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Photon Energy Conversion Enhances Perovskite Photovoltaics

1.1 The Growing Global Energy Crisis and the Role of PVs

The global energy landscape is undergoing a significant transformation, driven by escalating energy demands, environmental concerns, and technological advancements. Photovoltaic (PV) technology, which converts sunlight directly into electricity, has emerged as a pivotal player in this transition. This section delves into the current global energy crisis and examines the critical role of PVs in addressing these challenges [1].

1.1.1 The Global Energy Crisis

As of 2024, the world is grappling with an unprecedented energy crisis characterized by soaring demand, supply constraints, and environmental degradation [2]. Global energy consumption has reached record levels, propelled by population growth, industrialization, and urbanization, particularly in emerging economies. This surge in demand has strained existing energy infrastructures and heightened competition for finite fossil fuel resources. Concurrently, the environmental ramifications of fossil fuel dependence have become increasingly apparent. The International Energy Agency (IEA) reports that carbon dioxide emissions from energy reached an all-time high in 2023, exacerbating climate change and its associated impacts, such as extreme weather events and rising sea levels [1, 3, 4]. The urgency to transition to sustainable energy sources has never been more pronounced.

1.1.2 The Role of PVs

PV technology has experienced unprecedented growth and innovation, cementing its position as a cornerstone of renewable energy solutions [5–7]. The remarkable progress in this field highlights its critical role in addressing the global energy crisis

and transitioning toward a sustainable energy future. One of the most notable achievements of PV technology is its rapid global deployment. In 2024, global PV installations are expected to exceed 500 gigawatts (GW), reflecting a substantial increase from previous years. This remarkable growth has been driven by advancements in manufacturing techniques, such as automation and improved material utilization, which have lowered production costs and increased scalability. As a result, PV technology is now able to meet rising energy demands in a more efficient and timely manner, making it an essential part of global energy strategies.

A significant factor contributing to the widespread adoption of PV systems is their cost competitiveness. Over the past decade, the cost of solar PV has declined dramatically, transforming it into one of the most affordable sources of electricity. This cost reduction is largely attributed to economies of scale, technological improvements, and increased market competition. In many regions, the cost of electricity generated by solar PV is now lower than that of conventional fossil fuels, such as coal and natural gas. This affordability has not only accelerated adoption in industrialized nations but also opened opportunities for developing countries to enhance their energy security and provide access to electricity in underserved communities.

The environmental benefits of PV technology further underscore its importance in global energy transitions. Unlike fossil fuels, solar PV systems generate electricity without emitting greenhouse gases during operation. This characteristic makes them a vital tool in combating climate change and reducing the environmental footprint of energy production. The widespread deployment of PV systems has already led to significant reductions in carbon dioxide emissions, aligning with international climate goals such as the Paris Agreement. Additionally, solar energy systems contribute to reduced air and water pollution, further enhancing their environmental credentials.

Technological advancements have also played a pivotal role in the evolution and adoption of PV technology. Ongoing research and development efforts have yielded continuous improvements in solar cell efficiency, with modern cells achieving conversion rates that were previously unattainable. At the same time, innovative applications, such as building-integrated photovoltaics (BIPVs) and flexible solar panels [8–13], have expanded the versatility and appeal of solar energy systems. These advancements enable PV technology to be seamlessly integrated into urban environments, agricultural systems, and transportation networks, demonstrating its adaptability to diverse applications and sectors.

The global embrace of PV technology is evident through substantial investments and supportive policies. For instance, the United States is expected to add a record 36.4 GW of utility-scale solar capacity in 2024, nearly doubling the previous year's additions. Similarly, countries such as India have mandated the use of locally manufactured solar cells in clean energy projects, starting June 2026, aiming to bolster domestic manufacturing and reduce reliance on imports.

Furthermore, international collaborations and agreements have been instrumental in promoting PV adoption. The IEA's World Energy Outlook 2024 emphasizes the critical role of solar energy in achieving net-zero emissions by 2050, highlighting

the need for continued investment and policy support to sustain the momentum of PV deployment.

PV technology has become a transformative force in the renewable energy sector, characterized by rapid deployment, cost-effectiveness, environmental benefits, and technological versatility. Its ability to address pressing energy and climate challenges, coupled with robust policy support and global collaboration, positions PV technology as a linchpin of the sustainable energy transition. As innovation and adoption continue to accelerate, solar energy is poised to play an even greater role in shaping a cleaner, greener, and more equitable energy future.

1.1.3 Challenges and Future Outlook

Despite the promising trajectory, challenges persist in the widespread adoption of PV technology. Grid integration, energy storage solutions, and the need for advancements in PV efficiency require ongoing attention. Additionally, geopolitical factors, such as resource nationalism and trade policies, can influence the global supply chain for PV components, necessitating strategic planning and international cooperation.

