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Current trends and future prospects in perovskite solar cells: A review focused on efficiency, stability, and design innovations

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Abstract

Perovskite solar cells (PSCs) have been represented as the next rising star in the field of photovoltaics due to their high efficiency that can be fabricated at very low cost and has a superior photophysical property. Recent improvements have raised PSC efficiency to the point where they can effectively compete with traditional silicon-based cells making them a viable option for modern solar energy systems. This literature review, therefore, synthesizes the recent studies that have delved deeper into the efficiency improvements, stability enhancements, and architectural innovations taking place within the domain of the PSCs. The development of efficiency in power conversion has made much progress through multi-cation perovskites, interface engineering, and tandem cell configurations, as demonstrated by the works of Yao *et al*., T. Chen *et al*., and many others. However, their stabilities under environmental conditions are still challenging. Some studies even point to an advancement in the research of encapsulation techniques or suggest materials with an effort to reach more stable compositions, such as Zhu *et al*. and Kung *et al*. Architectural innovations, for example, the one shown by Rahmany and Etgar, which demonstrate the flexibility of PSCs to a large degree in different applications, include building-integrated photovoltaics and semi-transparent solar cells. The review is concluded with a discussion on the importance of continued research, multidisciplinary approaches to the existing challenges, and the realization of full potential by PSCs. As perovskite technology advances, it seems to promise a very noticeable influence in the solar power industry with more efficient, stable, and flexible solutions to solar energy.

Keywords: Perovskite solar cells, photovoltaic efficiency, solar cell stability, tandem solar cells, building-integrated photovoltaics (BIPV)

1. Introduction

1.1. Overview of perovskite solar cells

Perovskite solar cells (PSCs) have arisen as the potentially game-changing technology in the domain of photovoltaics and displayed mind-blowing progress in terms of efficiency and production cost. (Roy *et al*., 2022) [24] Named after the mineral perovskite, which has a crystal structure, perovskites are characterized with properties alike to that of the mineral. Also, there is the high absorption coefficient and tunable bandgap, which comes with long charge-carrier diffusion lengths. Since the first proof of perovskite solar cells in 2009, their power conversion efficiency has leapt from 3.8% to above 25%, rivaling the punch thrown by traditional silicon-based cells. (Zhang *et al*., 2022) [32] One could bring this astonishingly high improvement in efficiency, reported by Yao *et al*., to the attention of researchers as a potential game-changer for the practice of solar energy conversion. (Yao *et al*., 2019) [31].

1.2 Significance and research focus

The significance behind these perovskite solar cells is the potential to reduce the manufacturing cost of solar energy to a level where it becomes affordable for all. That would make it easy to manufacture PVCs from solutions, then enabling potential roll-to-roll printing and other inexpensive processing techniques that are impossible with silicon. (Andersen *et al*., 2014) [1] Moreover, as it has been established in the study made by Rahmany and Etgar, the flexible properties of perovskites may make them applicable to every kind of solar application, including flexible and transparent solar modules. (Rahmany & Etgar, 2020) [23].

1.3 Focus areas in perovskite solar cell research

Current research in the field of perovskite solar cells can be categorized into three main areas: pushing efficiency, stability improvement, and novel cell architectures.

- **Efficiency Improvements:** The need for efficiency improvement demands perovskite research. It includes optimization of the composition and structure of the perovskite layer. (Tailor *et al*., 2020) [26] For example, the work of T. Chen *et al*. and Yao *et al*. have discussed the introduction of multiple cations and, in the other case, utilization of low-dimensional perovskites as a way of controlling crystallization, thus enhancing electronic properties and further efficiency. (T. Chen *et al*., 2018; Yao *et al*., 2019) [5, 31] Tandem solar cells, such as those described by Yao *et al*., layer multiple perovskite films with differing bandgaps onto them to harvest the full spectrum of solar radiation, thus bringing efficiencies closer to the theoretical limits. (Yao *et al*., 2019) [31].

- **Stability Challenges:** Meanwhile, although the perovskite solar cells pose a high-power conversion efficiency, they are always dogged with some issues of stability. (Chowdhury *et al*., 2023) [7] The core reason is that they have a sensitivity to the environment's moisture, heat, and UV light. (Kore *et al*., 2024) [14] Stability over the long term, at no cost to performance, is a requirement for commercial viability. This may involve the integration of more stable materials, encapsulation methodologies, and novel compositions discussed by authors such as Li *et al*. (Li *et al*., 2023) [16].
- **Innovative Architectures:** The sculptural appeal of the beauty in perovskite gives beautiful architectures that can be customized for specific applications. First, among the innovations proposed by Rahmany and Etgar are the semitransparent cells that double up as windows, generating power. (Rahmany & Etgar, 2020) [23]. Other architectural advancements are the combination of cells with construction materials and flexible solar panels that have the potential to revolutionize the way photovoltaics are integrated into day-to-day materials.

