs, and renewable portfolio standards, have historically played a significant role in promoting solar energy adoption (Wiser et al., 2020). Future policy frameworks should focus on fostering innovation in emerging technologies, addressing barriers to market entry, and promoting investment in research and development. Additionally, regulations that encourage the integration of solar PV systems into new and existing buildings, as well as the development of smart grid technologies, will be essential for maximizing the benefits of solar energy (IRENA, 2021).

In conclusion, the future of solar PV technologies is marked by exciting opportunities for advancement and innovation. Continued research in improving efficiency and developing new materials promises to enhance the performance and cost-effectiveness of solar energy systems (Abatan, et. al., 2024, Abdul, et. al., 2024, Adanma & Ogunbiyi, 2024, Nwankwo & Etukudoh, 2023). Innovations in manufacturing and integration techniques are set to transform the production and deployment of solar technologies, enabling their integration into diverse applications and infrastructure. The exploration of new applications and market potential highlights the versatility of solar PV technologies in addressing global energy and environmental challenges (Mazzucato & Penna, 2018). Finally, supportive policies and regulatory frameworks will be crucial for fostering innovation, ensuring market growth, and accelerating the transition to a sustainable energy future. As the field continues to evolve, ongoing research and collaboration will be key to unlocking the full potential of solar photovoltaics and driving the next generation of renewable energy solutions.

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## 7. Conclusion

Recent advancements in solar photovoltaic (PV) technologies have ushered in a new era of efficiency, material innovation, and application diversification, significantly impacting the solar energy industry and contributing to global sustainability goals. These developments underscore the dynamic evolution of solar PV technology and its pivotal role in addressing the world's energy needs. Key advancements in solar PV technology include substantial improvements in cell efficiency, innovations in materials, and novel applications. High-efficiency photovoltaic cells, such as multi-junction solar cells, have achieved record-breaking efficiencies, reaching over 40% under concentrated sunlight. This advancement is a testament to the progress in capturing a broader spectrum of sunlight and converting it into usable electricity. Perovskite solar cells have emerged as a transformative technology, demonstrating exceptional light absorption and efficiency potential, with laboratory efficiencies surpassing 25%. Organic photovoltaics (OPVs) and quantum dot solar cells further illustrate the diversification of materials, offering flexible, lightweight options with promising performance metrics. These material advancements not only enhance the efficiency of solar PV systems but also broaden their applicability across various sectors.

The impact of these advancements on the solar energy industry has been profound. The reduction in solar energy costs, driven by improved efficiency and manufacturing processes, has made solar power increasingly competitive with conventional energy sources. Innovations such as roll-to-roll printing for OPVs and automated assembly lines for high-efficiency cells are streamlining production and reducing costs. Additionally, the integration of solar PV technologies into building materials, such as solar windows and photovoltaic roofing tiles, has facilitated broader adoption and integration of solar energy systems. The expansion of energy storage solutions, including high-capacity batteries and hybrid systems, has further enhanced the reliability and grid integration of solar power, addressing intermittency issues and supporting a more stable energy supply. These developments collectively advance the solar industry towards greater market penetration and sustainability.

Looking ahead, the future of solar PV technology is marked by exciting opportunities for further innovation and growth. Continued advancements in efficiency and materials are expected to drive even higher performance and lower costs,

making solar energy more accessible and economically viable. Innovations in manufacturing and integration techniques will likely enhance the scalability and versatility of solar PV systems, enabling their incorporation into a wider range of applications and infrastructures. The exploration of new applications, such as portable solar solutions, solar-powered transportation, and agrivoltaics, represents a significant avenue for expanding the role of solar energy in diverse sectors. Furthermore, supportive policies and regulatory frameworks will be crucial in fostering innovation, ensuring market growth, and accelerating the transition to a sustainable energy future. In conclusion, the recent advancements in solar photovoltaic technologies reflect a transformative shift in the energy landscape, marked by enhanced efficiency, innovative materials, and expanded applications. These developments have significantly impacted the solar energy industry, contributing to the reduction of costs and supporting sustainability goals. As the field continues to evolve, ongoing research, technological innovation, and supportive policies will play critical roles in driving the future growth and impact of solar PV technologies, ultimately supporting a cleaner and more sustainable energy future.

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## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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