Looking ahead, the role of PVs in the global energy mix is poised to expand further. Projections indicate that solar energy could account for a substantial share of global electricity generation by 2030, driven by continuous technological innovations and supportive policy frameworks. The integration of PV technology with energy storage systems and smart grid solutions will be pivotal in enhancing energy reliability and meeting the dynamic demands of the future.

Thus, PVs stand as a cornerstone in the global endeavor to address the energy crisis. Its rapid deployment, cost-effectiveness, and environmental benefits make it an indispensable component of sustainable energy strategies worldwide. Continued investment, innovation, and policy support will be essential in harnessing the full potential of PV technology to achieve a resilient and sustainable energy future.

1.2 Emergence of Perovskite Photovoltaics

Perovskite solar cells (PSCs) have rapidly emerged as a transformative technology in the field of PVs, offering the potential for high efficiency and low-cost solar energy conversion. This section delves into the historical development of PSCs, highlighting key technological milestones and the inherent advantages that make them a promising alternative to traditional silicon-based solar cells.

1.2.1 Historical Development and Key Technological Milestones

The journey of perovskite materials in solar cell applications began with the discovery of the mineral perovskite (calcium titanium oxide [CaTiO_3]) in 1839 by German mineralogist Gustav Rose. Named after Russian mineralogist Lev Perovski, the perovskite structure is characterized by the general formula ABX_3 , where “A” and

“B” are cations of differing sizes, and “X” is an anion, typically oxygen or a halide. This versatile crystal structure allows for a wide range of elemental compositions, enabling the tuning of various material properties.

The application of perovskite materials in PVs gained significant attention in 2009 when Tsutomu Miyasaka and colleagues reported a perovskite-based, dye-sensitized solar cell with a power conversion efficiency (PCE) of 3.8% [14]. However, these early devices exhibited poor stability due to the use of liquid electrolytes, leading to rapid degradation. A pivotal advancement occurred in 2012 when researchers demonstrated that replacing the liquid electrolyte with a solid-state hole transport material significantly improved both the efficiency and the stability of PSCs. This innovation led to a PCE exceeding 10%, marking a substantial leap in performance. Until 2024, the PCEs of PSCs have reached 27%.

1.2.2 Subsequent Years Witnessed a Series of Breakthroughs

Here is a timeline of the development of PSCs from 2009 to 2024, with key milestones and important research achievements for each year:

2009: First introduction of perovskite materials for solar cells: the concept of using perovskite materials in solar cells was introduced. Tsutomu Miyasaka and co-workers discovered that organometal halide perovskites act as visible-light sensitizers for photovoltaic cells and offer excellent light absorption and charge transport properties, setting the foundation for future advancements [14].

2011: Nam-Gyu Park and co-workers reported a 6.5% efficient perovskite quantum-dot-sensitized solar cell. They fabricated a highly efficient perovskite quantum-dot-sensitized solar cell using MAPbI₃ nanocrystals. By spin-coating an equimolar mixture of methylammonium iodide (MAI) and PbI₂ in γ -butyrolactone onto a nanocrystalline TiO₂ surface, they achieved a solar-to-electrical conversion efficiency of 6.54% and a maximum external quantum efficiency (EQE) of 78.6% at 530 nm, setting a record among reported inorganic quantum dot sensitizers [15].

2012: Breakthrough in efficiency: Nam-Gyu Park's team was the first to report a solid-state organic-inorganic hybrid PSC with an efficiency close to 10%, which is considered a milestone in the development of Perovskite Photovoltaics [16]. In the same year, Henry Snaith's team in the UK introduced chlorine into the perovskite structure for the first time and used the inorganic compound aluminum oxide (Al₂O₃) to replace titanium dioxide (TiO₂), demonstrating that perovskite can serve not only as a light-absorbing layer but also as an electron transport layer, achieving a cell efficiency of 10.9% [17].

In 2013, Snaith and his colleagues fabricated perovskite films using a co-evaporation method, creating a novel planar heterojunction cell with an efficiency of 15.4%, garnering worldwide attention [18].

2015: First perovskite photovoltaics surpassing 20% efficiency: the efficiency of perovskite photovoltaics surpassed 20% for the first time, achieving an efficiency of 20.1% by a team at the University of Oxford. This set a new benchmark for PSC performance.

2016: Stability improvement: research focused on enhancing the stability of perovskite photovoltaics, which had previously been a challenge due to their

degradation in humid and high-temperature environments. The introduction of new materials, such as hole-transport layers, helped improve long-term stability.

2017: Record efficiency of 22% achieved: researchers reached a new efficiency record of 22.1% for perovskite photovoltaics, bringing them closer to commercial viability. This year also saw significant efforts in scaling up perovskite photovoltaics for practical applications.

