Review

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Review

Advancements in Photovoltaic Cell Materials: Silicon, Organic, and Perovskite Solar Cells

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Abstract: The evolution of photovoltaic cells is intrinsically linked to advancements in the materials from which they are fabricated. This review paper provides an in-depth analysis of the latest developments in silicon-based, organic, and perovskite solar cells, which are at the forefront of photovoltaic research. We scrutinize the unique characteristics, advantages, and limitations of each material class, emphasizing their contributions to efficiency, stability, and commercial viability. Silicon-based cells are explored for their enduring relevance and recent innovations in crystalline structures. Organic photovoltaic cells are examined for their flexibility and potential for low-cost production, while perovskites are highlighted for their remarkable efficiency gains and ease of fabrication. The paper also addresses the challenges of material stability, scalability, and environmental impact, offering a balanced perspective on the current state and future potential of these material technologies.

Keywords: photovoltaic cells; silicon-based solar cells; organic-based cells; perovskite solar cells

1. Introduction

The journey of photovoltaic (PV) cell technology is a testament to human ingenuity and the relentless pursuit of sustainable energy solutions. From the early days of solar energy exploration to the sophisticated systems of today, the evolution of PV cells has been marked by groundbreaking advancements in materials and manufacturing processes. The initial phase of solar cell development was characterized by the use of crystalline silicon, a material that has maintained its prominence due to its proven efficiency and durability [1]. The progression from the initial 15% efficiency in the 1950s to the current levels nearing 28% epitomizes the significant strides made in enhancing solar cell performance [2]. This evolution is a clear indicator of how material advancements have been instrumental in propelling the solar industry forward.

The significance of material advancements in solar cell technology extends beyond mere efficiency improvements. In the context of escalating environmental concerns and the global imperative for renewable energy sources, solar energy emerges as a beacon of hope. The notable reduction in solar energy generation costs over the past decade is a direct consequence of advancements in materials, alongside innovations in technology and enhanced panel efficiencies [1]. The pursuit of new materials, novel concepts, and innovative approaches in solar cell development is central to achieving high efficiencies at reduced costs. This endeavor is not just about enhancing technology; it is about democratizing access to solar energy, making it a feasible option for a broader segment of the global population [3].

With that in mind, this review aims to provide an analysis of the advancements in photovoltaic cell materials, with a particular focus on silicon-based, organic, and perovskite solar cells. Each of these materials brings unique attributes and challenges to the table, collectively shaping the current and future landscape of solar energy technology. The review will delve into the historical context of these materials, explore recent innovations, and project future prospects. It will offer insights into their efficiency, commercial viability, and environmental implications. A comparative analysis across these material classes will shed light on their efficiency, stability, and scalability, underscoring the specific challenges and potential solutions inherent to each type. In addition to a technical analysis, the review will address broader implications of these material advancements. Topics such as material stability, scalability, manufacturing techniques, and the environmental impact of solar cell production will be thoroughly examined. The objective is to present a holistic view of the current state of PV technology, while also identifying emerging trends and potential breakthroughs that could significantly influence the future of solar energy. Furthermore, policy and market dynamics will be discussed, exploring the potential of integrating solar cells into the global energy mix and the factors that will drive their widespread adoption.

2. Silicon-based solar cells

2.1. Historical Context and Enduring Relevance

Silicon-based solar cells have not only been the cornerstone of the photovoltaic industry for decades but also a symbol of the relentless pursuit of renewable energy sources. The journey began in 1954 with the development of the first practical silicon solar cell at Bell Labs, marking a pivotal moment in the history of solar energy [4]. This invention, achieving an efficiency of about 6%, was a significant leap from earlier solar energy attempts, which were largely inefficient and impractical for widespread use [4].

The dominance of silicon in the photovoltaic market can be attributed to several key factors. Firstly, silicon is the second most abundant element in the Earth's crust, making it readily available for solar cell production [5]. This abundance has been a critical factor in the widespread adoption and scalability of silicon-based solar cells. Secondly, the semiconductor properties of silicon make it an ideal material for converting sunlight into electricity. Its bandgap is well-suited for absorbing a broad range of the solar spectrum, thereby maximizing energy conversion efficiency [5].

Over the years, the manufacturing processes for silicon solar cells have undergone significant evolution, transitioning from simple p-n junctions to more complex designs that enhance light absorption and minimize energy losses [6]. The development of crystalline silicon technology, both in monocrystalline and polycrystalline forms, has been central to this evolution. Monocrystalline silicon cells, known for their higher efficiency due to their uniform crystalline structure, have become increasingly popular in high-performance applications [6]. On the other hand, polycrystalline silicon cells, made from multiple silicon crystals, offer a more cost-effective solution, albeit with slightly lower efficiency [6].

The 1970s and 1980s marked significant milestones in the development of silicon-based solar cells, with the introduction of new technologies such as surface passivation and anti-reflective coatings [7]. These innovations were crucial in enhancing the efficiency and durability of silicon solar cells, propelling them to the forefront of solar energy solutions. By the late 20th century, silicon solar cells had firmly established themselves as the standard in the photovoltaic industry, with efficiencies surpassing 15% [7].

In the 21st century, the focus shifted towards further improving efficiency and reducing the cost of silicon solar cells. The introduction of PERC (Passivated Emitter and Rear Cell) technology and the development of bifacial solar cells are examples of innovations that have significantly boosted the performance of silicon-based solar cells [8]. These advancements have not only improved efficiency but also extended the lifespan of solar panels, making them more appealing for both residential and commercial applications [8].

2.2. Recent Innovations in Crystalline Silicon Structures

Crystalline silicon (c-Si) solar cells, recent years have been marked by groundbreaking innovations aimed at transcending the traditional efficiency limits. These advancements are pivotal in sustaining silicon's competitiveness in the rapidly evolving photovoltaic market. A notable

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example is the work by Zhang *et al.* [9], which delves into the realm of perovskite/crystalline silicon tandem solar cells. Their research systematically reviews the latest progress in this area, focusing on the structure of perovskite top cells, intermediate interconnection layers, and crystalline silicon bottom cells. They emphasize the importance of optical and electrical engineering in each layer, highlighting how these aspects are integral throughout the device preparation process. This study is significant as it demonstrates the potential of tandem cells to achieve efficiencies above 30%, a remarkable feat in solar cell technology [9].

Another significant contribution comes from Singh *et al.* [10] that presents the creation of c-Si bottom cells using high-temperature polycrystalline-SiOx (poly-SiOx) carrier-selective passivating contacts (CSPCs), a promising approach for high-efficiency tandem cells (see Figure 1). The research involved tuning ultra-thin SiOx layers and optimizing the passivation of both p-type and n-type doped poly-SiOx CSPCs, with a focus on p-type doped poly-SiOx CSPC on textured interfaces through a two-step annealing process. The integration of these optimized bottom cells into four-terminal (4T) and two-terminal (2T) tandem structures led to a conversion efficiency of 28.1% and 23.2%, respectively.

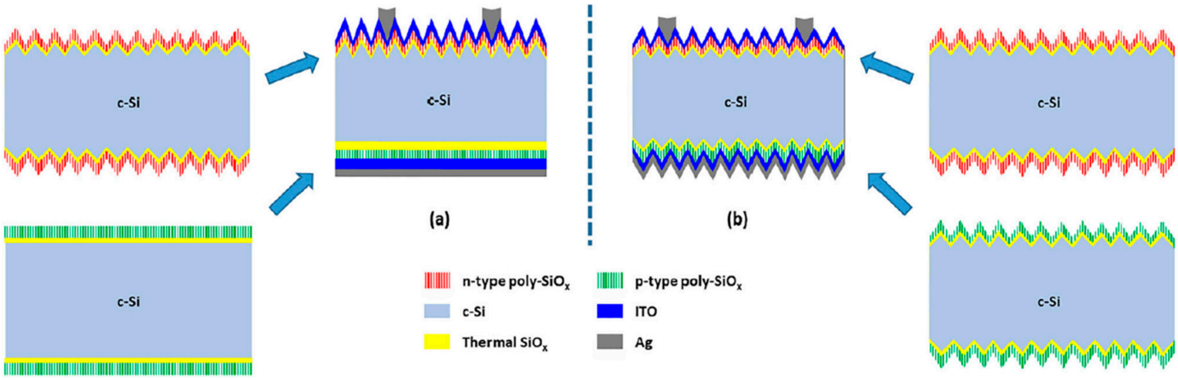

Figure 1. (a) A single-side textured (SST) poly-SiOx passivated crystalline silicon (c-Si) solar cell, featuring symmetric n-type doped poly-SiOx on a double-side textured (DST) substrate at the top and symmetric p-type doped poly-SiOx on a double-side polished (DSP) substrate at the bottom; (b) A DST poly-SiOx passivated c-Si solar cell, equipped with symmetric n-type doped poly-SiOx on the top and symmetric p-type doped poly-SiOx, both situated on DST substrates. 'ITO' refers to indium tin oxide. Reprinted with permission from ref. [10], Copyright 2023, Progress in Photovoltaics: Research and Applications.

Furthering the innovation in thin crystalline silicon solar cells, the study by Xie *et al.* [11] reported significant advancements in the efficiency of thin crystalline silicon (c-Si) solar cells, a promising alternative to the traditional, thicker c-Si solar cells, due to their cost-effectiveness and enhanced flexibility. Their approach involved the implementation of advanced cell design optimizations, focusing on a prototype with a thickness of 20 μm. The results of their optimizations are notable: the short-circuit current density increased from 34.3 mA/cm^2 to 38.2 mA/cm^2, the open-circuit voltage improved from 632 mV to 684 mV, and the fill factor exhibited an enhancement from 76.2% to 80.8%. These improvements collectively resulted in a significant absolute efficiency increase of 4.6%, elevating the overall efficiency from 16.5% to 21.1%. The experimental outcomes were corroborated by device simulations, providing a comprehensive understanding of the efficiency enhancements achieved through our optimized design strategies.

Additionally, the work by Yamamoto *et al.* [12] present a 29.2% power conversion efficiency in a two-terminal (2T) perovskite/crystalline Si heterojunction tandem solar cell, using a 145 μm thick industrial Czochralski (CZ) Si wafer. This achievement, a notable advancement in 2T-tandem solar cell technology, is primarily due to structural optimizations like improved surface passivation of the perovskite layer and advanced light management techniques. Addressing the industrial application challenges, the authors also explored the potential of four-terminal (4T) tandem solar cells as a viable alternative. Leveraging on their foundational technologies, which have already realized a 22.2%

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efficient perovskite single junction solar cell module and a 26% efficient heterojunction back-contact solar cell, they demonstrated the feasibility of achieving around 30% conversion efficiency in 4T perovskite/heterojunction crystalline Si tandem solar cells, with a significantly reduced cell size of approximately 64 cm^2.

2.3. Efficiency and Commercial Viability Analysis

The efficiency of silicon-based solar cells has seen a remarkable increase over the years, with commercial monocrystalline silicon solar cells now achieving efficiencies of over 20% [13]. This improvement is largely attributed to the incorporation of advanced materials and innovative cell designs. A significant contribution to this advancement is the widespread adoption of passivated emitter and rear cell (PERC) technology, which offers higher efficiency and lower production costs compared to traditional c-Si cells [13].

J. Müller's work [13] highlights the significant improvements in cost reduction and conversion efficiency increase achieved in large-scale industrial production over the last decade. This progress has made photovoltaics (PV) cost-competitive with other electricity generation methods. Müller discusses the key concepts and methods based on Hanwha Q CELLS' experience, including the fast transfer of cell technologies from laboratory to production and accelerated progress in cell efficiency, quality, and reliability. The study notes that cell conversion efficiency has increased by 0.5%abs per year, with average cell conversion efficiencies exceeding 20% using boron-doped p-type multicrystalline (mc-Si) and 22% using Czochralski-grown silicon (Cz-Si) substrates [13].

In an effort to reduce the cost of photovoltaic (PV) power generation, Irie and group [14] focused on three primary objectives: lowering the manufacturing costs of PV modules, improving the efficiencies of cells and modules, and extending the long-term output power warranty of PV modules. They developed a high-quality and cost-effective seed-cast wafer, which achieved an efficiency of 20.54% with passivated emitter and rear cells (PERCs). Additionally, the authors addressed module longevity concerns by identifying and mitigating key degradation modes, including ohmic contact degradation and potential-induced degradation (PID). To assess the durability of their modules under real-world conditions, they conducted extensive stress tests, simulating environments with ultraviolet light, heat, humidity, and electrical potential differences. These tests, including those on field-aged modules, demonstrated that their technology can ensure a module lifetime exceeding 30 years, with resistance to PID, particularly in the context of Japanese domestic environments, marking a significant advancement in PV module technology.