This is well in line with the reviewed findings herein, which point out a very strong trend in this direction of addressing these challenges through innovation of materials, processing techniques, and integration with new technologies like machine learning for optimization of materials. Works by T. Chen *et al*., Jingwei Zhu, and numerous others impress upon the need for interdisciplinarity to overcome the challenges that current perovskite technologies face so that their potential in solar applications is well supported and realized.

2. Efficiency improvements

2.1 Strategies for enhancing power conversion efficiency

These have consequently motivated various material composition innovations, device architecture, and processing techniques with the aim of improving the power conversion efficiency (PCE) of perovskite solar cells (PSCs). (Maziviero *et al*., 2024) [20] These mainly involve the effects that are aimed at maximizing the absorption of solar radiation, charge separation, and transport and recombination losses minimization.

- **Material composition:** The optimization of the composition for the perovskite material is one of the efficient methods. “The use of multi-cation strategies in perovskite solar cells (PSCs) has proven effective in enhancing both the stability and electronic properties of these materials.” (Yang *et al*., 2020) [29] For example, Jingwei Zhu *et al*. considered the integration of a mixed cation approach to the stabilization of the perovskite structure in enhancing thermal stability, which directly throws light on improved efficiency of electronic properties. (Zhu *et al*., 2022) [34].
- **Device Architecture:** “The architecture of perovskite solar cells is indeed crucial for their performance.” (Salim *et al*., 2015) [25] Innovations in architectures, such as planar heterojunctions and mesoscopic architectures, have been suggested with a purpose to improve charge transport and reduce recombination losses. (Liu *et al*., 2013) [18] In this regard, Gil-Escrig *et al*. optimize the interface layers in the structure of the cell for a better alignment of energy levels and an easier charge transfer. (Gil-Escrig *et al*., 2020) [11].
- **Processing Techniques:** Advances in processing techniques, including solvent engineering and controlled crystallization, have provided for better film forming and higher crystal quality, both contributing directly to efficiency. (Y. Chen *et al*., 2023) [6] For example, Yao *et al*. had indicated that the controlled crystallization technique would bring out highly uniform, defect-free layers of perovskite, which could significantly improve the operation stability and efficiency of the cells. (Yao *et al*., 2019) [31].

2.2 Multi-cation perovskites

On the other hand, the integration of multi-cation perovskites becomes a promising strategy in raising the stability and efficiency of perovskite solar cells. (Wang *et al*., 2023) [28]. The former has considered exploiting the best properties of different cation combinations to the material to enhance the perovskite crystal properties. For instance, Yao *et al*. discussed the case of a perovskite composition doped by a number of cations, which showed both increased thermal stability and decreased ionic migration rate - one of the important conditions for high efficiency in operation. (Yao *et al*., 2019) [31].

2.3 Interface engineering

Another important area directly affecting the PCE of PSCs is interface engineering, which serves to enhance charge carrier separation, thereby reducing charge recombination. (Dai *et al*., 2021) [8] Kung *et al*. reported new electron- and hole-transport materials that match the energy levels with much better perfection of the perovskite layer, hence enabling much more efficient charge extraction. (Kung *et al*., 2019) [31] This approach increased the open-circuit voltage, but at the same time increased the efficiency of the collection of charges overall in the solar cell.

2.4 Low-dimensional materials

Incorporation of low-dimensional materials such as two-dimensional perovskites and quantum dots has been made to control crystal growth and enhance electronic properties in the perovskite solar cell. (Elahi *et al*., 2022) These materials are prospective barriers that usually have a quantum structure and act in the recombination of the carriers of load. The example for that, according to the study of Rahmany and Etgar, could be the use of low-dimensional perovskites to semi-transparent solar cells, which have improved light harvesting characteristics and, in turn, get developed directly into cell efficiency.