2018: Commercialization efforts and scaling-up: major companies, including the German firm Helmholtz-Zentrum Berlin, began scaling up the production of perovskite photovoltaics, focusing on improving mass production techniques and achieving long-term durability. Several pilot projects aimed at commercializing perovskite photovoltaics were initiated.

2019: Efficiency of 25.2% achieved: researchers at the University of Korea reported achieving 25.2% efficiency for perovskite photovoltaics, a major milestone indicating that perovskite photovoltaics had become competitive with silicon-based solar cells.

2020: Perovskite–silicon tandem cells reach 29.1% efficiency: a breakthrough occurred when researchers combined perovskite and silicon in tandem solar cells, reaching an efficiency of 29.1%. This demonstrated the potential for perovskite photovoltaics to complement silicon-based technologies and provide even higher efficiencies.

2022: Commercialization and industrial production advancements: major advancements were made toward large-scale manufacturing of perovskite photovoltaics, with companies such as Oxford PV and others scaling up production for commercial markets. The focus shifted toward developing cost-effective, stable, and efficient perovskite solar modules.

2024: Perovskite–silicon tandem solar cells surpass 34% efficiency: a new efficiency record of 34.6% was achieved for perovskite–silicon tandem solar cells, positioning perovskite technology as a strong contender in the renewable energy market. The commercialization of perovskite photovoltaics is rapidly advancing, with several companies planning to mass-produce high-efficiency modules.

This timeline highlights the rapid evolution of perovskite photovoltaics, with continual improvements in efficiency, stability, and commercialization prospects. The field is now one of the most exciting areas of research in renewable energy technology. Presently, the research focus has shifted toward scalability and commercialization, with efforts to develop large-area PSCs and tandem configurations. Notably, perovskite–silicon tandem cells achieved efficiencies exceeding 34%, demonstrating the potential to surpass the Shockley–Queisser limit for single-junction solar cells. In the future, research continues to address challenges related to long-term stability, scalability, and environmental concerns, with the goal of bringing PSCs to commercial viability.

1.2.3 Advantages of Perovskite Photovoltaics

PSCs have revolutionized the PV landscape due to their exceptional efficiency, cost-effectiveness, and versatility compared to traditional silicon-based solar cells. One of the most significant advantages of PSCs is their rapid improvement in PCE.

Since their initial development in 2009, when the PCE was a mere 3.8%, PSCs have seen unparalleled growth, reaching over 27% in just a decade. This progress highlights the material's exceptional light-harvesting capabilities, which stem from its high absorption coefficient and tunable electronic properties. In fact, theoretical studies suggest that single-junction PSCs can achieve a maximum efficiency of 31%, while multi-junction or tandem PSCs have the potential to reach an astounding 45%. These values significantly surpass the efficiency limit of 29.4% for silicon-based solar cells, establishing PSCs as a leading candidate for next-generation PVs.

In addition to their efficiency, PSCs hold a distinct advantage in terms of fabrication processes. Unlike silicon solar cells, which require high-temperature and energy-intensive manufacturing, perovskite materials can be processed using solution-based techniques at low temperatures. Methods such as spin-coating, blade coating, and inkjet printing enable scalable and versatile fabrication, greatly reducing production costs. Furthermore, perovskite materials are inherently less sensitive to impurities, meaning that high-performance devices can be produced even with material purities as low as 90%. This contrasts sharply with the stringent purity requirements of silicon PVs, which demand ultrapure silicon at significant expense. By lowering both energy and material costs, PSCs pave the way for more accessible and affordable solar energy solutions, particularly in regions with limited manufacturing infrastructure.

The availability and abundance of perovskite's constituent materials further enhance its cost-effectiveness and scalability. Perovskite materials, typically composed of inexpensive elements, such as lead, tin, and halides, are far more abundant compared to the raw materials required for silicon-based solar cells. This abundance ensures that PSCs can be produced on a large scale without concerns over material scarcity. Moreover, ongoing research into lead-free alternatives, such as tin-based perovskites, aims to mitigate environmental and toxicity concerns associated with lead-containing formulations, further improving the technology's sustainability and public acceptance.

Another significant advantage of PSCs lies in their flexibility and lightweight nature. Perovskite materials can be deposited onto flexible substrates, such as plastics or thin films, without compromising their performance. This capability opens up new avenues for integrating PSCs into nontraditional applications, including wearable electronics, portable energy devices, and BIPVs. Flexible and lightweight PSCs are particularly attractive for futuristic designs, such as solar-powered fabrics, curved surfaces, and transparent solar windows. These advancements make PSCs highly versatile and capable of meeting the growing demand for solar energy in both conventional and innovative applications.