Augusto and colleagues [15] reported significant advancements in silicon solar cell technologies, with several technologies now surpassing or nearing 26% efficiency. This progress is largely due to the integration of dielectric and amorphous silicon-based passivation layers and the reduction of metal/silicon contact areas, leading to surface saturation current densities below 3 fA cm^{-2}. They found that in passivated contact solar cells, the majority of recombination at open-circuit is due to fundamental processes like Auger and radiative recombination, accounting for over three-quarters of total recombination. However, this fraction decreases significantly at the maximum power point, where surface and bulk Shockley–Read–Hall recombination mechanisms become prevalent. Their study emphasizes the importance of reducing bulk recombination and enhancing surface passivation to improve solar cell performance under operational conditions. The authors demonstrated that thinner wafers and lower surface saturation current densities below 1 fA cm^{-2} are crucial for increasing the practical efficiency limit by up to 0.6% absolute. For high-quality n-type bulk silicon with a minority-carrier lifetime of 10 ms, they identified an optimal wafer thickness range of 40–60 μm, significantly different from the previously assumed 110 μm. Within this thickness range, achieving surface saturation current densities near 0.1 fA cm^{-2} is essential to approach the fundamental efficiency limit. Experimentally, they have achieved surface saturation currents below 0.5 fA cm^{-2} on pi/CZ/in structures across a range of wafer thicknesses (35–170 μm), indicating the potential to attain open-circuit voltages close to 770 mV and bandgap-voltage offsets near 350 mV. Finally, the authors suggest using the bandgap-voltage offset as a comparative metric for evaluating the quality of champion experimental solar cells across various commercially relevant photovoltaic cell absorbers and architectures.

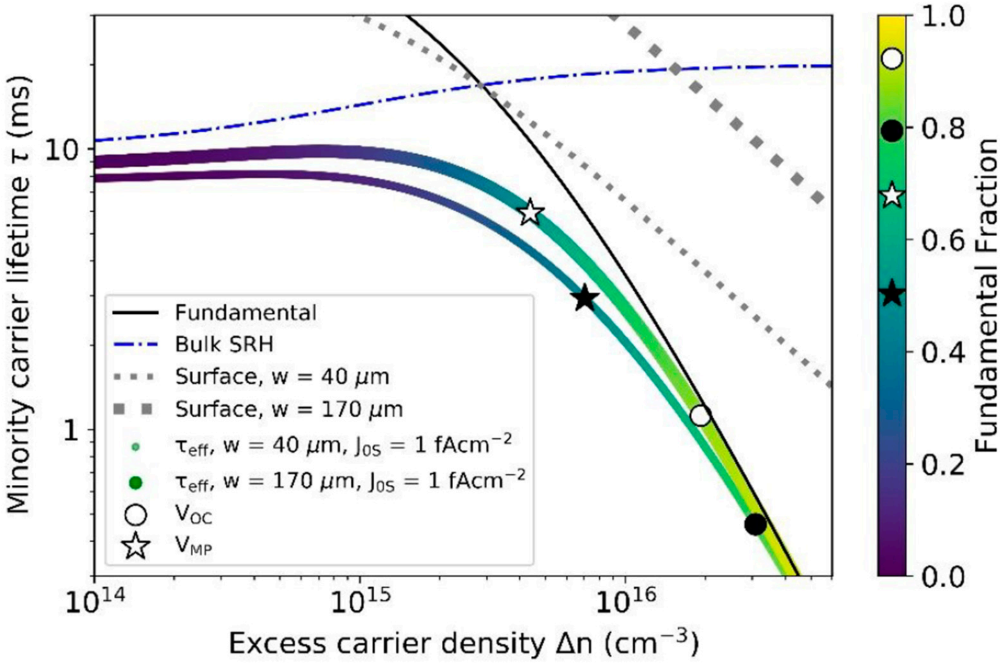

Figure 2. Model for the effective minority-carrier lifetime in structures using n-type wafers of thicknesses 170 μm and 40 μm. These wafers are characterized by a bulk Shockley-Read-Hall (SRH) lifetime of 10 ms, a bulk resistivity of 3.55 Ωcm (equivalent to a dopant concentration of 1.3×10^{15} cm^{-3}), and a combined surface recombination velocity (J0S) of 1 $fAcm^{-2}$ from both surfaces. In the accompanying plots, various curves are used to distinguish between different recombination mechanisms. A color bar is included to denote the proportion of fundamental recombination, which encompasses both Auger and radiative processes. The generation current for these wafers is determined based on the Lambertian light trapping limit appropriate for each specific thickness. Additionally, markers within the color bar highlight the proportions of fundamental recombination at the points of maximum power and during open-circuit injections. Reprinted with permission from ref. [15], Copyright 2020, Journal of Materials Chemistry A.

Mao's research [16] explores the dominance and evolution of crystalline silicon solar cells in the photovoltaic market, focusing on the transition from polycrystalline to more cost-effective monocrystalline silicon cells, driven by advancements in silicon materials and wafer technologies. The study highlights the increasing conversion efficiency of monocrystalline cells, particularly through high-efficiency technologies like Passivated Emitter and Rear Cell (PERC). They analyzed and forecast the future of solar cell industrialization, concluding that N-type Tunnel Oxide Passivated Contact (TOPCon) solar cell technology is poised to become the next mainstream technology after PERC. Additionally, the authors identified Interdigitated Back Contact (IBC) structures and selective all-passive contact technologies as viable paths to achieving high-efficiency solar cells. This synthesis of efficiency, cost, and technological compatibility underlines the potential for the industrialization of cost-effective, high-efficiency monocrystalline silicon solar cells.

In terms of commercial viability, silicon solar cells continue to benefit from economies of scale and well-established supply chains. The cost of silicon PV cells has decreased significantly, making solar energy more competitive with traditional energy sources. However, the market also faces challenges such as the need for more sustainable manufacturing processes and the management of end-of-life solar panels.

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2.4. Challenges and Future Outlook

Despite their success, silicon-based solar cells face several challenges. One of the primary challenges is the nearing of the theoretical efficiency limit for single-junction silicon cells [17]. This limitation has necessitated the exploration of new designs, such as tandem cells. Rong *et al.* [17] review the progress in perovskite solar cells (PSCs), which are increasingly being considered for tandem applications with silicon cells. They note that PSCs have achieved lab-scale power conversion efficiencies of 23.3%, rivaling commercial multicrystalline silicon solar cells. However, stability and upscaling for mass production remain critical concerns for the commercialization of PSCs [17].

Environmental concerns associated with the production and disposal of silicon PV cells are also significant challenges. Lunardi *et al.* [18] examined the expanding role of solar photovoltaics (PV) as a sustainable and low-carbon electricity source, focusing on life cycle assessment (LCA) of current and emerging solar cell technologies, predominantly silicon wafer cells and prospective silicon/thin-film tandem devices. They demonstrated that efficiency enhancements, especially through the integration of atomic hydrogen in silicon wafers, offer significant environmental benefits, justifying the additional inputs required. The study also underscores the importance of top-cell material stability in tandem solar cells to prolong the lifespan of the underlying silicon bottom cell. Addressing the end-of-life scenario for PV modules, traditionally destined for landfills, the authors highlight the urgent need for sustainable recycling practices in light of the rapid global adoption of photovoltaics. Despite challenges in environmentally and financially viable dismantling of PV modules, their research is directed towards developing effective recycling methods, including chemical, thermal, and mechanical techniques, to optimize material recovery and foster sustainable industry practices.

Wang *et al.* [19] introduce a simple solvent engineering technique involving the use of starch additive in a MAPbI3-based one-step spin coating process at room temperature, aimed at efficiently depositing perovskite on textured silicon surfaces for perovskite/Si monolithic tandem solar cells (TSCs) (see Figure 3). The authors investigated the influence of different starch concentrations on the morphological, structural, optical, and photovoltaic properties of the perovskite films. The results showed that starch improved solution viscosity and formed hydrogen bonds with $CH_3NH_3^+$, facilitating the formation of perovskite films with a crystal structure compatible with textured silicon surfaces. A concentration of 5 wt% starch enables complete coverage of textured silicon surfaces with an average film thickness of around 600 nm. This approach not only stabilizes the crystal structure and device performance of the perovskite film and the planar solar cell but also locks water molecules at the perovskite grain boundaries due to the presence of starch. Their findings demonstrated the potential of this method in achieving uniform light absorption in perovskite layers and a well-matched current density in perovskite/Si monolithic TSCs, with a best-calculated cell efficiency exceeding 29%.

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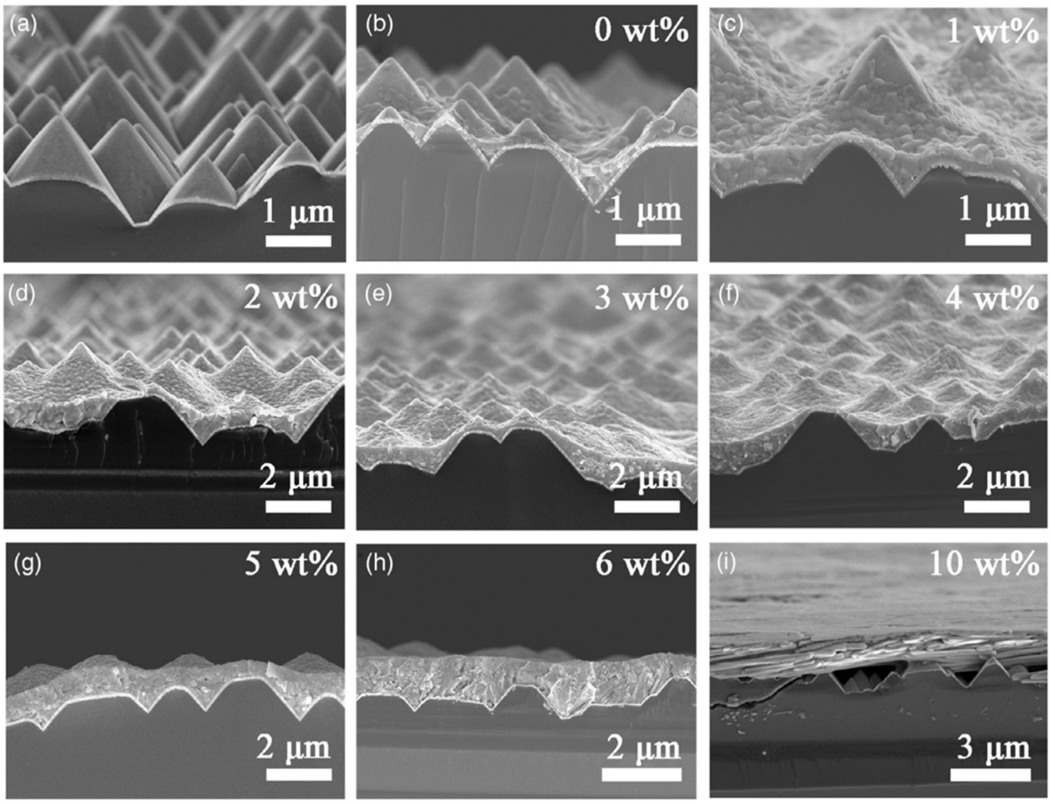

Figure 3. Cross-sectional scanning electron microscopy (SEM) images illustrate: a) a silicon surface textured with pure pyramids, and b) to i) the same pyramid-textured silicon surface overlaid with perovskite films, each with varying starch ratios. These ratios include b) 0 wt%, c) 1 wt%, d) 2 wt%, e) 3 wt%, f) 4 wt%, g) 5 wt%, h) 6 wt%, and i) 10 wt%. Reprinted with permission from ref. [19], Copyright 2020, Energy Technology.

Zhao *et al.* [20] provide a detailed exploration of recent advances in photovoltaic technologies, specifically focusing on organic and perovskite-based solar cells. The authors explore the intricacies of crystallization mechanisms in these cells, underlining their crucial role in influencing cell efficiency and performance. Their work also addresses the pivotal challenge of material stability, highlighting innovative approaches in charging materials to boost solar cell efficiency and durability. Additionally, it explores the commercial potential of these technologies, emphasizing scalable fabrication techniques and the promising capabilities of tandem solar cells, which are capable of exceeding the traditional Shockley–Queisser limit, thus heralding a new era in solar energy technology.