2.5 Tandem solar cells

The tandem solar cells are, therefore, a great leap in maximization of the photovoltaic efficiency of perovskite solar cells. Thus, these cells by stacking different multiple layers of perovskite with diverse bandgaps are such that they could potentially harvest a much broader range of solar radiation spectrum. (Ašmontas & Mujahid, 2023) [2] Yao *et al*. explain an ingenious design of a four-terminal tandem solar cell that has an optical splitting system. The system splits and guides the incident photons to different sub-cells optimized for those frequencies. This allows sub-cells to work independently at their full efficiencies, and thus greatly enhances the performance of the system in general.

In short, perovskite-based cells may enhance their efficiency using a multifaceted approach that includes device material properties, architectures, and processing techniques. In conjunction with these, the dawn of advanced materials - multi-cation perovskites and strategic interface engineering, beside low-dimensional materials - takes a very strategic role in pushing the frontiers of what is possible with perovskite photovoltaics. As many of the considered studies showed, tandem solar cells might become the most exciting way to breakthrough beyond single-junction efficiency limits and, as a consequence, open a new door for solar technology in general.

3. Stability challenges

3.1 Addressing stability issues in perovskite solar cells

Stability, therefore, comes in as one of the key issues that relate to the commercial viability of perovskite solar cells (PSCs). Perovskite materials are susceptible to environmental factors, including moisture, temperature, and UV radiation, therefore fast degradation with an impact on the long-term performance in the devices. (Mazumdar *et al*., 2021) [21] Material innovation has subsequently contributed to recent research, device encapsulation, and development toward inherently more stable perovskite compositions.

3.2 Material degradation under environmental conditions

Major degradation modes in PSCs are mainly brought about by perovskite material reacting with moisture and oxygen, therefore decomposing the perovskite structure. (Boyd *et al*., 2018) [4]. This question was studied by Zhu *et al*. through analyzing how environmental exposure affects perovskite compositions. It was concluded that perovskites having high ionic character in the chemical bonding exhibited a more vulnerable tendency to moisture degradation. (Zhu *et al*., 2022) [34] This has driven efforts toward engineering per the environmental resilience of compositions that have covalent character.

Perovskite materials are prone to degradation due to exposure to UV light. Photo-degradation processes are likely to occur when the UV light can be broken down by the perovskite structure and the organic components of the cell. (Deng *et al*., 2021) [9] To avoid that, they have developed UV-stable perovskite formulations either directly by the incorporation of UV blockers within the perovskite layer or by protective layers to filter damaging radiation. (Park *et al*., 2016) [22].

3.3 Developing more stable materials and encapsulation techniques

Encapsulation techniques aid largely in the protection of perovskite solar cells from environmental exposure. Gil-Escrig *et al*. proposed a novel and advanced encapsulation, using composite layers, which are moisture-proof and simultaneously transparent, such that the protective layer does not hinder the optical performance of the cell. They do so by using materials like glass and flexible polymers that, in a single case, can protect the sensitive perovskite layer from oxygen and water vapor but still remain flexible to make the devices for many applications.

This has also led to the development of new perovskite compositions with the use of more stable materials. Rahmany and Etgar first introduced modifications in the perovskite structure through mixed halide content, which has been reported to enhance both thermal and moisture stability. This approach allowed for a perovskite composition that would realize stable behavior under changing environmental conditions, showing marked improvement in both operational lifespan and retention of efficiency.

3.4 Introduction of new materials enhancing thermal stability and moisture resistance

Another key issue is the thermal stability in practical deployment for PSCs. On the other hand, Kung *et al*. reported on the thermal properties and concluded that the thermal stability of perovskite materials was quite robust since their crystal structures were associated with low-dimensional perovskites. These materials retain their functional properties even at high temperatures, much needed for efficiency under real field service, where the solar cells often go into large thermal cycles.

There has also been an emphasis on moisture resistance in recent research. T. Chen *et al*. developed the integration of hydrophobic layers within the perovskite cell structure that should repel water and shut out the ingress of moisture. They also developed new perovskite formulations that intrinsically resist moisture by altering the ionic bonds within the perovskite crystal, and hence are less hygroscopic.

In conclusion, effective addressing of the stability challenges of the perovskite solar cells requires a multipronged approach, which includes the development of new materials with inherent stability, the development of advanced encapsulation techniques, and engineering of the architecture of the cell to reduce exposure to degradative conditions. (Bist *et al*., 2023) The results reported in in this review are considered breakthroughs on the way to a commercial, high-efficient, long-term-stable perovskite solar cell.

