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Research Article

An Overview of High-Efficiency Perovskite and Perovskite-Based Tandem Solar Cells: Progress in 2025

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About Article

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ABSTRACT
In 2025, perovskite-silicon tandem cells had attained verified efficiencies over 34%, and this paper outlines the major advancements in PSCs. Focusing on the materials and interface engineering solutions that have led to stability and efficiency improvements, we also take a look at how far we've come in making lead-free alternatives sellable.

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1. INTRODUCTION

A thin-film photovoltaic (PV) technology, perovskite solar cells (PSCs) have great promise because of their long carrier diffusion length, high light absorption coefficient, and the adaptability of metal halide perovskites for processing in solutions (Wang *et al.*, 2019; Jiang *et al.*, 2019; Jung *et al.*, 2019, Wu *et al.*, 2019; Deng *et al.*, 2019). At present, the highest power conversion efficiency (PCE) achieved by perovskite solar cells (PSCs) is 25.5%, which is higher than the record efficiency of CIGS solar cells and is on par with or slightly higher than crystalline silicon (Si) solar cells. A number of deposition techniques, such as screen printing, doctor-blade coating, slot-die coating, and spray deposition, have been scaled up, which has allowed for the development of large perovskite solar modules and charge transport layers. Recent validation of an 800 cm^2 PSC sub-module showed an efficiency above 18% (Green *et al.*, 2021), suggesting great potential for real-world use. Theoretically, Perovskite-based tandem solar cells have made great strides forward compared to single-junction Perovskite solar cells, thanks to improvements in carrier diffusion length and reductions in defect density in both wide-band gap and narrow-band gap Perovskite absorbers (Luo *et al.*, 2021; Gu *et al.*, 2020; Xiao *et al.*, 2020). Now, tandems based on Perovskite have achieved efficiencies higher than 29% (Al Ashouri *et al.*, 2020).

Recent breakthroughs have markedly enhanced Perovskite solar cells' resistance to heat, light, and humidity over the long term, in addition to improvements in efficiency. This can be attributed to advancements in cell encapsulation techniques to mitigate lead leakage from a damaged PSC module, additive engineering, the creation of diffusion barriers to prevent ion migration, and the formulation of chemically inert carbon-based electrodes. The printed PSCs were demonstrated to comply with IEC61215:2016, a prominent international standard for established photovoltaic technology. The toxicity of lead in Pb-containing Perovskite solar cells (PSCs) has prompted environmental concerns, prompting research toward ecologically benign lead-free Perovskite materials as PSCs advance toward commercial viability (Wu *et al.*, 2021).

This analysis delineates the imminent challenges to PSC commercialization, summarizes notable studies on PSCs published by global research entities in 2025, and offers a succinct perspective on prospective research topics for the subsequent phase.

2. LITERATURE REVIEW

Recent developments in interface engineering and efforts to decrease non-radiative losses have led to a dramatic increase in the efficiency of perovskite-based tandem solar cells. For example, a perovskite/silicon tandem cell was claimed to have been fabricated in which interface passivation was instrumental by Chin *et al.* (2023). The energy gaps and defect states at the perovskite-silicon junction were successfully minimized by the researchers by inserting customized interlayers. The high interfacial recombination rate, which usually limits efficiency increases, was one of the key hurdles encountered in such systems. The device achieved a record efficiency of 31.25 percent, breaking the usual limits of single-junction silicon cells, by chemically treating and controlled crystallizing the perovskite layer to offset these non-radiative losses (Chin *et al.*, 2023).

In a similar vein, Mariotti *et al.* (2023) employed trihalides as intermediary layers to create novel interface engineering solutions. These chemicals reduced non-radiative recombination at crucial interfaces by improving band alignment between the charge-transporting layers and the perovskite absorber. An important challenge with this method was that perovskite materials are chemically unstable, thus their performance would quickly degrade if they were directly interfaced with conventional transport layers. The tandem devices achieved an efficiency higher than 32%, which is the highest recorded for perovskite-based tandems to date, thanks to the addition of trihalides, which formed a chemically stable barrier while maintaining structural integrity (Mariotti *et al.*, 2023).