The future outlook for silicon-based solar cells is promising, with ongoing research focused on enhancing efficiency and reducing costs. Innovations such as the integration of perovskite layers with silicon to create tandem cells, and the use of nanotechnology for light management, are expected to play a significant role in the next generation of silicon PV cells. Moreover, the industry is moving towards more sustainable practices, including the use of greener materials and the development of efficient recycling methods for solar panel components.

3. Organic Photovoltaic Cells

Organic Photovoltaic Cells (OPVs) are a pivotal innovation in solar technology, distinguished by their utilization of carbon-based materials. These materials, including polymers and small molecules, are primarily organic semiconductors, setting OPVs apart from traditional inorganic solar cells [21]. The unique properties of these materials, such as flexibility, semi-transparency, and the ability to be processed at low temperatures, make them highly adaptable for diverse applications, extending beyond the conventional scope of solar panels [21].

The journey of OPVs began with the discovery of the photovoltaic effect in organic materials. The initial breakthrough in OPVs was marked by the development of the "Tang cell" in 1986, a two-layer device comprising copper phthalocyanine and perylene diimide [22]. This discovery laid the foundation for the evolution of OPVs, leading to the concept of bulk heterojunction (BHJ) solar cells in the early 1990s [22]. BHJ cells, composed of a blend of donor and acceptor materials, typically involve a combination of a polymer or small molecule donor with a fullerene-based acceptor. This structure facilitates efficient charge separation and transport, crucial for high photovoltaic performance [22].

A significant aspect of OPV research focuses on the synthesis and development of novel organic semiconducting materials. These materials are designed to optimize light absorption, charge transport, and overall device efficiency [23]. Innovations in material science have led to the creation of various photovoltaic polymers, each offering distinct advantages in terms of absorption spectrum, molecular ordering, and electronic properties. For instance, the incorporation of carbon nanotubes and other nanostructured materials into the active layer of OPVs has been explored to enhance charge transport and improve overall cell efficiency [23]. These advancements aim to address the inherent limitations of organic materials, such as their relatively narrow absorption spectra and less efficient charge carrier mobility compared to inorganic materials [23].

Despite the progress, OPVs face challenges, particularly in terms of efficiency and stability. The efficiency of OPVs, although improving rapidly, still falls short of their inorganic counterparts [24]. Stability is another critical issue, as organic materials are prone to degradation under environmental stressors like UV radiation, oxygen, and moisture. Addressing these challenges involves not only material innovation but also advancements in device engineering and encapsulation techniques. The ongoing research in this field is driven by the potential of OPVs to offer a low-cost, environmentally friendly, and versatile alternative to traditional solar technologies [24].

3.1. Advantages: Flexibility and Low-Cost Production Potential

The flexibility of OPVs is a standout feature, primarily due to the organic materials used in their construction. This flexibility enables OPVs to be integrated into a variety of applications where traditional, rigid solar cells are impractical [25]. For example, a study [25] demonstrated the potential of OPVs in indoor settings, showcasing their adaptability to different light conditions and environments.

The roll-to-roll manufacturing process is crucial in enhancing the low-cost production potential of OPVs. This technique, which involves printing photovoltaic materials onto flexible substrates, is less energy-intensive and more cost-effective compared to traditional silicon cell production methods [26]. Li and colleagues [26] focus on advancements in OPV cells. It discusses the development of a small molecule named DERHD7T, designed for improved solar absorption and film quality in OPV cells. This molecule achieved a record power conversion efficiency (PCE) of 6.1%, surpassing previous benchmarks for small molecule based OPV devices. The study highlights the molecule's synthesis, thermal stability, and performance characteristics like high molar absorption, effective charge mobility, and device fabrication techniques. The research underscores the potential of small molecules in OPV technology, offering a promising alternative to polymer-based systems.

The commercial viability of roll-to-roll manufactured OPVs hinges on effective encapsulation techniques. Encapsulation is essential for protecting organic materials from environmental degradation. Juillard *et al.* [27] investigated the impact of roll-to-roll flexible encapsulation on OPV devices, focusing on mitigating environmental degradation and enhancing device longevity. They conducted a comprehensive assessment of both the performance and mechanical reliability of encapsulated devices. Using a novel peeling technique, the authors analyzed the interfacial strengths within multilayered OPV devices on a flexible poly(ethylene terephthalate) substrate. This approach revealed significant weaknesses at two specific interfaces: between the active layer and hole transporting layer, and the transparent conducting electrode and electron transporting layer. To correct the weakness, the group explored various surface treatments, finding that optimized UV-ozone treatment significantly improved the adhesion of zinc oxide (ZnO) layers, as confirmed by IR spectroscopy and contact angle measurements (see Figure 4). The study concluded that enhancing interfacial adhesion not only improves device performance but also increases resilience to the stresses of roll-to-roll encapsulation.

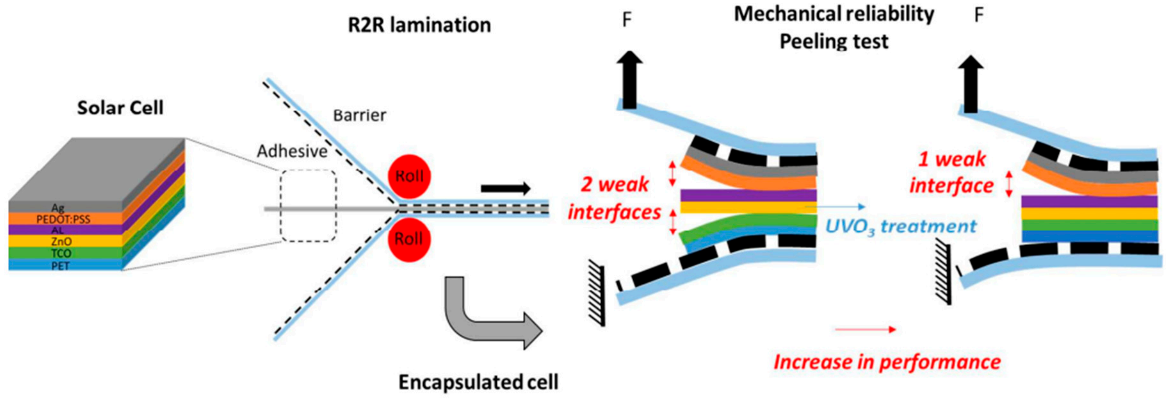

Figure 4. Process flow for enhancing the durability and performance of organic photovoltaic devices. It shows a multi-layered solar cell structure being encapsulated through roll-to-roll (R2R) lamination, identifying two weak interfaces prone to separation. A mechanical peeling test is used to assess the mechanical reliability. Subsequently, UV-ozone (UVO_3) treatment is applied to one of the interfaces, resulting in improved adhesion, a reduction to one weak interface, and an overall increase in the solar cell's performance. Reprinted with permission from ref. [27], Copyright 2018, ACS Applied Materials and Interfaces.

Recent advancements have seen OPVs achieve significant efficiencies, especially in indoor lighting conditions. Cui *et al.* [25] report on the potential of OPV cells for indoor applications. OPV technology, characterized by its capacity for large-area, lightweight, and flexible solar panel production via low-cost roll-to-roll methods, has seen rapid improvements in power conversion efficiency (PCE). Specifically, the group optimized OPV cells for indoor lighting conditions, achieving a top PCE of 22% with 1 cm^2 cells under 1000 lux LED illumination. These cells also exhibit enhanced stability under continuous indoor light, underscoring the importance of developing wide-bandgap active materials tailored for indoor OPV applications, which could significantly elevate photovoltaic performance.

3.2. Performance Metrics: Efficiency and Stability

Organic Photovoltaic Cells (OPVs) have seen significant advancements in terms of power conversion efficiency (PCE) and stability, two critical performance metrics in solar technology. Recent developments in OPV technology have led to substantial improvements in PCE. A notable example is the work by Wang *et al.* [28], where the authors explore the potential of OPV cells for indoor applications, addressing the challenge of energetic disorder under low illuminance. They demonstrated that concentrated indoor light mitigates energetic disorder, enhancing open-circuit voltage and fill factor, with PB2:FCC-Cl-based cells achieving a remarkable 33.0% PCE at 20,000 lux. Additionally, the group reported superior stability of OPV cells under such conditions, noting over 30,000 hours of intrinsic lifetime for the PBDB-TF:Y6 system. The integration with optical waveguide concentrators suggests a pathway for low-cost manufacturing, underscoring the necessity of developing concentrated OPV cells for future indoor applications. Additionally, Ma *et al.* [29] presented a strategy for enhancing both the mechanical robustness and photovoltaic performance of all-polymer OPV cells, making them suitable for flexible wearable devices. The authors introduced a high molecular weight polymer donor, PBDB-TF, into a PBQx-TF:PY-IT blend to improve the bulk heterojunction morphology, resulting in more efficient charge transport and enhanced mechanical stress dissipation. This ternary blend film yields OPV cells with a maximum PCE of 18.2% and an impressive fill factor of 0.796, maintaining a PCE of 16.5% even under mechanical stress, offering a viable approach to fortify all-polymer OPV cells.

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Despite these efficiency improvements, stability remains a major challenge for OPVs. The organic materials used in OPVs are often more susceptible to environmental degradation factors like oxygen and moisture. Wu and team [30] critically reviewed the recent research progress on the stability of high-performance OSCs, discussing factors limiting device lifetime such as metastable morphology, air, irradiation, heat, and mechanical stresses. Their review emphasizes the need for ongoing research in material design and device engineering to enhance the stability of OPVs [30].

The efficiency of OPVs under standard solar conditions still lags behind that of conventional solar cells. However, their performance in indoor environments, as demonstrated by Wang *et al.* [28], suggests a niche where OPVs could be particularly effective. The unique spectral characteristics of indoor lighting compared to outdoor sunlight play a significant role in this context. The high tunability in optical absorption and insensitivity to series resistance and active layer thickness make OPVs promising for indoor applications [28].

3.3. Technological Challenges and Prospects for Scalability

Scaling OPVs for widespread use involves overcoming several technological challenges, particularly concerning the inherent instability of organic materials and the complexities of large-scale production. The primary challenge in scaling OPVs is the inherent instability of organic materials. These materials can degrade under environmental stressors such as UV light, oxygen, and moisture. Sutherland *et al.* [31] argues that the development of flexible barrier encapsulation is essential, demanding materials with exceptional moisture resistance, high transparency, and durability against mechanical stress. Their review discusses these challenges in detail and examines the latest advancements in flexible encapsulation materials, suggesting directions for future research. Figure 5 shows four distinct routes through which moisture and oxygen can penetrate flexible encapsulates PSC and OPV devices.

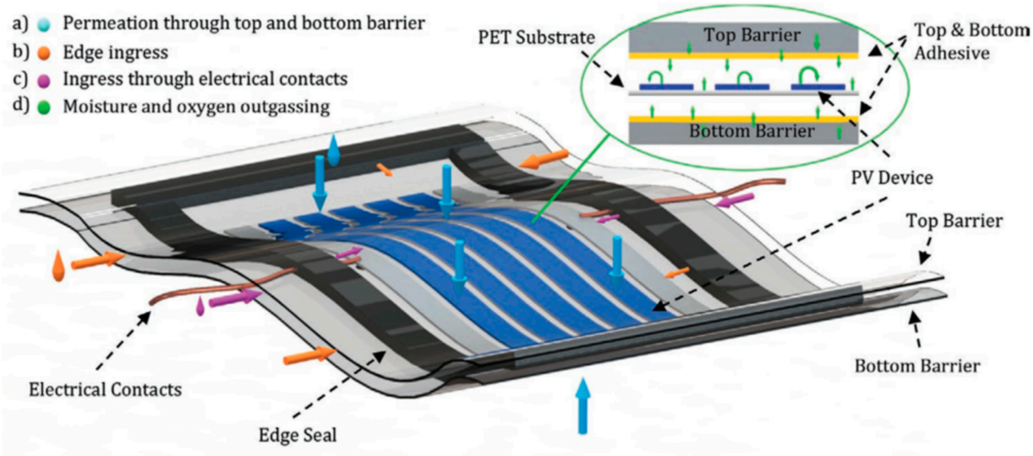

Figure 5. The depiction shows four distinct routes through which moisture and oxygen can penetrate flexible encapsulated PSC and OPV devices, leading to expedited degradation and diminished operational life. Reprinted with permission from ref. [31], Copyright 2021, Advanced Energy Materials.