4. Architectural innovations

4.1. Innovative architectures in perovskite solar cells

Perovskite solar cells architecture is very important in device efficiency and stability, but also for the flexibility of their application. Recent progress considers, above all, the elaboration of new architectural solutions that bring improvements not only in performance but also toward widened potential applications in real-world settings. (Khalid & Mallick, 2023) [13].

4.2 Semitransparent cells and building-integrated photovoltaics (BIPV)

One of the novelties in building material searches, which would encompass photovoltaic technology within its components, is semitransparent perovskite solar cells. Rahmany and Etgar have previously made progress in this direction with semitransparent cells, which allowed a compromise between transparency and efficiency. Such cells use selective light-absorbing layers that can convert the solar radiation into electricity while allowing enough light to pass through, and they are therefore ideal for such windows.

Building-integrated photovoltaics (BIPV) is the integration of photovoltaic material on or into building systems. (Jelle, 2015) [12] Gil-Escrig *et al*. showed integration between perovskite solar cells and various building materials for energy production down to their artistic utilization in building design. This integration reduces not only the overall energy costs of the buildings but also relegates and promotes the use of renewable sources of energy within urban environments.

4.3 Novel interfacial layers

Interfacial layers can be designed to efficiently transport electrons and holes, thus improving the efficiency of PSC devices. (Vasilopoulou *et al*., 2020) [27] The design of new efficient interfacial layers based on organic and inorganic material has been discussed to pave the path of charge separation and transport. These layers are devised in such a way that the energy levels at the interfaces g*et al*igned, which helps reduce recombination losses and thus increases the overall efficiency of the solar cells.

4.4 Geometrical configurations and hybrid organic-inorganic perovskites

Another domain that innovative design could further enhance performance is the one related to the geometrical configuration of perovskite solar cells. Yao *et al*. have presented several studies on the variations in stacking configuration of the tandem solar cells, in which a stack of multilayers of perovskite cells with varied bandgaps are used to capture the sun's light of a wider spectrum. (Yao *et al*., 2019) [31] All these contribute, together with operational and personnel costs, to the cost of solar photovoltaic energy.

What is fascinating about hybrid organic-inorganic perovskites is the fact that they trap light better than before. Such materials derive additional properties from the organic and inorganic constituents, making them stable and effective. (Luo *et al*., 2020) [19] This was also highlighted by Kung *et al*., who brought out the use of hybrid perovskites showing superior environmental resistance and superior efficiency. (Kung *et al*., 2019) [15] These are the areas of application to be mentioned, where the normal perovskites may fail because of environmental exposure.

This overall leads to more efficiency, durability, and versatility in solar energy solutions. Architecturally innovative in perovskite solar cells pave the way. While from semi-transparent cells that can be integrated with windows of buildings to advanced perovskite interfacial layers optimally enhancing the charge transport, are driving toward the wider penetration of perovskite solar technology. Works of researchers such as Rahmany, Etgar, Gil-Eskridge, Zhu, and Yao ensure that the type of architecture proposed in the current work strongly determines the potential of these innovative architectures. The perovskite solar cells have a broad view for applied scope of the proposed device architectures that will bring change to efficiency and application and hence become one of the cornerstones for future photovoltaic technologies.

5. Future directions

5.1 Addressing existing challenges and opening new avenues

Future development of perovskite solar cells (PSCs) depends on solving major current issues such as the toxicity of lead perovskites, durability and stability of PSCs, and practical applicability and large-scale commercialization driven by new, innovative research and technological development. (J. Zhang *et al*., 2023) [33] Careful discussion of the papers considered reveals promising directions of research that will have a high potential to influence the directions being established for perovskite photovoltaics.

5.2 Scalability of production techniques

Among the major challenges is the scalability of production processes. It often involves taking technology or process fabrication methods that have proven quite effective, especially for demonstrations at the laboratory scale, but are either not translatable directly into mass production processes or require some adaptation, for they suffer from cost, efficiency, or material usage concerns. Yao *et al*. investigated advanced deposition techniques that are less disadvantageous for scale-up in terms of cell efficiency loss. The coming years will see more research into the development of roll-to-roll (R2R) processing and printing techniques that will enable cheap mass production of PSCs with higher throughput. (T. Yang *et al*., 2021) [8] Another very promising area for the development of scalable tandem configurations is the need for good control of the thickness of every layer, which has an excellent, independent impact. Preservation of quality and performance of every layer in the stack throughout upscaling is crucial for the high efficiency of tandems towards PSCs at commercial levels.