Liang *et al.* (2023) showed that tandem designs combining perovskite and the compound semiconductor $CuInSe_2$ (CIS) have potential, which is another important discovery. With an efficiency of 29.9 percent, their idea proved to be commercially viable. The coupling with perovskite brought new hurdles, despite CIS's excellent stability and scale production capabilities, in contrast to silicon. The main problem was that the two materials had different thermal expansion rates, which led to mechanical stress and microcrack formation. A combination of improving deposition techniques to provide smoother, more uniform surfaces and introducing elastic buffer layers to absorb mechanical strain solved this problem. In addition, a further economic study demonstrated that perovskite/CIS tandems may be produced at cost-effective prices, which further supports their feasibility for widespread use (Liang *et al.*, 2023).

Some of the most promising candidates in the photovoltaic industry presently are perovskite-based tandems, according to the revised NREL efficiency chart (2024). Theoretically pushing performance limits and proving themselves as real solutions, perovskites are redefining the future of solar energy with their high power conversion efficiency, cost-effective production, and adaptable integration with varied materials (National Renewable Energy Laboratory, 2024).

3. METHODOLOGY

3.1. Perovskite material fundamentals

Perovskite, a mineral identified in the Russian Ural Mountains in 1839, possesses significant potential as a light-absorbing agent in the advancement of sophisticated solar cells. The nomenclature is attributed to the Russian mineralogist L.A. Perovski (Mariotti *et al.*, 2023). Perovskite, or calcium titanium oxide, is an inert compound having the chemical formula $CaTiO_3$. It is part of a class of compounds with a chemical makeup analogous to $CaTiO_3$ (ABX3). In the ABX3 structure (Liang *et al.*, 2023), seen in Figure 1, the cubic lattice is occupied by a substantial monovalent cation A, a minor bivalent metal cation B residing in octahedral spaces, and an anion X. The anion X is inherently a halogen, nevertheless, carbon, oxygen, or nitrogen are also possible. When the anion is O^{2-}, cations A and B are usually bivalent, but in this configuration, they are tetravalent. On the other hand, univalent cations occupy the A site and bivalent cations the B site when halogens act as anions in a perovskite structure (National Renewable Energy Laboratory, 2024).

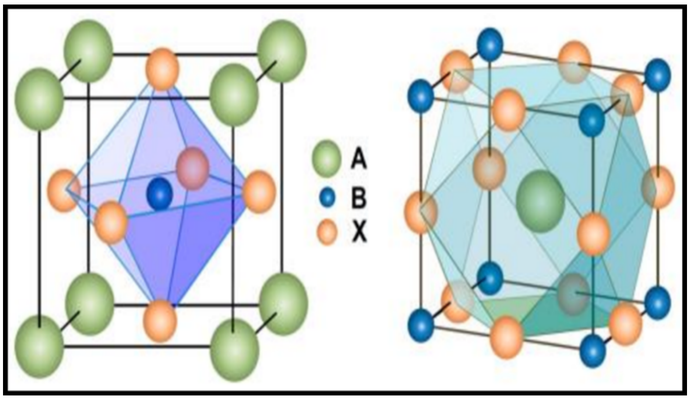

Figure 1. Illustrates a bigger ABX3 perovskite structure with the A cation occupying the cubic octahedral site and the BX6 octahedral cation.

Perovskite solar cells often employ $MAPbI_3$, $FAPbBr_3$, and $CsPbCl_3$, which are prototypical ABX3 light-absorbing chemicals. The configuration of ions within the Perovskite crystal structure of a unit cell is affected by the tolerance factor (t), pressure (P), and temperature (T). The mineral quality can be improved by choosing orthorhombic, tetragonal, and cubic structures for the Perovskite crystal (Liang *et al.*, 2023). The stability of Perovskite crystal formations is determined by the tolerance factor (t). In an optimal three-dimensional Perovskite structure, the (t) parameter is 1.0, although it varies from 0.8 to 1.0 in suboptimal conditions. A low (t) factor results in less structured perovskite crystal structures, such as orthorhombic and tetragonal forms. Likewise, when MA^+ and Cs^+ are employed to synthesize multi-cation perovskite alloys, the resultant materials have properties akin to those containing only FA^+. Consequently, perovskites, incorporating FA^+, can be considered more stable than those comprising solely MA^+ and Cs^+ (Habibi *et al.*, 2016).