Transitioning from small-area lab cells to large-scale, industrially viable OPV modules presents significant challenges. Wachsmuth and colleagues [32] explored the upscaling of OPV from small-area lab cells to solution-processed modules compatible with industrial roll-to-roll (R2R) printing. This process involved meticulous material selection and optimization of each layer in the OPV stack, including the photoactive and charge transporting layers, as well as the solution-processed top electrode. The authors also conducted long-term stability tests (thermal and light exposure) and successfully scaled up the device area by over 100 times. The result was a semitransparent OPV module with a 10.8% power conversion efficiency on a 10.2 cm^2 area, meeting industrial R2R printing requirements, thus paving the way for large-scale production (see Figure 6).

Encapsulation plays a crucial role in enhancing the stability of OPVs, especially in the context of large-scale production. E. Destouesse *et al.* [33] successfully implemented both roll-to-roll (R2R) and sheet-to-sheet (S2S) methods to develop ITO-free OPV devices using the non-fullerene PBDB-T:ITIC material system. The fabrication involved R2R vacuum sputtering and S2S slot-die coating, all conducted under ambient conditions, yielding devices with a power conversion efficiency of 5.5%. The authors also investigated the relationship between various barrier films, including commercially available and sputtered inorganic coatings on ultra-clean PET, and the longevity of these OPV devices. The findings mark a significant advancement in the industrial-scale production of OPV devices.

The future of OPVs in large-scale applications hinges on addressing these challenges. Continued advancements in material stability, encapsulation techniques, and upscaling processes are crucial for the long-term viability and commercial success of OPVs. As these technological hurdles are overcome, OPVs hold the promise of becoming a key player in the renewable energy sector, offering a sustainable and cost-effective alternative to traditional solar technologies.

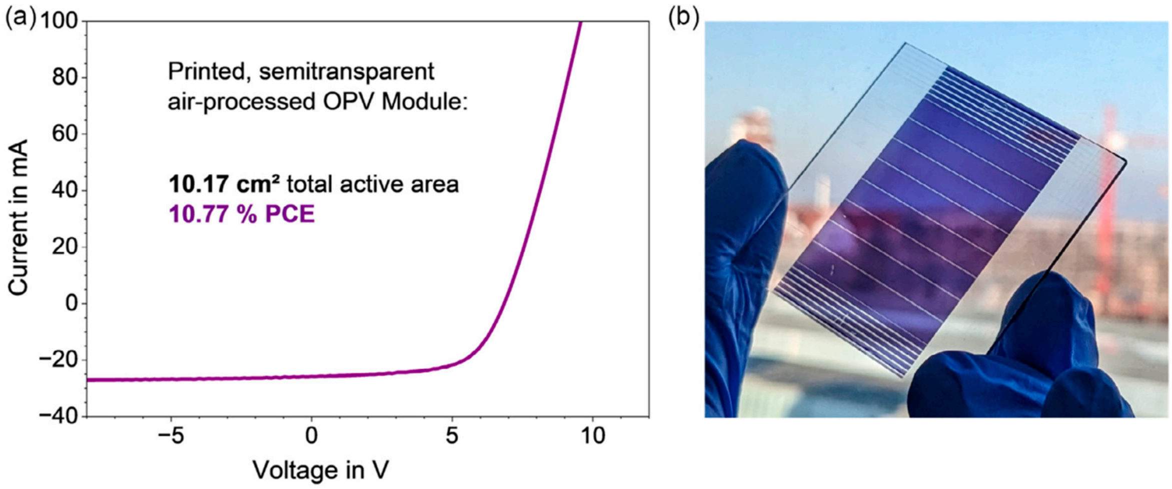

Figure 6. The image shows (a) the J-V curve and (b) a photograph of a semitransparent module that has been fully processed in solution and in air. This module, positioned on a glass/ITO substrate, consists of eight cells connected in series and covers a total active area of 10.17 cm^2, including a back-reflector. Reprinted with permission from ref. [32], Copyright 2023, Solar RRL.

4. Perovskite Solar Cells

Perovskite solar cells (PSCs) have rapidly emerged as a promising photovoltaic technology, primarily due to their excellent optoelectronic properties and ease of fabrication [34]. A review by Yang *et al.* [35] focuses on the advancements of all-inorganic $CsPbX_3$ perovskites, known for their excellent optoelectronic properties and stability, with applications in electronic devices. The power conversion efficiency of $CsPbX_3$ perovskite solar cells has remarkably increased from 2.9% in 2015 to 21.0%. Emphasis is placed on optimizing perovskite film quality through crystallization kinetics modulation and defect suppression. The review covers fundamental aspects of $CsPbX_3$ perovskites, strategies for crystallization modulation, and methods to enhance inorganic perovskite solar cell efficiency, while also discussing future development prospects.

Organic-inorganic hybrids are known for their broad absorption spectra, long recombination lifetimes, and impressive electron mobility [35]. Zhou *et al.* [36] delve into the progression of perovskite photovoltaic technology, highlighting its rapid development due to advances in understanding the thin-film microstructures of metal halide perovskites. The authors focused on three crucial microstructure types: grain boundaries, intragrain defects, and surfaces. Their impacts on optoelectronic properties, device efficiency, and stability are discussed, emphasizing the importance of tailored characterizations to understand these effects. They also examined the microstructures' roles in degradation modes and present examples where fundamental insights have

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led to state-of-the-art perovskite solar cells. The paper concludes with a call for further exploration of hidden microstructures and advanced characterizations to enhance our understanding of microstructure-property-performance relationships in solar cells.

The unique economic advantage of PSCs lies in their solution-processible fabrication, compatible with large-scale deposition techniques such as roll-to-roll processing, blade coating, or inkjet printing [37]. This adaptability potentially lowers solar cell fabrication costs significantly, making them a key player in the renewable energy sector. Additionally, the exploration of lead-free perovskite materials, such as antimony-based perovskites, is gaining traction due to their unique optoelectronic properties, conventional fabrication processes, low toxicity levels, and high stability values, as reviewed by Thomas [37]. Similarly, Chakraborty *et al.* [38] examined the potential of various lead (Pb)-free materials for use in hybrid halide perovskite solar cells (PSCs). Their work highlights the research efforts to find suitable lead alternatives in PSCs, with a focus on homovalent (Sn^{2+}, Ge^{2+}, Cu^{2+}) and heterovalent (Sb^{3+}, Bi^{3+}, Ti^{4+}) materials. Although these materials show promising physical properties to replace lead, their power conversion efficiencies (PCEs) are generally lower compared to lead-based counterparts.

4.1. Efficiency Gains and Fabrication Techniques

Perovskite solar cells (PSCs) have demonstrated remarkable progress in power conversion efficiencies (PCE), with recent reports indicating efficiencies reaching up to 26.1% [39]. This rapid improvement in PCE is attributed to advancements in fabrication techniques and material engineering. Pathak *et al.* [39] discusses the evolving technological requirements for effective energy production and conversion, with a focus on the rise of sustainable and renewable energy sources, particularly solar energy conversion via photovoltaic cells. The work highlights the significant increase in power conversion efficiency of perovskite solar cells from 3% to 26.1%, and the challenges in transitioning from laboratory PSCs to commercialization. Key topics include scalable fabrication processes for perovskite solar modules (PSMs), fabrication challenges, recent advancements in PSM stability, and future prospects for PSMs, providing insights into thin film coating technologies and future development directions.

Innovative fabrication methods, such as the electro-hydrodynamic spraying route inspired by 'Marangoni flow', have enabled the production of perovskite thin film solar cells with superior current-voltage characteristics [40]. This method not only enhances efficiency but also reduces lead wastage, addressing environmental concerns associated with PSCs. Pourjafari *et al.* [40] focuses on carbon-based, hole-conductor-free perovskite solar cells (C-PSCs), a promising candidate for commercial photovoltaic technology due to their high stability, ease of fabrication, and low cost. The authors explore various strategies to enhance charge separation, extraction, and transport in C-PSCs to improve power conversion efficiency. These include the use of novel or modified electron and hole transport materials, and carbon electrodes. Their work also covers the working principles of printing techniques for C-PSC fabrication and discusses scalable deposition techniques for manufacturing perovskite solar modules.

Furthermore, the work by Nejand *et al.* [41] developed a monolithic all-perovskite tandem photovoltaics, which combine the benefits of low-cost and high-efficiency solar energy harvesting inherent in all-thin-film technologies. The authors explain that until now, such tandem solar cells have been limited to lab-scale production using non-scalable techniques. Addressing this, their work introduced all-perovskite tandem modules fabricated through scalable methods like blade coating and vacuum deposition. These modules showcased power conversion efficiencies up to 19.1% over a substantial aperture area of 12.25 cm^2. They also maintain a high geometric fill factor of 94.7% and exhibit stable power output. When compared to their spin-coated tandem cells, which have an efficiency of 23.5% over a much smaller area, these scalable modules marked a significant step forward in making all-perovskite tandem photovoltaics more commercially viable. Electroluminescence imaging and laser-beam-induced current mapping techniques were employed to ensure uniform current collection across the module, minimizing losses in key areas like open-circuit voltage and fill factor.

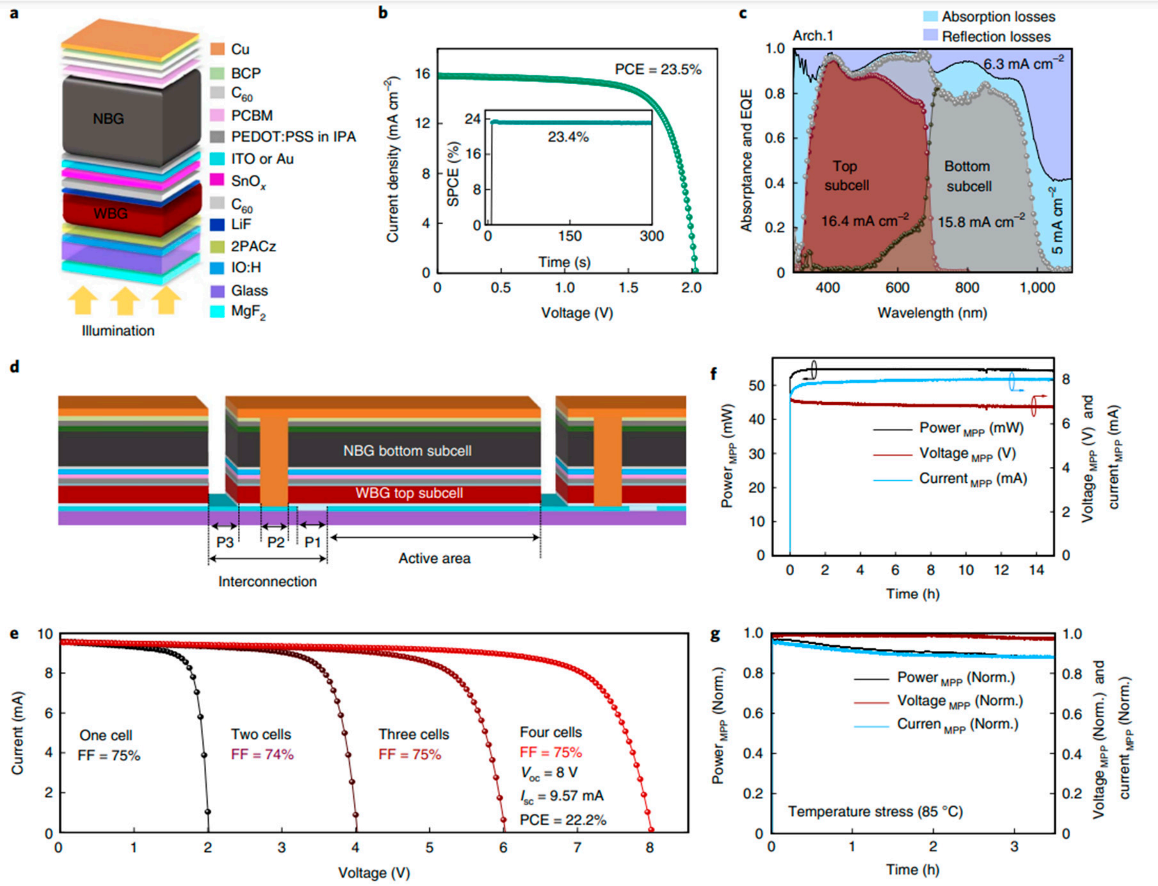

Figure 7. Development and efficacy of comprehensive perovskite-based tandem solar cells and modules are detailed. a outline the structural design and composition of these tandem solar cells, highlighting the use of sputtered indium tin oxide layers (around 15 nm thick) and thinly spread Au films (about 1-2 nm thick) as the recombination layer. 'NBG' and 'WBG' refer to the narrow and wide bandgaps, respectively. b shows the Current density–voltage (J–V) profile and efficiency of power conversion at the maximum power point over five minutes for top-performing tandem devices are presented (see inset). c discusses the External Quantum Efficiency (EQE) of the upper and lower subcells, along with their combined effect (shown as a grey line) and the overall absorption, calculated as 1 minus the reflectance (depicted as a black line). This section also explains the light and dark blue areas, which indicate the parasitic absorption and reflection losses, respectively, and their impact on current density. d provides a diagrammatic representation of the interconnected two-terminal all-perovskite tandem solar module, not to scale, highlighting its active area and scribing lines. The color scheme for the module layers matches that of the tandem solar cells. e describes the J–V characteristics of individual tandem cell stripes within the module, including fill factors and the impact of progressively incorporating cell stripes into the analysis. f details the power, voltage, and current at the module's maximum power point under continuous AM 1.5G lighting. g presents the normalized power, voltage, and current at the maximum power point when subjected to temperature stress at 85°C in a nitrogen environment. The first three sections (a–c) pertain to tandem solar cells, while the latter sections (d–g) focus on tandem modules. Reprinted with permission from ref. [41], Copyright 2022, Nature Energy.