The tunability of the perovskite bandgap is another key feature that sets PSCs apart. By adjusting the chemical composition of perovskite materials – typically through the substitution of cations (e.g. methylammonium and formamidinium) or halides (e.g. iodide, bromide, and chloride) – researchers can precisely control the material's bandgap. This tunability allows PSCs to optimize light absorption across the solar spectrum, enhancing their efficiency under various lighting conditions. It also enables the creation of tandem solar cells, where wide-bandgap perovskites are

paired with narrow-bandgap materials to achieve complementary light absorption. Such tandem architectures have demonstrated remarkable efficiencies, surpassing what is achievable with single-junction silicon devices.

Lastly, the ease of fabrication associated with perovskite materials has been a driving force behind their rapid development. Perovskites are solution-processable, which means they can be deposited using simple and cost-effective techniques. This flexibility in manufacturing makes it possible to produce large-area PSCs, as well as devices with complex geometries, without requiring specialized equipment. Techniques such as slot-die coating and roll-to-roll printing are being developed to enable the mass production of perovskite solar modules, further bridging the gap between laboratory-scale performance and real-world deployment.

In summary, the emergence of PSCs represents a paradigm shift in PV technology. Their unparalleled efficiency, low fabrication costs, material abundance, lightweight flexibility, tunable bandgap, and scalable manufacturing processes provide a comprehensive solution to many of the limitations faced by traditional silicon-based solar cells. While challenges such as long-term stability and environmental concerns remain, ongoing research continues to push the boundaries of PSC performance and reliability. With their remarkable advantages, PSCs have the potential to transform solar energy into an affordable, efficient, and ubiquitous power source, accelerating the global transition to sustainable energy.

1.2.4 Challenges and Future Prospects

Despite their remarkable progress and potential, PSCs face significant challenges that must be resolved for them to achieve commercial viability. These challenges primarily revolve around issues of stability, toxicity, and scalability, which hinder their widespread adoption.

The long-term operational stability of PSCs remains one of the most pressing issues [19–22]. Perovskite materials are inherently susceptible to degradation when exposed to environmental factors such as moisture, oxygen, heat, and UV light. Moisture and oxygen intrusion can lead to the dissolution of the perovskite crystal structure, resulting in rapid performance loss. Similarly, UV light and thermal exposure can cause material degradation or phase instability, further reducing the efficiency and lifespan of PSC devices. Addressing these stability issues is crucial for ensuring reliable operation over decades, akin to the stability standards of silicon-based solar cells.

Efforts to enhance stability have primarily focused on encapsulation techniques and material engineering. Advanced encapsulation methods using barrier layers, such as polymers and glass coatings, can effectively protect PSCs from environmental exposure. Additionally, compositional engineering – such as replacing volatile organic cations (e.g. methylammonium) with more stable alternatives such as formamidinium or cesium – has significantly improved thermal and structural stability. Further advancements in passivation techniques, which reduce defects and recombination sites in the perovskite layer, are also critical for improving device durability.

Another major challenge in PSC technology is the widespread use of lead in high-efficiency formulations [23–25]. Lead is a toxic heavy metal with well-documented environmental and health risks. Concerns over potential lead leakage during the lifecycle of PSCs, especially in the event of device damage or improper disposal, have raised significant regulatory and public acceptance issues. This challenge necessitates the development of lead-free perovskite alternatives.

Current research into lead-free perovskites has focused on replacing lead with other metals, such as tin, bismuth, or antimony. Tin-based perovskites (e.g. CsSnI_3) have shown promise due to their similar electronic properties, but they are highly sensitive to oxidation, leading to rapid degradation. Strategies to stabilize tin-based perovskites, such as the use of reducing agents or protective layers, are under active investigation. While lead-free alternatives are a critical area of development, they currently lag behind lead-based PSCs in terms of efficiency and stability. Thus, balancing environmental concerns with performance remains a key challenge.

The transition from laboratory-scale prototypes to commercially viable, large-area PSC modules presents additional hurdles [26–31]. Fabricating uniform and defect-free perovskite films over large areas is challenging due to the material's sensitivity to processing conditions. Variability in film thickness, crystal quality, and defect density can lead to performance inconsistencies in large-area devices.

Moreover, integrating PSCs with existing PV technologies, such as silicon-based solar panels, requires overcoming compatibility issues in terms of device architecture and fabrication processes. For instance, tandem perovskite–silicon cells demand precise alignment of subcell bandgaps and current matching to maximize efficiency. Additionally, roll-to-roll manufacturing, which is essential for large-scale production, introduces complexities in maintaining uniformity and reproducibility during deposition.

Advances in scalable deposition techniques, such as slot-die coating, spray coating, and blade coating, are paving the way for large-area PSC manufacturing. These methods aim to combine high-throughput production with consistent film quality. Furthermore, improvements in ink formulations, drying conditions, and substrate design are helping to bridge the gap between laboratory and commercial-scale devices.