3.2. Solar cells combining perovskites and silicon

C-Si is the best material to use for tandem solar cells made of wide-bandgap perovskites because of its dominant position in the current photovoltaic market, which is due to its high power output, long history of reliability, strong supply chains, and rapidly falling production costs. Increasing the power output of crystalline silicon solar panels without significantly changing production costs is possible through the integration of perovskite solar cells with crystalline silicon. There are a few different kinds of tandem cells. One is the mechanically stacked cell, which can have two or four terminals. Another is the homogeneous stacked cell, which has two terminals as well (Mohammed *et al.*, 2024). To attain high power conversion efficiencies over 30%, approximately 1.1-eV crystalline silicon must be combined with wide-bandgap perovskites exhibiting the bandgap ranges from 1.6 to 1.75 eV, as shown in Figure 2. The most efficient monolithic perovskite/c-Si tandem solar cells that have been certified so far are achieved by Oxford PV, is 28.0%, exceeding the 26.6% PCE of the most efficient single-junction Si cells (Subhani *et al.*, 2025).

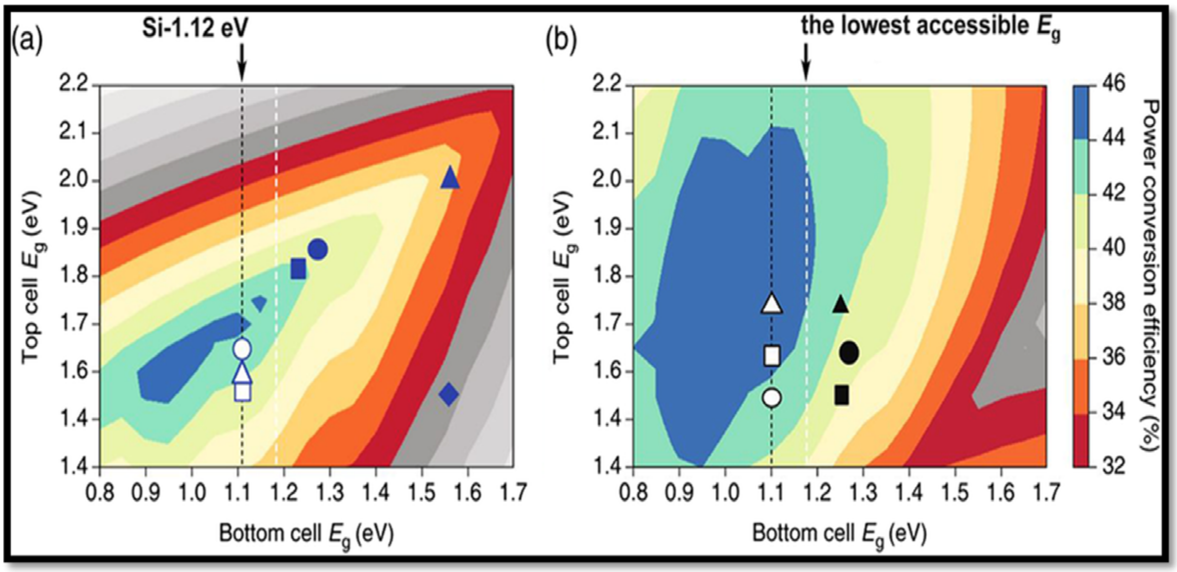

Figure 2. Efficiency limits of 2-T and 4-T tandem solar cells, according to theory. Sil, CIGS, and low-bandgap perovskites' bandgaps are shown by the dashed lines.

3.3. Working Principle of PSCs

Solar cells work by absorbing light, separating charges, transporting charges, and collecting charges. Efficiently implementing these procedures requires careful consideration of the optoelectronic qualities of potential light harvesters. An intrinsic semiconductor light harvester, for example, necessitates a p-i-n junction. On the flip side, a p-n junction is required when the light collector displays n-type or p-type properties, because these materials can transfer electrons or holes to the light collector, respectively.The balanced charge transport features of organometallic perovskite materials make them useful in p-i-n and p-n junction topologies (Chen *et al.*, 2017). For $CH_3NH_3PbI_3$, which was synthesized in various ways using a combination of CH_3NH_3I + PbI_2 and an alternate mixture of $3CH_3NH_3I$ + $PbCl_2$, the electron and hole transport properties were documented. The X-ray diffraction patterns always showed indexing as tetragonal $CH_3NH_3PbI_3$ (Jandary & Saleh, 2019), regardless of the synthesis method. The intricate nature of the perovskite environment results in an incomplete comprehension among researchers concerning the formation and accumulation of charges in perovskite solar cells (PSCs). Thus, the characterization of attributes in perovskite solar cells remains dependent on the same principles utilized for silicon solar cells (Song *et al.*, 2019). The perovskite layer absorbs photons and excitons upon exposure to sunshine. Upon the separation of excitons, the exons can produce both electrons and holes due to the variances in the requisite energies of the excitons within the perovskite materialAt the boundary between the charge transport and hole transport layers, exciton dissociation takes place. Figure 3 shows the process of simultaneously guiding the holes into the hole transport layer and then transferring them to the cathode, which is usually formed of metal. The opposite is true for the electron transport layer (ETL), which receives electrons from the dumps and sends them on their way to the fluorine-doped tin oxide (FTO) anode (Hamed *et al.*, 2025). While the metallic electrode collects electrons and holes, the hostage electrode is linked to an external circuit in order to produce current.