Chowdhury *et al.* [34] explored the effects of perovskite films, which show a concerning 20% performance degradation. The study emphasizes the need for a deep understanding of the fabrication process's impact on device stability, considering it crucial for future progress. They provide a detailed examination of various fabrication methods, including spin coating, doctor blade, sequential deposition, hybrid chemical vapor deposition, and layer-by-layer approaches (see Figure 8). The group also covers the evolution of PSC structures, transitioning from regular to inverted configurations, and shifts in material usage from organic to inorganic, highlighting innovations in perovskite materials. A key focus is the operational stability of PSCs, offering insights into extending their operational life and thus promoting their commercialization by overcoming the stability hurdle.

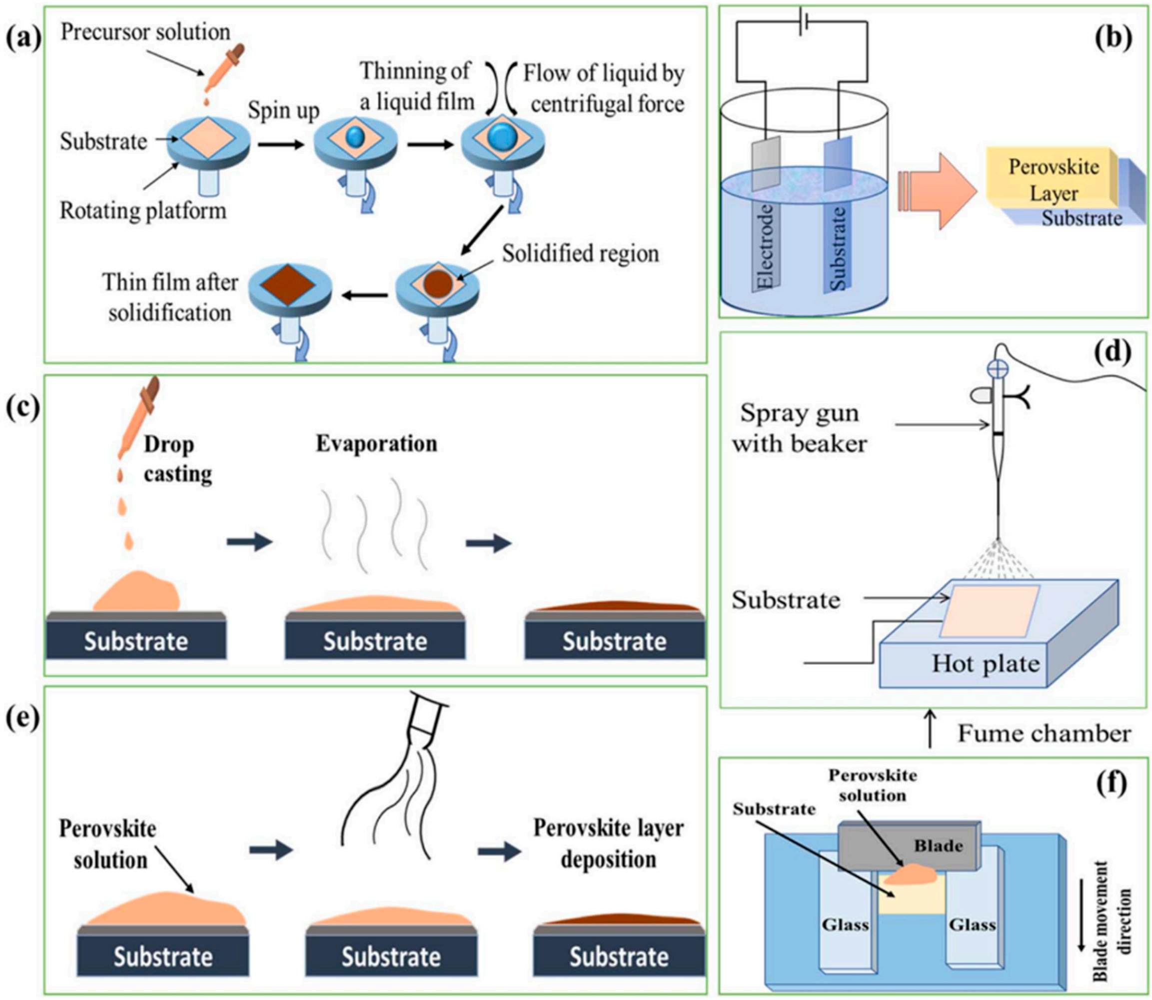

Figure 8. Fabrication methods for solution-based perovskite solar cells (PSCs) include: (a) the spin coating technique, (b) the method of electrochemical deposition, (c) the drop casting approach, (d) spray coating procedures, (e) the blow-drying process, and (f) blade coating techniques. Reprinted with permission from ref. [34], Copyright 2022, RSC Advances.

4.2. Comparative Analysis with Silicon and Organic Cells

Perovskite solar cells have emerged as a competitive alternative to traditional silicon-based solar cells, offering a unique blend of high efficiency and low-cost production potential. Hussain *et al.* [42] highlight that while silicon-based solar cells are approaching their efficiency limits, perovskite-based cells have demonstrated efficiencies of approximately 26%, surpassing many conventional silicon cells [42]. This remarkable efficiency, combined with the low-cost production techniques similar to those used in organic photovoltaics, positions PSCs as a potential bridge between the high efficiency of silicon cells and the economic advantages of organic cells.

Giannouli [43] presents a comprehensive comparative assessment of third-generation photovoltaic technologies, including dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), and PSCs, as alternatives to silicon solar cells. This study emphasizes the need for further research to improve the efficiency and stability of these devices while keeping production costs minimal. PSCs, in particular, are noted for their rapid development and potential for sustainable solar energy applications [43].

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The work of Zhu *et al.* [44] reported a notable advancement in perovskite solar cell technology through the integration of two-dimensional perovskites within a three-dimensional framework, a method that traditionally enhances stability but has struggled with achieving high power conversion efficiencies. The author's approach breakthrough involved incorporating n-type, low-optical-gap conjugated organic molecules into this 2D:3D perovskite composite, resulting in ternary perovskite–organic composites. These composites showed extended absorption in the near-infrared region, improved film morphology, larger crystallinity, balanced charge transport, efficient photoinduced charge transfer, and reduced counter-ion movement. This approach has led to solar cells with PCEs over 23%, among the highest for perovskite solar cells with a p–i–n structure, alongside significantly enhanced stability and reduced photocurrent hysteresis. This study highlights the potential of ternary perovskite–organic composite thin films in developing high-performance perovskite solar cells, combining improved stability and efficiency.

Lee *at al.* [45] presented an in-depth analysis of the challenges and current status of upscaling perovskite solar cells for commercialization, noting a significant efficiency gap between a large 804 cm^2 perovskite module (17.9% efficiency) and a much smaller 0.09 cm^2 cell (25.2% efficiency). To contextualize these findings, the authors explored the development and upscaling history of commercialized solar technologies, including silicon, copper indium gallium sulfur/selenide (CIGS), and CdTe, with module sizes reaching approximately 25,000 cm^2 (see Figure 9). The study also examined other photovoltaic technologies such as GaAs, organic, dye-sensitized, and perovskite/silicon tandem solar cells, analyzing their operating mechanisms and development paths. The study allowed the group to draw parallels and contrasts in development strategies across different solar cell types, leading them to propose an optimal direction for the upscaling of perovskite solar cells. The authors concluded that lessons from the historical evolution of various solar technologies offer a fundamental understanding of the relative and absolute development stages of perovskite solar cells, providing a unique perspective that could guide the upscaling and advancement of this promising technology.

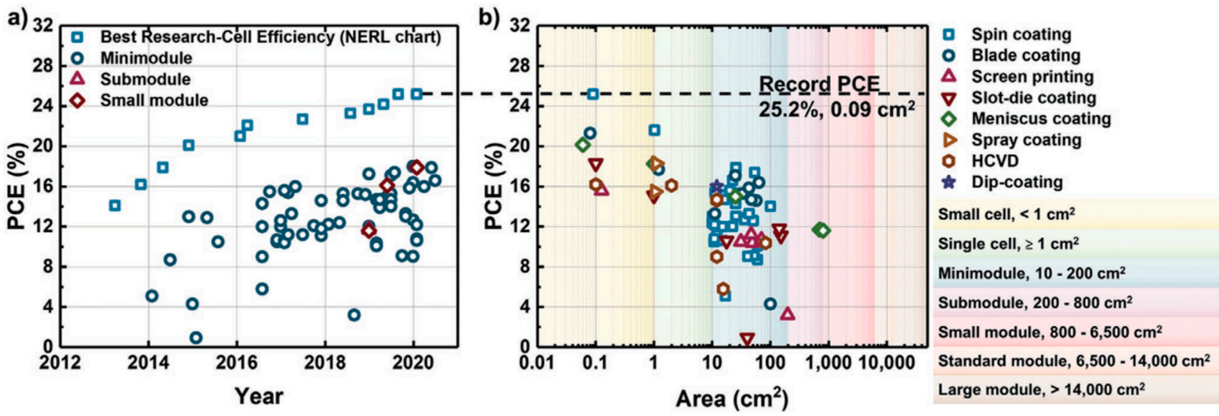

Figure 9. a, b) Progression Trends in Perovskite Solar Cells: a) Depicts the Power Conversion Efficiency (PCE) over the years for various cell sizes; b) Shows the relationship between PCE and cell size for different fabrication methods. Reprinted with permission from ref. [45], Copyright 2020, Advances Materials.

4.3. Stability and Environmental Impact Considerations

Perovskite solar cells face significant challenges related to stability and environmental impact, which are critical barriers to their commercialization. Kymakis [46] emphasizes that the long-term stability of PSCs under ambient operating conditions, particularly against environmental hazards such as heat and moisture, is a major hurdle. The degradation of PSCs under prolonged illumination and chemical decomposition due to the presence of water, thermal stress, UV radiation, and electrochemical reactions at the interfaces are key issues that need addressing. The best recorded operating lifetime of PSCs is 1000 hours at maximum power and 60°C for mesoscopic solar cells, highlighting the importance of interface engineering in improving stability [46].

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Dou and Chen [47] discuss the degradation mechanisms in perovskite solar cells and a thorough review of interfacial engineering, with a particular focus on its effects on flexible perovskite solar cells. Based on recent research progress, the authors examine the current challenges and future directions, aiming to contribute to the advancement and commercialization of flexible perovskite solar cells. Their work offers valuable insights and perspectives, underscoring the importance of interface engineering in enhancing the performance of flexible photovoltaic technologies.