To overcome these challenges, ongoing research is exploring innovative strategies across several domains. Stability improvements remain a top priority, with significant progress being made in the development of robust encapsulation systems and chemically stable perovskite compositions. Tandem architectures, such as perovskite–silicon and perovskite–perovskite configurations, offer a promising path to achieve efficiencies well beyond the limits of single-junction cells. These tandem devices leverage the tunable bandgap of perovskites to optimize light absorption across the solar spectrum, potentially reaching theoretical efficiencies exceeding 40%.

In addition to technical advancements, sustainable manufacturing practices and circular economy principles are gaining attention. Recycling and recovery of perovskite materials, along with eco-friendly encapsulation approaches, could mitigate environmental concerns and improve the lifecycle sustainability of PSCs.

Collaborations between academia, industry, and policymakers are also crucial for accelerating the commercialization of PSCs. Standardized testing protocols for stability, efficiency, and environmental impact are needed to ensure that PSCs meet the rigorous demands of real-world deployment. Furthermore, government incentives and funding programs can drive investments in research and infrastructure to bring PSC technology to the market.

While challenges remain, the future of PSCs is incredibly promising. Advances in stability, toxicity mitigation, and scalability are steadily closing the gap between laboratory performance and commercial viability. As these challenges are addressed, PSCs are poised to revolutionize the PV industry, offering a high-efficiency, low-cost, and sustainable solution for global energy needs. With continued innovation and collaboration, PSCs have the potential to become a cornerstone of the renewable energy landscape, contributing significantly to the transition toward a more sustainable future.

1.3 Challenges in Spectral Response and Photon Management of Perovskite Photovoltaics

PSCs exhibit exceptional optical properties, including a high absorption coefficient and a tunable bandgap, making them highly efficient in converting sunlight into electricity. However, limitations in their spectral response and photon management continue to pose significant challenges. Addressing these issues is crucial for PSCs to achieve their theoretical efficiency potential and practical applicability in real-world solar energy systems.

1.3.1 Limited Spectral Utilization

One of the primary challenges in PSCs is their inability to fully utilize the solar spectrum, particularly in the NIR and UV regions. Most perovskite materials exhibit bandgaps in the range of 1.5–1.7 eV, which makes them highly efficient at absorbing visible light but less effective in the NIR region, which accounts for nearly 40% of the solar spectrum's energy. As a result, photons with energies below the material's bandgap pass through the active layer without being absorbed, leading to sub-bandgap energy losses. On the other hand, high-energy photons in the UV region often exceed the bandgap energy, resulting in thermalization losses where the excess energy is dissipated as heat. Combined, these limitations significantly reduce the overall efficiency of PSCs.

To address these spectral mismatches, innovative strategies such as bandgap engineering and tandem cell architectures have been explored. Bandgap engineering involves the precise tuning of the perovskite material's composition to absorb a broader range of wavelengths. Mixed halide perovskites, for example, have shown promise in extending spectral response by incorporating elements such as bromine and iodine. However, achieving long-term stability and maintaining high efficiencies across varying bandgap compositions remains a challenge.

1.3.2 Photon Management Challenges

Photon management, which encompasses strategies to enhance light absorption, minimize reflection losses, and maximize the interaction of photons with the active layer, is another critical area for PSC development. Despite the high absorption coefficient of perovskites, photon losses still occur due to factors such as reflection at the device surface, suboptimal light trapping, and parasitic absorption within non-active layers (e.g. charge transport layers (CTLs) and electrodes).

1.3.2.1 Surface Reflection and Light Scattering

A significant portion of incident sunlight is reflected off the surface of the PSC device, particularly at the air–glass interface. This reflection loss reduces the amount of light entering the active layer. While antireflective coatings (antireflective coatings) can mitigate this issue, designing antireflective coatings compatible with the unique fabrication processes and operational conditions of PSCs is challenging. For instance, antireflective coatings must remain stable under UV exposure, moisture, and thermal cycling – factors that are already problematic for PSCs.

1.3.2.2 Light Trapping and Optical Path Optimization

Efficient light trapping is essential for thin-film PSCs to ensure that photons travel longer optical paths within the active layer, maximizing absorption. Traditional approaches, such as texturing or structuring the surface of the substrate, are less effective for perovskites due to their sensitivity to defects and uniformity requirements. Advanced light-trapping techniques, including nanophotonic structures and plasmonic enhancements, have been proposed to address this issue. However, integrating these complex designs into scalable and cost-effective fabrication processes remains an obstacle.

1.3.2.3 Parasitic Absorption and Losses in Non-active Layers

Non-active layers, such as the CTLs and electrodes, contribute to photon losses by absorbing or reflecting light that could otherwise be utilized by the perovskite layer. For example, the transparent conductive oxide (TCO) layers used as electrodes can absorb a portion of the incident light, reducing the overall efficiency of the device. Addressing this challenge requires the development of transparent, conductive materials with minimal parasitic absorption, as well as optimizing the refractive indices of the CTLs to enhance light transmission.