5.3 Introduction of eco-friendly materials

The most important roadblock to full market adoption of perovskite solar cells is the environmental impact; in particular, the high content of lead in many perovskite compositions. (B. Liu *et al*., 2024) [17] Both Zhu *et al*. and Kung *et al*. emphasized how the ability of lead-free perovskite materials could enable the development of lead-free materials without bringing in new environmental risks. That could open the way for research into alternatives: non-toxic materials such as tin-based perovskites or purely organic perovskite analogs. These could be the precursors enabling entirely new, eco-friendly solar cells that may just be more efficient. More so, the usage of more recyclable or biodegradable constituents could be improved for the sustainability of technology using perovskite solar cells.

5.4 Further exploration of tandem cell configurations
Perovskite tandem solar cells offer an opportunity to finally exceed the theoretical efficiency limit given by single-junction solar cells. Work by Yao *et al*. demonstrated that it may be possible to use an optical splitting system in order to maximize the efficiency of each sub-cell by targeting specific segments of the solar spectrum. Thus, in future work, it would be interesting to study the incorporation of a perovskite layer with other photovoltaic materials, for example, silicon or CIGS, for the production of tandem hybrid cells capturing the beneficial properties of a perovskite system. In other words, this technology will require further optimization of the interlayer interfaces and the development of novel interlayer materials for tandems to effectively capture light within a broader spectral range.
Finally, the future research directions that need to be set in the perovskite solar cell technology are to increase the performance and stability of the cell, making it possible to produce the cells sustainably at a large scale and integration into every possible application. Important issues within this scope are the scalability of production processes, the development of more ecological materials, and new architectural configurations, such as tandem cells, for example. With the level of innovation and research that is going around, be it the works of Yao, Zhu, and Kung, there is no doubt that perovskite solar cells hold the key technology for the future in renewables.

6. Conclusion
6.1 Revolutionizing the solar power industry with perovskite solar cells
Perovskite solar cells (PSCs) reveal tremendous prospects for the solar energy sector and have emerged as new formidable rivals against conventional, dominated photovoltaic technologies. Efficiency, stability, and innovative architecture provided the same results in studies reviewed herein, including those of Yao *et al*. and Zhu *et al*., which are testimony to the reason this technology is gaining wider application and implementation.

6.2 Key points and potential of perovskite solar cells
- **Efficiency improvements:** According to authors like Yao *et al*. and T. Chen *et al*., large enhancement has been achieved with the power conversion efficiency for PSCs through tandem cell material composition, interface engineering, and development. Those resulted from efforts in efficiencies that matched or even beat those of conventional solar cells, hence showing that perovskites have the potential to be a leading technology in the solar market.
- **Stability challenges:** Still, this challenge of stability, according to Zhu *et al*. and Kung *et al*., articulates the biggest one yet to overcome, with continuing comments. Consequently, efforts are aligned with the development of more stable materials and further advancement of encapsulation techniques, which will be critically important for the good long-term performance and durability of PSCs under the influence of environmental stressors.
- **Architectural innovations:** Some innovative architectures, under exploration by researchers, have expanded the possible fields of application for PSCs. Among these are building-integrated photovoltaics (BIPV) and semitransparent solar cells. In fact, perovskite solar cells hold extremely high potential for use - from the ones mentioned above to those which only differ from the environmental ones or the functional ones.

6.3 Importance of continued research and collaboration
Further development of solar perovskites will, therefore, highly depend on the continued research and collaboration of different members of the scientific community. For instance, scaling up the technology to meet very demanding conditions of scaling, eco-friendliness, and continuum interconnection into already established solar markets would require multidisciplinary efforts. It is, therefore, very important that there is cooperation of chemists, material scientists, and engineers with the industry to translate lab-scale successes into commercial viability. The article by Gil-Escrig *et al*. emphasizes the same.
In addition, the development of non-toxic and sustainable material could further improve by insights from environmental science, while scalable manufacturing processes will rely on engineering insights. Last but not the least, public-private partnerships could be yet more instrumental in accelerating work on the development of a regulatory framework and market pathways that would support faster uptake of perovskite technologies.
In summary, the possibilities of the perovskite solar cells being a game-changer in the solar power landscape are too enormous, with giant strides already demonstrated in improving its efficiency, stability, and versatility. As the authors of the discussed studies detail, the ongoing research keeps on opening new avenues for further optimization and practical application. These developments promise a future where the use of perovskite-based cells registers quite significant impacts on global energy production. Continued research and collaboration still remain key to overcoming the challenges at hand and realizing the full potentials of this exciting technology.

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