Chi and Banerjee [48] reported the advancements and ongoing challenges in metal halide perovskite solar cells, which are nearing their theoretical efficiency limits thanks to global research efforts. The authors explain that the current challenge lies in developing devices that not only achieve these efficiencies but also demonstrate sufficient stability and minimal degradation for practical applications. They identified that degradation in these cells is significantly influenced by external factors such as moisture, oxygen, light, and heat (see Figure 10). While encapsulation effectively counters moisture and oxygen-induced degradation, mitigating light and heat degradation requires enhancing the materials and interfaces of the cells. Their study elaborates on the degradation mechanisms due to light and heat in each major layer of the device and discusses strategies for degradation reduction and stability enhancement. These strategies involve compositional and interfacial engineering approaches, such as site-based substitution in the perovskite lattice, doping in charge transport layers, and various passivation methods using materials like small molecules, polymers, and perovskite quantum dots. Their findings provide crucial insights into the suppression of degradation and the enhancement of stability in perovskite solar cells, guiding the design of efficient and durable solar energy devices.

Meng *et al.* [49] present a significant advancement in third-generation photovoltaic technology, focusing on the development of lead-free perovskite solar cells. Addressing environmental and health concerns associated with lead (Pb), the authors introduce a novel lead-free double perovskite material, $Cs_2InBiBr_6$, notable for its small direct bandgap of 1.27 eV and excellent thermodynamic and mechanical stability. Their research involved using a solar cell capacitance simulator to analyze a cell structure comprising FTO, ETL, $Cs_2InBiBr_6$, HTL, and Au, aiming to optimize efficiency by selecting appropriate hole transport and electron transmission materials. They also explored the effects of absorber layer thickness, doping densities, and total defect density on cell performance. Employing advanced characterization methods like Mott-Schottky analysis, the group investigated the impact of interfaces on device functionality. Their findings revealed that a solar cell configuration of $FTO/TiO_2/Cs_2InBiBr_6/Cu_2O/Au$ achieves an impressive PCE of 23.64% (see Figure 11), demonstrating the significant potential of $Cs_2InBiBr_6$ as a lead-free double perovskite solar cell absorber layer. This breakthrough indicates a promising future for environmentally sustainable and efficient perovskite solar cells.

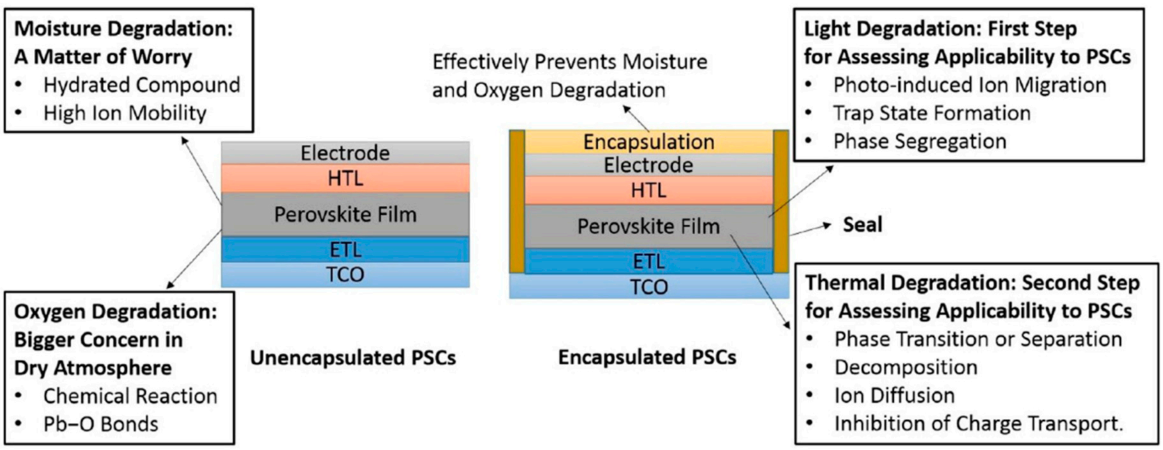

Figure 10. Comprehensive Overview of Degradation Mechanisms in Perovskite Absorbers Due to External Environmental Influences. Reprinted with permission from ref. [48], Copyright 2021, ACS Chemistry of Materials.

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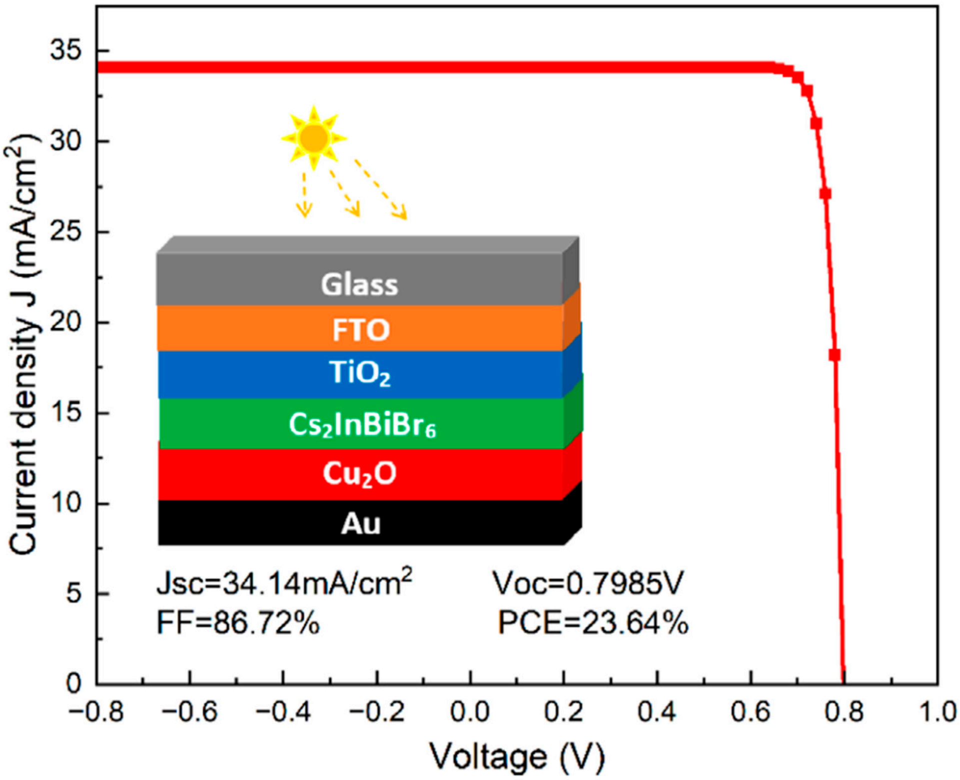

Figure 11. Comprehensive Overview of Degradation Mechanisms in Perovskite Absorbers Due to External Environmental Influences. Reprinted with permission from ref. [49], Copyright 2023, Advanced Theory and Simulations.

Table 1 provides a comprehensive comparison of three key solar cell technologies: silicon-based, organic, and perovskite. It systematically outlines the advantages, disadvantages, and recent advancements for each type, offering insights into their market positions, technological strengths, and challenges. The advantages section emphasizes factors like efficiency, cost, and application versatility, while the disadvantages highlight environmental, stability, and manufacturing concerns. Recent accomplishments focus on groundbreaking research and technological improvements.

Table 1. Comparative Analysis of Silicon-based, Organic, and Perovskite Solar Cells: Advantages, Disadvantages, and Recent Progress.

Type of Solar Cell	Advantages	Disadvantages	Recent Accomplishments	References
Silicon-based	- Market dominance and proven track record - High-efficiency rates, with cells achieving over 25% efficiency - Good performance in diverse climates - Continuous improvements in	- High energy consumption in production, contributing to a larger carbon footprint - Bulkiness and heavier weight, making installation challenging	- Development of PERC cells enhancing efficiency - Advent of bifacial solar cells - Tandem cells combining silicon with other materials to surpass efficiency limits	[4,8,10,17,19],

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	manufacturing processes leading to reduced costs	- Environmental concerns in manufacturing and disposal		
Organic	- Potential for low-cost, large-scale production - Highly versatile for different applications - Environmentally friendly materials and production processes - Possibility of semi-transparent and colored cells	- Lower efficiency rates compared to silicon and perovskite cells - Susceptibility to degradation under environmental exposure - Challenges in achieving stability and performance at a commercial scale	- Development of more stable materials - Efficiency improvements in lab settings	[21,27,29,31–33]
Perovskite	- Rapid improvement in efficiency, with lab-scale cells reaching over 25% - Low production costs and potential for simple manufacturing processes - Versatile material properties allowing for tandem cell configurations and flexible applications	- Stability issues and durability concerns - Environmental and health concerns due to lead content - Challenges in upscaling production for large-scale applications	- Stability enhancement - Lead-free alternatives exploration - Advancements in scalable manufacturing techniques	[34,35,43,49]

5. Cross-Material Analysis

5.1. Efficiency and Stability of Photovoltaic Materials

The effective deployment of photovoltaic materials in commercial systems is extensively influenced by their conversion efficiency, which is bounded by the theoretical Shockley–Queisser (S-Q) limit [50]. This limit is a key determinant in understanding the maximum potential efficiency of photovoltaic cells based on their semiconductor material's inherent properties. The efficiency of these materials is further impacted by their stability over time and the intricacies involved in their manufacturing. The solar spectrum, covering a vast range of wavelengths, interacts differently with various photovoltaic materials, influencing their ability to absorb light and convert it into electricity.

Materials like silicon have specific energy thresholds for photon absorption, dictating their efficiency in energy conversion. For instance, in silicon-based cells, photons with energy below 1.1 eV fail to induce excitation. Any excess photon energy, rather than contributing to electrical output, increases the temperature of the cells, negatively impacting their efficiency. This absorption spectrum

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varies widely among different materials, each with its theoretical efficiency limit, often below the maximum potential outlined by mono-crystalline silicon [51].

Moreover, the efficiency of photovoltaic cells is not solely dependent on the material's inherent properties. External factors such as reflections from the cell surface, the electrical resistance within the cell, contamination of the active components, and the presence of crystal defects critically affect the cell's performance [52]. These factors collectively contribute to losses in efficiency, underlining the complexity in optimizing solar energy conversion [52].

In addition to these material and design-related factors, practical aspects such as the alignment of the solar panels, the angle of the sun's incidence, and the geographical location of the installation play significant roles [53]. These factors influence the operational temperature, the amount of sunlight received per day, and the heat levels within the system, all of which have a direct impact on the efficiency of the photovoltaic systems.

The effectiveness of crystalline silicon solar cells, for example, is significantly influenced by the absorption factor, which is a measure of the solar irradiance that the cells can capture. This factor is critical for regulating the temperature of the cells and can be experimentally determined through reflection and transmission studies. Innovations in the texture of crystalline silicon wafers have been shown to enhance this absorption factor, thereby reducing reflective losses and potentially increasing the efficiency of the cells [54].

In the realm of bifacial crystalline silicon photovoltaic cells, there is a growing interest due to their potential for higher energy yields [55]. These cells are distinguished from monofacial cells by their ability to absorb light from both sides, which is facilitated by advanced performance metrics and sophisticated simulation models [55].

Recent advancements in silicon heterojunction solar cells and the development of carrier-selective contacts have shown promising results in enhancing the efficiency of photovoltaic cells [56]. Furthermore, research into hybrid polymer semiconductor materials has shed light on their photon absorption and exciton generation capabilities. While these materials currently exhibit lower efficiencies compared to traditional semiconductor devices, they represent a significant area of research and development in the quest for more efficient photovoltaic solutions [56].

In solar cells, the inability to absorb all incident light and collect all generated carriers results in a lower short-circuit current than the maximum achievable for a given band gap (Eg) [57]. The open-circuit voltage is also reduced from the ideal S-Q limit due to various recombination phenomena, as well as defects in the bulk, interface, and surface of the cells [57]. Additional losses from resistance, contact issues, and other nonideal factors further decrease the fill factor, which is a measure of the cell's operational efficiency. Consequently, these factors result in practical efficiencies that are substantially lower than the theoretical maximum defined by the S-Q limit for a given band gap. In this regard, Polman *et al.* [58] conducted a comprehensive analysis of various photovoltaic materials, as illustrated in their study (see Figure 12). They assessed two critical parameters for each material: (i) the current ratio $j = J_{sc}/J_{SQ}$, reflecting the effectiveness of light coupling, absorption, and entrapment in the cell's active layers, and its dependence on carrier collection efficiency; and (ii) the voltage ratio $v = V_{oc}/V_{SQ}$, associated predominantly with carrier recombination in the bulk, surfaces, and interfaces [58]. The combination of the voltage ratio v and the fill factor ratio $f = FF/FF_{SQ}$ serves to delineate the overall electrical constraints of a cell. Figure 12 displays the proportion of the S-Q detailed-balance limit achieved for voltage and current by the analyzed materials, with lines around certain data points indicating the variability in band gaps used in the S-Q calculations, reflective of uncertainties in the band gap of the record cell [58].