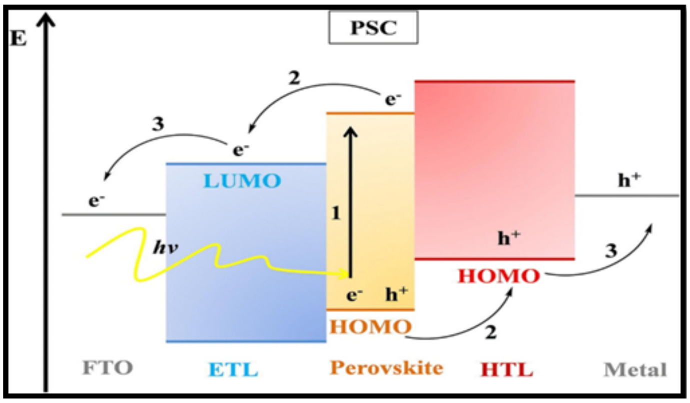

Figure 3. Illustrate the principles and operation of PSCs.

4. RESULTS AND DISCUSSION

The National Renewable Energy Laboratory (NREL) reports that perovskite solar cells have reached 26.1% peak efficiency in the lab, which is on par with traditional silicon cells. Researchers have found a way to combine the best features of both materials silicon's superior long-term stability and perovskite's capacity to absorb high-energy portions of the solar spectrum by integrating the two in tandem architectures. Thanks to their complementary strengths, tandem devices have recently achieved an efficiency level of 34.6% (Snaith *et al.*, 2014), setting a new benchmark for performance. Table 1 summarizes the present efficiency levels of various types of perovskite-based solar cells. In comparison to other configurations, such as the all-perovskite tandem (28.2%), perovskite-organic tandem (26.7%), and perovskite-CIGS flexible cells (23.64%), the perovskite-silicon tandem stands out with the highest recorded efficiency of 34.85%. The environmental benefits of lead-free tin halide perovskites aren't enough to make up for their 16.65% efficiency gap. The remarkable efficiency of perovskite-silicon tandems is mainly due to the fact that the two absorbers have complimentary optical characteristics; specifically, perovskite is good at capturing high-energy photons and silicon is good at using low-energy photons. Due to its optimum use of the solar spectrum and silicon's demonstrated endurance, the perovskite-silicon tandem architecture is now the most promising and efficient design for solar cells.

Table 1. Various types of solar cells and their efficiency

Solar Cell Type	Efficiency
Single junction perovskite	26.7%
Perovskite–Silicon Tandem	34.85%
All Perovskite Tandem	28.2%
Perovskite–Organic Tandem	26.7%
Perovskite–CIGS Flexible	23.64%
Tin Halide (Pb free) PSC	16.65%

5. CONCLUSION

Rapid efficiency gains and design flexibility highlight the promise of perovskite solar cells for next-generation solar applications, making them a big step forward in renewable energy technology. But before large-scale commercialization can happen, a number of important obstacles still need to be overcome. Problems with scalability in fabrication processes, the usage of harmful lead-based chemicals, and long-term stability in the face of environmental stresses are still holding back broad use. Moreover, to translate lab results into marketable products, it is crucial to establish cost-effective, environmentally friendly production methods and guarantee consistent performance in large-area modules. Overcoming these gaps will determine perovskites' final significance in the global renewable energy landscape, despite the fact that continuing research and innovation clearly imply they could alter the solar energy market.

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