1.3.2.4 Emerging Solutions and Future Directions

Several innovative approaches are being explored to overcome these spectral and photon management challenges. For example, UC and DC techniques are being investigated to extend the spectral response of PSCs. UC involves converting low-energy NIR photons into higher-energy photons that can be absorbed by the perovskite layer, while DC splits high-energy UV photons into multiple low-energy photons to reduce thermalization losses. Although these techniques show promise, they currently suffer from low quantum efficiency and require further development for practical implementation.

Additionally, tandem architectures combining perovskite layers with other materials, such as silicon or organic PVs, have demonstrated significant potential in optimizing spectral utilization. By pairing wide-bandgap perovskites with materials that efficiently absorb NIR light, tandem cells can achieve efficiencies exceeding the limits of single-junction devices. However, challenges in current matching, thermal stability, and fabrication complexity must be addressed to enable large-scale deployment of these architectures.

While PSCs have made tremendous strides in efficiency and adaptability, their spectral response and photon management challenges remain critical bottlenecks to achieving their full potential. Addressing these issues requires a multidisciplinary approach, combining advancements in material science, optical engineering, and device architecture. By overcoming these hurdles, PSCs could revolutionize solar energy technology, paving the way for highly efficient, cost-effective, and scalable renewable energy solutions.

1.4 Photon Management Strategies: Addressing Energy Losses in PSCs

To overcome these limitations, researchers have focused on photon management strategies that aim to optimize light absorption, minimize energy losses, and improve charge carrier generation and transport. Photon management involves the design and implementation of materials, structures, and processes that enhance the interaction between light and solar cells. These strategies include the following.

1.4.1 UC and DC

UC involves converting low-energy NIR photons into high-energy visible photons that can be absorbed by the perovskite layer. This process relies on rare-earth-doped materials (e.g. $\text{NaYF}_4:\text{Yb}^{3+}, \text{Er}^{3+}$), which absorb NIR light and emit visible light through sequential photon absorption. By utilizing the NIR spectrum, UC effectively expands the light absorption range of PSCs and reduces sub-bandgap energy loss.

DC materials, such as nanocrystals, organic dyes, and rare-earth oxides, convert high-energy UV photons into two or more lower-energy photons. This not only reduces thermalization losses but also enhances stability by protecting the perovskite layer from UV-induced degradation.

1.4.2 Tandem and Graded Structures

Tandem solar cells integrate multiple subcells with complementary bandgaps to capture different portions of the solar spectrum. In a tandem configuration, high-energy photons are absorbed by a wide-bandgap top cell, while lower-energy photons pass through and are absorbed by a narrow-bandgap bottom cell. Perovskites are particularly well-suited for tandem structures due to their tunable bandgap and high efficiency. Recent studies have demonstrated perovskite-silicon

tandem cells with efficiencies exceeding 30%, showcasing their potential to surpass the Shockley–Queisser limit for single-junction devices.

1.4.3 Plasmonic Enhancements

Plasmonic nanostructures, such as metallic nanoparticles (e.g. Au and Ag), enhance light absorption in PSCs through localized surface plasmon resonance (LSPR). LSPR generates strong localized electromagnetic fields, which increase the optical path length and enable light trapping within the perovskite layer. Plasmonic effects can also improve charge carrier generation and transport by reducing recombination losses.

1.4.4 Texturing and Light-Trapping Structures

Surface texturing and internal light-trapping structures can enhance light absorption by increasing the optical path length of photons within the active layer. Micro- and nanostructures, such as nanorods, nanoholes, and nanopillars, scatter incident light and confine it within the device, resulting in improved absorption without increasing material thickness.

1.4.5 Antireflective Coatings

Fresnel reflection at the air–glass interface leads to significant optical losses in PSCs. Antireflective coatings, such as nanoporous materials and graded refractive index layers, reduce surface reflection and improve light transmission into the device. By minimizing optical losses, antireflective coatings contribute to higher Short Circuit Current Density (J_{sc}) and overall efficiency.

1.4.6 Luminescent Solar Concentrators (LSCs)

Luminescent solar concentrators (LSCs) utilize luminescent materials to absorb sunlight, re-emit it at specific wavelengths, and guide the light to the edges of the concentrator, where solar cells are located. Perovskite nanocrystals (e.g. CsPbBr_3) have shown great promise for LSC applications due to their high photoluminescence quantum yield (PLQY), tunable emission spectra, and strong optical absorption.

1.5 The Scope of This Work

This book provides a comprehensive and systematic exploration of photon management strategies for improving the efficiency and performance of PSCs. Unlike existing reviews, which focus on isolated techniques, this work integrates multiple strategies – UC, DC, tandem architectures, plasmonic enhancements, light trapping, antireflective coatings, and LSCs – into a unified framework. The key objectives of this book are to (i) analyze the fundamental mechanisms of photon

management strategies and their impact on energy loss reduction, (ii) summarize recent experimental and theoretical advancements in integrating these strategies into PSCs, and (iii) identify the challenges and limitations of current approaches and propose future research directions for high-efficiency, cost-effective PSCs. Furthermore, the book highlights the broader implications of photon management for related fields, such as optoelectronics, light-emitting diodes, and photocatalysis.