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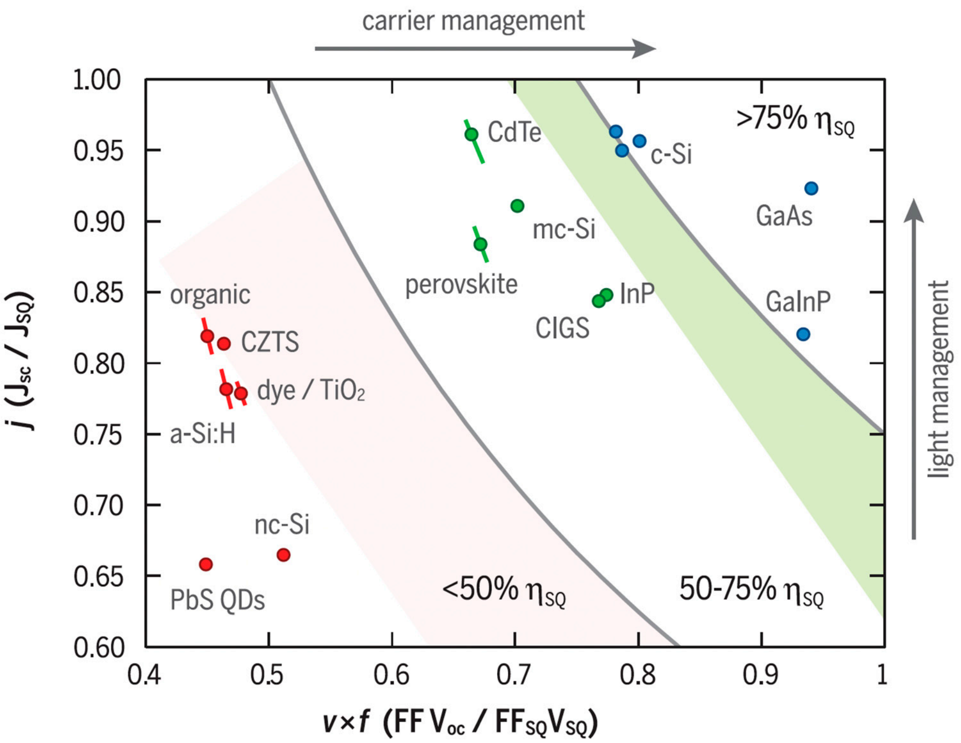

Figure 12. Fraction of the S-Q theoretical maximum for voltage and current attained by the different photovoltaic materials. The arrows displayed on the top and right axes of the graph represent the enhancement of cell efficiency through better light management and augmented charge carrier collection. The term 'η_{SQ}' is used to denote the maximum efficiency achievable as per the S-Q model. Reprinted with permission from ref. [58], Copyright 2016, Science.

Conversion efficiency data, while crucial, does not fully capture the durability or longevity of solar cells in delivering maximum output or maintaining their photovoltaic properties after production [59]. First-generation solar cells, notably those based on silicon, have shown remarkable durability, with some units still operational decades after installation. This longevity is contrasted with the challenges faced by third-generation solar cells, particularly in maintaining internal stability over extended periods [60]. Technological advancements in the 21st century have brought significant developments in organic and hybrid photovoltaic research. These newer types of solar cells offer advantages such as lower production costs and reduced environmental impact. However, their market adoption is hindered by their vulnerability to environmental factors like atmospheric conditions and biological agents, which can lead to rapid degradation [60]. Degradation rates for silicon and thin-film solar cells have been extensively documented since their commercial inception over fifty years ago. Most manufacturers of photovoltaic modules offer warranties of 25 to 30 years, aligning with an expected power drop of less than 20% during that period [60]. Recent models of solar cells, manufactured post-2000, show varied but generally lower degradation rates across different types of silicon cells. Some companies have reported some of the lowest degradation rates in the industry, achieved through innovative material choices [61]. Despite these advancements, third-generation solar cells, particularly those based on organic materials, face significant challenges. They often struggle to achieve efficiencies above 10% and are prone to rapid decomposition under exposure to light, drastically reducing their operational lifespan. This presents a major limitation for the practical application of these materials in long-term solar energy solutions.

Recent advancements in solar technology have significantly enhanced the robustness and efficiency of materials used in solar photovoltaic systems, enabling them to withstand extreme weather conditions and temperatures in various environments. In particular, perovskite solar cells have emerged as a key area for innovation in terms of long-term stability. The integration of nanoscale metal-organic frameworks (MOFs), with their flexible structures and expansive surface areas, has

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proven vital in improving the stability and performance of perovskite cells [62]. To further advance these technologies, a comprehensive understanding of the processes of photodegradation and thermal degradation in hybrid perovskite cells is crucial. Additionally, employing interfacial engineering techniques with hydrophobic materials and exploring the 2D/3D design concept have been pivotal in enhancing the long-term stability of these photovoltaic materials [53]. These technological strides represent a significant departure from the early stages of solar technology, demonstrating the growing potential of solar photovoltaic systems to remain durable and efficient over prolonged periods.

5.2. Commercial Viability and Scalability

In the field of photovoltaic materials, every practical material used for the development of photovoltaic devices undergoes continuous processes of standardization and reformulation. This is crucial for enhancing their properties, characteristics, longevity, and practical viability. Improvement is a possibility for all materials, and this section will explore such advancements, particularly focusing on materials like silicon, organic, and perovskite. These materials are at the forefront of research and development in the photovoltaic field, with ongoing efforts to optimize their performance and applicability in solar energy technologies.

Crystalline silicon, accounting for approximately 90% of the global photovoltaic market, has experienced steady growth over the years [63]. Despite this, alternatives to improve efficiency and reduce associated costs have been explored. Recently, advancements in efficiency, manufacturing processes, material savings, and economies of scale have significantly reduced production costs, with reductions nearing 75%. However, these improvements, particularly in cost reduction, are not sufficient to meet climate targets set by the Panel on Climate Change using photovoltaic technology [64]. Thin silicon wafers emerged as a cost-reduction strategy, initially lacking market momentum. Consequently, reducing silicon wafer thickness could be a viable path to further reduce production costs. In an insightful study by Liu *et al.* [63], the impact of silicon thickness reduction in photovoltaic systems on market expansion is analyzed. This research reveals that adopting advanced technologies with effective surface passivation can achieve comparable efficiencies between 50 μm and 160 μm Si wafers. Economically, thinner wafers are advantageous in terms of manufacturing capital expenditure, module cost, and levelized cost of electricity, particularly for utility-scale photovoltaic systems [63]. Further thinning of wafers could significantly reduce costs, making the technology more economically competitive, with efficiencies comparable to conventional silicon systems. The limited adoption of thin silicon technology in photovoltaic devices, despite its potential benefits, is due to several factors. Firstly, drastic shifts in production methodologies introduce significant inertia. Secondly, there's a concern about reduced yield in production [65]. Handling thin silicon wafers during device assembly is challenging, as their fragility leads to a significant breakage rate. This not only impacts the overall yield but also adds to the complexity and cost of manufacturing processes in photovoltaic production. Thirdly, there is a potential loss in device efficiency, a critical factor for market competitiveness [66]. This efficiency reduction is attributed to the incomplete absorption of photons, particularly in the near-infrared region, due to the reduced thickness of the semiconductor. Silicon, with its indirect bandgap, requires a relatively long optical path to effectively absorb near-bandgap photons. This issue necessitates innovative solutions to enhance photon absorption without compromising the benefits of using thinner wafers. In this regard, two promising approaches have been developed: i) the use of black silicon with nano-scale texturing [67], and ii) the innovation in encapsulation materials [68]. Finally, substantial costs are associated with altering existing manufacturing and processing techniques [65]. These challenges create a complex landscape for the implementation of thin silicon technology, requiring not just technological solutions but also economic and strategic planning.

Organic photovoltaic materials (OPVs) exhibit potential advantages over their inorganic counterparts due to several factors such as ease of processing, tunability of optoelectronic properties, and inherent material flexibility allowing for adaptation to different surfaces and shapes [69]. These materials have seen significant progress in efficiency, approaching a 20% threshold, primarily due to

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technological advancements like the development of new materials and alternative fabrication techniques [69]. However, achieving commercial viability for OPVs presents notable challenges, especially in maintaining efficiency and stability during large-scale production, alongside the issue of high production costs [63]. A key limiting factor for OPVs is their lower thermal and photochemical stability compared to inorganic semiconductors [63]. This reduced stability is often attributed to the presence of highly reactive double bonds and weaker intermolecular forces [32]. Despite these limitations, substantial efforts have been dedicated to the development of OPVs. This includes optimizing new material designs and investigating photophysical processes that underlie their efficiency. Understanding these processes is crucial, as it informs strategies for enhancing stability and performance, which are imperative for their practical application. This ongoing research and development are pivotal in overcoming the challenges faced by OPVs and unlocking their full potential in various applications, from consumer electronics to large-scale renewable energy solutions. Despite the limitations of OPVs, there is an anticipation that in the near future, billions of devices could be interconnected through the "Internet of Things" (IoT) [70]. For this interconnected network, OPVs, with their rapid response and relatively low energy production, could be ideal. They offer the potential for seamlessly integrating energy harvesting capabilities into a myriad of devices and surfaces, facilitating a widespread, energy-efficient IoT network. The development of such systems would significantly advance the implementation of IoT in everyday applications, revolutionizing how devices communicate and operate within this interconnected framework.

In the realm of advancing photovoltaic technologies, significant strides have been made in the commercial viability and scalability of perovskite materials. Different efforts have been primarily focused on the large-area coating of perovskites and the fabrication of high-efficiency solar modules. The latest efficiency benchmarks, as indicated in the solar cell efficiency table (version 62) [71], demonstrate the practicality of these materials in real-world applications. A notable Power Conversion Efficiency (PCE) of 24.35% was achieved for a module with an area of 1 cm^2, and a substantial efficiency of 22.4% was recorded for a larger module spanning 26 cm^2 [71]. These figures underscore the potential of perovskites in scalable solar energy solutions.

The transition from laboratory-scale experiments to large-scale applications necessitates a reevaluation of the standard practices used in perovskite film formation. Typically, polar aprotic solvents such as dimethyl sulfoxide or N,N-dimethylformamide (DMF), which are effective in small-scale spin-coating procedures, face challenges when applied to larger areas [72]. Their slow evaporation rates and strong interaction with components like Lewis acidic PbI_2 in the coating solution can lead to non-uniform films, a significant barrier in scaling up production. To address these challenges, the chemistry of precursors has been adjusted, prioritizing solvents that offer a balance between evaporation rate and interaction with perovskite constituents. Innovations in precursor engineering have led to the development of coating solutions suitable for large-area applications. For instance, the use of acetonitrile or 2-methoxyethanol as a solvent has shown promising results in maintaining uniformity and quality of perovskite films on larger substrates [73]. This advancement is critical, considering that the quality of the perovskite layer directly influences the efficiency and durability of photovoltaic modules. Moreover, the introduction of cluster forms of perovskites and the strategic use of lead acetate as a kinetic controller have further enhanced the film quality and, consequently, the overall performance of perovskite-based solar cells [74]. These developments not only mark a significant step towards the commercialization of perovskite photovoltaic materials but also highlight the scalability of these technologies. The ability to produce high-quality perovskite films over large areas efficiently paves the way for their widespread adoption in the solar energy sector. This scalability is vital for meeting the growing demands for renewable energy sources and positions perovskite materials as a key player in the future of solar technology.

5.3. Environmental Impact

The environmental impacts of organic, silicon, and perovskite photovoltaics are diverse and significantly influence sustainable energy solutions. These materials, each at the forefront of solar technology, present unique advantages and challenges. A comprehensive understanding of their

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environmental impact requires examining the entire life cycle, including manufacturing processes, energy efficiency, recycling potential, and overall sustainability.