1.6 Structure of the Book

This book is organized into the following chapters:

Chapter 1 introduces the challenges of solar energy utilization, the emergence of PSCs, and the need for photon management strategies.

Chapter 2 explores UC processes, materials, and their integration into PSCs for NIR light harvesting.

Chapter 3 introduces DC mechanisms and their role in enhancing UV light utilization and stability.

Chapter 4 presents tandem solar cell architectures and their potential to achieve efficiencies beyond single-junction limits.

Chapter 5 examines plasmonic effects and their applications in light absorption enhancement.

Chapter 6 focuses on light-trapping structures and texturing techniques for improved optical confinement.

Chapter 7 analyzes antireflective coatings and their role in reducing reflection losses.

Chapter 8 introduces LSCs and their potential for BIPVs.

Chapter 9 concludes with a summary of key findings, challenges, and future directions.

In the book, we proposed that photon management strategies hold the key to unlocking the full potential in photon energy conversion for utilizing the energy of PSCs. By addressing the challenges of spectral mismatch, energy losses, and optical limitations, these strategies pave the way for highly efficient, stable, and cost-effective solar technologies. This book provides a comprehensive foundation for researchers and practitioners to explore innovative approaches in photon management, with the ultimate goal of realizing next-generation PVs that can drive the global transition to sustainable energy.

References

- 1 Liu, Z., Deng, Z., Davis, S.J., and Ciais, P. (2024). Global carbon emissions in 2023. *Nature Reviews Earth and Environment* 5 (4): 253–254.
- 2 Corbos, R.-A., Bunea, O.-I., and Jiroveanu, D.-C. (2023). The effects of the energy crisis on the energy-saving behavior of young people. *Energy Strategy Reviews* 49: 101184. <https://doi.org/10.1016/j.esr.2023.101184>.

- 3 Hendryx, M. (2024). The energy transition: where we came from, where we are, and where we are going. In: *Sustainable Development and Rural Public Health: From Fossil Fuels to Greener Futures* (ed. M. Hendryx), 13–22. Springer.
- 4 Valavanidis, A. (2016). Global electricity generation from renewable sources. *Journal* 2 (5): 99–110.
- 5 Gao, W., Ding, J., Ma, Q. et al. (2024). Synergistic modulation of orientation and steric hindrance induced by alkyl chain length in ammonium salt passivator toward high-performance inverted perovskite solar cells and modules. *Advanced Materials* 2413304. <https://doi.org/10.1002/adma.202413304>.
- 6 Liu, B., Ren, X., Li, R. et al. (2024). Stabilizing top interface by molecular locking strategy with polydentate chelating biomaterials towards efficient and stable perovskite solar cells in ambient air. *Advanced Materials* 36 (19): 2312679. <https://doi.org/10.1002/adma.202312679>.
- 7 Zhu, Y., Zhang, Z., Zhao, X. et al. (2024). Heterointerface energetics regulation strategy enabled efficient perovskite solar cells. *Advanced Energy Materials* 14 (13): 2303946. <https://doi.org/10.1002/aenm.202303946>.
- 8 Gong, J., Flatken, M., Abate, A. et al. (2019). The bloom of perovskite optoelectronics: fundamental science matters. *ACS Energy Letters* 4 (4): 861–865. <https://doi.org/10.1021/acsenenergylett.9b00477>.
- 9 Rahmany, S. and Etgar, L. (2020). Semitransparent perovskite solar cells. *ACS Energy Letters* 5 (5): 1519–1531.
- 10 Koh, T.M., Wang, H., Ng, Y.F. et al. (2022). Halide perovskite solar cells for building integrated photovoltaics: transforming building façades into power generators. *Advanced Materials* 34 (25): 2104661. <https://doi.org/10.1002/adma.202104661>.
- 11 Rajagopal, A., Yao, K., and Jen Alex, K.Y. (2018). Toward perovskite solar cell commercialization: a perspective and research roadmap based on interfacial engineering. *Advanced Materials* 1800455. <https://doi.org/10.1002/adma.201800455>.
- 12 Furasova, A., Voroshilov, P., Saponi, D. et al. (2022). Nanophotonics for perovskite solar cells. *Advanced Photonics Research* 3 (9): 2100326. <https://doi.org/10.1002/adpr.202100326>.
- 13 Zhou, Y., Zhao, H., Ma, D., and Rosei, F. (2018). Harnessing the properties of colloidal quantum dots in luminescent solar concentrators. *Chemical Society Reviews* 47 (15): 5866–5890. <https://doi.org/10.1039/C7CS00701A>.
- 14 Kojima, A., Teshima, K., Shirai, Y., and Miyasaka, T. (2009). Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *Journal of the American Chemical Society* 131 (17): 6050–6051.
- 15 Im, J.-H., Lee, C.-R., Lee, J.-W. et al. (2011). 6.5% efficient perovskite quantum-dot-sensitized solar cell. *Nanoscale* 3 (10): 4088–4093. <https://doi.org/10.1039/C1NR10867K>.
- 16 Kim, H.-S., Lee, C.-R., Im, J.-H. et al. (2012). Lead iodide perovskite sensitized all-solid-state submicron thin film mesoscopic solar cell with efficiency exceeding 9%. *Scientific Reports* 2: 591. <https://doi.org/10.1038/srep00591>.
- 17 Lee, M.M., Teuscher, J., Miyasaka, T. et al. (2012). Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites. *Science* 338 (6107): 643–647. <https://doi.org/10.1126/science.1228604>.

- 18 Liu, M.Z., Johnston, M.B., and Snaith, H.J. (2013). Efficient planar hetero-junction perovskite solar cells by vapour deposition. *Nature* 501 (7467): 395–+. <https://doi.org/10.1038/nature12509>.
- 19 Aydin, E., Ugur, E., Yildirim, B.K. et al. (2023). Enhanced optoelectronic coupling for perovskite-silicon tandem solar cells. *Nature* 623: 732–738. <https://doi.org/10.1038/s41586-023-06667-4>.
- 20 Tan, S., Huang, T., Yavuz, I. et al. (2022). Stability-limiting heterointerfaces of perovskite photovoltaics. *Nature* 605 (7909): 268–273. <https://doi.org/10.1038/s41586-022-04604-5>.
- 21 Chen, S., Xiao, X., Gu, H., and Huang, J. (2021). Iodine reduction for reproducible and high-performance perovskite solar cells and modules. *Science Advances* 7 (10): eabe8130. <https://doi.org/10.1126/sciadv.abe8130>.
- 22 Wang, D., Wright, M., Elumalai, N.K., and Uddin, A. (2016). Stability of perovskite solar cells. *Solar Energy Materials and Solar Cells* 147: 255–275. <https://doi.org/10.1016/j.solmat.2015.12.025>.
- 23 Chen, M., Ju, M.-G., Carl, A.D. et al. (2018). Cesium titanium(IV) bromide thin films based stable lead-free perovskite solar cells. *Joule* 2 (3): 558–570. <https://doi.org/10.1016/j.joule.2018.01.009>.
- 24 Nishimura, K., Kamarudin, M.A., Hirotani, D. et al. (2020). Lead-free tin-halide perovskite solar cells with 13% efficiency. *Nano Energy* 74: 104858. <https://doi.org/10.1016/j.nanoen.2020.104858>.
- 25 Hao, F., Stoumpos, C.C., Cao, D.H. et al. (2014). Lead-free solid-state organic-inorganic halide perovskite solar cells. *Nature Photonics* 8 (6): 489–494. <https://doi.org/10.1038/nphoton.2014.82>.
- 26 Abdollahi Nejand, B., Nazari, P., Gharibzadeh, S. et al. (2017). All-inorganic large-area low-cost and durable flexible perovskite solar cells using copper foil as a substrate. *Chemical Communications* 53 (4): 747–750. <https://doi.org/10.1039/C6CC07573H>.
- 27 Kim, Y.C., Kim, K.H., Son, D.-Y. et al. (2017). Printable organometallic perovskite enables large-area, low-dose X-ray imaging. *Nature* 550 (7674): 87–91. <https://doi.org/10.1038/nature24032>.
- 28 Xiao, K., Lin, R., Han, Q. et al. (2020). All-perovskite tandem solar cells with 24.2% certified efficiency and area over 1 cm² using surface-anchoring zwitterionic antioxidant. *Nature Energy* 5 (11): 870–880. <https://doi.org/10.1038/s41560-020-00705-5>.
- 29 Chen, W., Wu, Y., Yue, Y. et al. (2015). Efficient and stable large-area perovskite solar cells with inorganic charge extraction layers. *Science* 350 (6263): 944–948.
- 30 Fuentes-Hernandez, C., Chou, W.-F., Khan, T.M. et al. (2020). Large-area low-noise flexible organic photodiodes for detecting faint visible light. *Science* 370 (6517): 698–701. <https://doi.org/10.1126/science.aba2624>.
- 31 Hong, S., Lee, J., Kang, H. et al. (2018). High-efficiency large-area perovskite photovoltaic modules achieved via electrochemically assembled metal-filamentary nanoelectrodes. *Science Advances* 4 (8): eaat3604. <https://doi.org/10.1126/sciadv.aat3604>.