Silicon-based photovoltaics, being the most prevalent solar technology, have undergone considerable advancements to mitigate their environmental impact, especially in manufacturing. Recent studies focus on the energy-intensive nature of silicon photovoltaic production. For instance, Zhang *et al.* [75] emphasized the need to minimize environmental impacts in thin-film silicon photovoltaic production, advocating integrated facilities and scenario functionality as key solutions. Maalouf's research also highlights that multicrystalline silicon demonstrates higher environmental impacts compared to thin-film technologies [76]. Jia *et al.* [77] further suggest that advancements in manufacturing technology and the adoption of less harmful materials can diminish the environmental effects of PV power plants, like CO_2 emissions and land use. Important strides in sustainability are also seen in the recycling efforts of silicon-based photovoltaics. Ziemińska-Stolarska *et al.* [78] note that recycling specific elements in silicon-based modules can reduce the total carbon footprint, marking significant progress in the industry's sustainability. Liang and You [79] add that localizing silicon PV manufacturing (reshoring) contributes to decarbonization by lowering greenhouse gas emissions and energy consumption. The environmental impacts of wide bandgap materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN), as discussed by S. Glaser *et al.* [80], are areas that require further exploration.

In the realm of organic photovoltaic materials, recent research has underscored the development of innovative materials and processing techniques. Yu-Wei Su et al. [81] discuss advancements such as sequential deposition and layer-by-layer methods that enhance power conversion efficiency and expand potential applications, including in agriculture and greenhouses. The integration of organic photovoltaic systems in buildings, as explored by Jānis Kramens *et al.* [82], suggests that these systems may offer more sustainable solutions for single-family buildings, particularly in reducing particulate matter formation and global warming impacts. Recycling in the organic photovoltaic sector, emphasized by Ziemińska-Stolarska *et al.* [78], plays a crucial role in diminishing the environmental load, with a significant focus on effective recycling and recovery methods. In additional research conducted by Solak *et al.* [83], it is emphasized that organic photovoltaics represent a clean and eco-friendly technology with significant potential to reduce greenhouse gas emissions. This characteristic positions them as a viable and sustainable alternative to fossil fuel-based energy sources. Solak's study highlights the environmental benefits of integrating organic photovoltaics in the pursuit of reducing our carbon footprint and advancing towards greener energy solutions.

Regarding the third type of materials studied in this review, perovskites are emerging as an efficient alternative to traditional photovoltaics. Leccisi and Fthenakis [84] conducted a comprehensive life cycle analysis comparing perovskite PV systems with crystalline-silicon and thin-film PV, finding that perovskites, especially those produced via roll-to-roll printing, have a lower environmental impact and comparable energy return on investment to single-crystalline-silicon PV within 12 years. Interfacial engineering in perovskite cells, crucial for addressing degradation from external factors, was a key focus of Kymakis's work [46]. The environmental sustainability of perovskite PV systems, as discussed by Weyand *et al.* [85], hinges on achieving a five-year lifetime to qualify as a climate-friendly technology globally. In another research, Tan *et al.* [86] emphasize the importance of life cycle sustainability assessment in supporting the sustainable development of solar power generation, including perovskite solar cells. The recycling of perovskite solar cells, as shown by Ziemińska-Stolarska *et al.* [78], can reduce the environmental load significantly, highlighting the importance of sustainable end-of-life management. In line with these developments, McCalmont *et al.* [87] demonstrated the economic viability of recycling perovskite photovoltaics, suggesting a shift towards more sustainable practices in the industry. This research underscores the potential for perovskite photovoltaics not only in terms of efficiency and performance but also in their lifecycle management, advocating for environmentally responsible and economically feasible recycling methods. Lastly, Leccisi *et al.* [88] also discuss the 'Direct Wafer' technology in perovskite solar cells,

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showing notable reductions in energy demand and global warming potential, indicative of more sustainable production methods.

The sustainability of photovoltaic technologies, including silicon, organic, and perovskite photovoltaics, has been analyzed using life cycle assessment methodology. Urbina's study [89] finds that solar electricity has lower impacts than fossil fuel electricity in various categories, emphasizing the need to consider potential risks arising from mineral scarcity in certain technologies. Another relevant aspect is the environmental impact of materials used in modern solar panels, such as transparent conductive materials, encapsulation polymers, and antireflective coatings, as discussed by Dallaev *et al.* [90].

In conclusion, the aspects that affect the environmental impact and potential recyclability of photovoltaic materials used in photovoltaic systems constitute a complex and evolving field. Continuous advancements and innovations are shaping a more sustainable future for solar energy. It is crucial to understand and address the environmental implications of these technologies for their long-term viability and effectiveness in contributing to global sustainability goals. These environmental aspects must develop in tandem with current systems and with new materials that will be developed and employed in this technology, ensuring a harmonious and sustainable advancement in the field of photovoltaics.

6. Innovations on the Horizon: Next-Generation of Photovoltaic Materials

Silicon has long been the dominant material in photovoltaic technology due to its abundant availability and well-established manufacturing processes. As the second most common element in the Earth's crust, silicon's natural abundance and mature processing techniques have made it the go-to choice for solar cell production for decades. However, despite its advantages, silicon's limitations in terms of efficiency and the complexities involved in its production have paved the way for exploring alternative materials. This shift is propelled by the need for more efficient energy conversion and the urge to reduce the environmental and economic costs linked to silicon PV technology.

The emergence of materials like perovskites, organic photovoltaics (OPV), and quantum dots marks a transformative phase in solar technology, promising a future where solar cells are not just more efficient, but also more adaptable, lightweight, and environmentally friendly.

Perovskites: Perovskite materials have rapidly gained attention in PV research due to their impressive power conversion efficiencies, jumping from 3.8% in 2009 to over 25% recently. Their rapid advancement reflects their unique properties and the intense research interest they have attracted. Perovskites offer low production costs and easy fabrication methods, making them economically attractive. These materials can be produced using simple techniques like solution processing, which are cheaper and less energy-intensive than traditional silicon methods. Perovskites can also be tailored at the molecular level to optimize light absorption, a crucial aspect in enhancing solar cell efficiency. When used in tandem solar cell architectures, layering them with silicon or other photovoltaic materials, they have the potential to exceed the efficiency limits of single-junction solar cells, making them a promising option for next-generation solar technologies [91–94].

Organic Photovoltaics (OPVs): OPVs signify a major shift in PV technology, being composed of carbon-based materials. These materials offer unique benefits like mechanical flexibility, leading to innovative applications such as foldable solar panels and integration into fabrics. The potential for transparent and colored solar cells opens up exciting possibilities for architectural design. While current efficiencies of OPVs are lower than those of silicon, ongoing research is continually improving their light absorption and charge transport properties, enhancing their performance [95].

Quantum Dots: Quantum dot solar cells utilize tiny semiconductor particles whose bandgap is tunable based on their size. This property allows them to absorb different wavelengths of light more efficiently than traditional materials. Quantum dots can be engineered to create multi-junction solar cells capable of absorbing a wider spectrum of sunlight, potentially achieving much higher efficiencies than current single-junction cells. An intriguing application of quantum dots is in 'spray-

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on' solar cells, which could revolutionize solar cell deployment by allowing photovoltaic materials to be applied to various surfaces, including buildings, vehicles, and clothing [91,96].

In addition to these new materials, advancements in solar technology include tandem solar cells, building-integrated photovoltaics (BIPV), and concentrated photovoltaic systems (CPV). Tandem cells combine different materials to capture a broader range of the solar spectrum, overcoming the limits of single-junction cells [97]. BIPV technology integrates photovoltaics into buildings, extending beyond rooftop installations to embed cells in windows, facades, and roofing materials, which is especially promising for urban areas with space constraints [98]. CPV systems use lenses or mirrors to focus sunlight onto small areas of high-efficiency solar cells, increasing power output per unit area and making them effective in regions with high solar irradiance [99].

The future of photovoltaic materials is deeply connected to interdisciplinary research, where the fusion of material science, nanotechnology, and engineering is vital to surpass current limitations and fully realize the potential of these technologies. Exploring hybrid systems combining different types of solar cells and developing novel nanostructured materials are crucial in advancing the field. Furthermore, the sustainability of these technologies is paramount, with an emphasis on recyclability and environmentally friendly production processes to ensure sustainable growth of solar technology.

The outlook for photovoltaic materials is both dynamic and full of promise. As we venture into the next era of materials and technologies, the focus is firmly on boosting efficiency, curbing costs, and unveiling novel applications. This progress is poised to make solar power not only more accessible but also a seamlessly integrated part of everyday life. The fusion of cutting-edge materials with advanced technologies is at the forefront of driving the solar energy revolution, playing a crucial role in steering us towards a future anchored in sustainable and renewable energy. This transformative phase in photovoltaic materials is a pivotal move towards fulfilling global energy needs in a manner that is both sustainable and environmentally conscious, heralding a new chapter in the utilization of solar energy.

7. Conclusions

Silicon solar cells, which currently dominate the solar energy industry, are lauded for their exceptional efficiency and robust stability. These cells are the product of decades of research and development, leading to their widespread adoption in different solar applications. However, despite their technological maturity, silicon cells still grapple with economic challenges. The key lies in optimizing production costs without compromising their performance, a task that demands innovative approaches in manufacturing techniques and material sourcing. Organic solar cells, on the other hand, present a fascinating contrast. They are celebrated for their versatility in production and the potential for reduced manufacturing costs, primarily due to their lightweight, flexible nature, and compatibility with roll-to-roll fabrication processes. This makes them particularly suitable for applications where traditional rigid panels are impractical. Nonetheless, these organic variants face significant obstacles in terms of efficiency and longevity. Their relatively lower efficiency rates, coupled with a susceptibility to degradation, underscore the need for continued research into novel organic photovoltaic materials and protective coatings that can extend their operational lifespan. Perovskite solar cells have emerged as a disruptive technology in the realm of solar energy. Characterized by their high efficiency and relatively simple fabrication process, they stand as a promising alternative to conventional photovoltaics. The remarkable progress in perovskite cell efficiency within a short period has generated considerable excitement in the research community. However, issues related to the stability of these cells, particularly under environmental stressors such as moisture and temperature fluctuations, pose significant challenges. Moreover, the environmental impact of perovskite cell materials, some of which may contain lead, raises concerns that necessitate the exploration of eco-friendly alternatives and recycling strategies.

In addressing these diverse challenges, the paper underscores the imperative for innovative research. Advancing solar energy technologies towards the pinnacles of sustainability, efficiency, and economic viability requires a multifaceted approach. It calls for concerted efforts in improving material properties – such as enhancing light absorption and charge transport mechanisms, boosting the development of novel materials, and refining existing ones. Simultaneously, it is critical to enhance manufacturing processes, making them more efficient, scalable, and environmentally benign. This includes exploring low-cost, high-throughput manufacturing techniques and developing sustainable supply chains. Furthermore, ensuring environmental safety is paramount. This involves not only minimizing the ecological footprint of solar cell production but also addressing the lifecycle impacts of these technologies, including end-of-life management and recycling. Research in this domain should aim at developing solar cells with minimal environmental impact, from cradle to grave.

In conclusion, this review paints a comprehensive picture of the current state and future directions of solar energy development. It calls for a balanced focus on material science, engineering innovations, and environmental considerations, paving the way for a future where solar energy is not only technologically advanced but also economically feasible and environmentally sustainable. This holistic approach will undoubtedly shape the trajectory of solar energy development in the years to come, playing a crucial role in the global transition to renewable energy sources.

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List of Acronyms

BHJ: Bulk heterojunction
BIPV: Building-integrated photovoltaics
c-Si: Crystalline silicon
CPV: Concentrated photovoltaic system
CIGS: Copper indium gallium sulfur/selenide
CSPC: Carrier selective passivating contact
Cz-Si: Czochralski-grown silicon
DST: Double-side textured
EQE: External quantum efficiency
ETL: Electron Transport Layer
FTO: Fluorine doped tin oxide
HTL: Hole Transport Layer
IBC: Interdigitated back contact
IoT: Internet of things
LCA: Life cycle assessment
MOF: Metal-organic framework
NBG: Narrow bandgap
OPV: Organic photovoltaic cell
OSC: Organic solar cell
PCE: Power conversion efficiency
PERC: Passivated emitter and rear cell
PID: Potential-induced degradation
PSC: Perovskite solar cell
PSM: Perovskite solar module
R2R: roll-to-roll
S2S: sheet-to-sheet
S-Q: Shockley-Queisser
SRH: Shockley-Read-Hall

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SST: Singe-side textured
TSC: Tandem solar cell
TOPCon: Tunnel oxide passivated contact
WBG: Wide bandgap

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