

Perovskite Solar Cells: Literature Review

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Abstract

The primary contender to replace conventional silicon solar cells in the future are perovskite solar cells (PSCs). In just over a decade, PSCs have progressed from a modest beginning of 3.8% in 2009 to reported efficiency of 25.7% for single-junction cells and 31.25% in July 2022 for multi-junction cells. This astonishing development, although promising on the one hand, also suggests that the potential may yet be discovered. This study elaborates on the opportunities and shortcomings of perovskite solar cells by analyzing their properties, before discussing current solutions and proposing future research focus so that PSCs can reach their potential.

Keyword: Perovskite solar cells

I. Introduction

With soaring energy demand and increasing concern about global warming caused by fossil fuels, the world has shifted focus to renewable energy. Out of the mix, solar energy, the most abundant and clean form of energy, plays a major part in our move toward net zero. Yet, despite the price drop, there has been little improvement in current silicon-based solar cells' efficiency. For top-selling silicon solar cells these days, the efficiency typically does not exceed 22%. Therefore, the solar industry needs breakthroughs in technology to fulfill its potential. Recently, perovskite solar cells have emerged and grabbed the attention of researchers all over the world with their unprecedented growth in efficiency and low manufacturing cost. Despite certain drawbacks, lots of research has been and will be done to make perovskite solar cells “the next big thing” in the renewable energy field.

Three generations of solar cells:

1. First-generation Silicon solar cells

The first generation's technology is based on silicon wafers either monocrystalline or polycrystalline with a thickness of between 300 and 400 microns. These conventional solar cells' exceptional performance has resulted in their global commercialization, but their main disadvantages are high energy consumption and high processing costs for silicon raw materials. At the moment, first-generation cells still represented 95% of the solar cell market.

2. Second-generation Thin film solar cells

Emerging in the late 1970s, with a thickness of nanometers to tens of micrometers, this type of solar cell's absorption rate drops, and its ability to transmit energy increases. III-V GaAs thin-film technology features the highest recorded efficiency at 68.9% [1], significantly exceeding that of a-Si, CdTe, and CIGS thin-film technologies at 14.0%, 22.1%, and 23.4%, respectively. However, the cost of GaAs technology is \$50 per watt, about a hundred times more than that of conventional thin-film cells. Therefore, CdTe and CIGS cells are primarily restricted to industrial uses, while a-Si films are used to replace conventional building materials, and GaAs photovoltaic cells are exclusive to space applications.

3. Third-generation Dye-sensitized solar cells

There are countless research being conducted on what is known as third-generation solar cells. There are 4 main types of third-generation solar cells. The first is Dye-sensitized solar cells (DSSCs), low-cost types of solar cells from the thin film group which mark the generation's beginning when published in 1991. It is based on a photoelectrochemical system in which a semiconductor is created between an anode and an electrolyte. Despite

the low price enabling them to compete with fossil fuel sources, its PCE remains low. Next, there are organic solar cells (OSCs) with organic electronics for light absorption and charge transfer. Although these can be mass manufactured at low cost with high adaptability because of the molecules employed, OSCs’ poor strength, stability issues, and low efficiency need to be addressed. The third type is quantum dot solar cells (QDSCs), which use quantum dots as the light-absorbing material. It is a potential replacement for bulk materials like silicon, CIGS, or CdTe, and with adjustable bandgaps spanning a broad spectrum of energies by adjusting size, the use of quantum dots in multi-junction devices is extremely appealing. The final type is recently emerging perovskite solar cells (PSCs). PSCs have been the fastest-evolving PV technology, with record PCE in single-junction structures rising from 3.8% in 2009 to 25.7% in 2021, as shown in Fig 1. Perovskite solar cells are considered the most promising third-generation solar cells due to their potential for very high efficiencies and extremely cheap production costs.

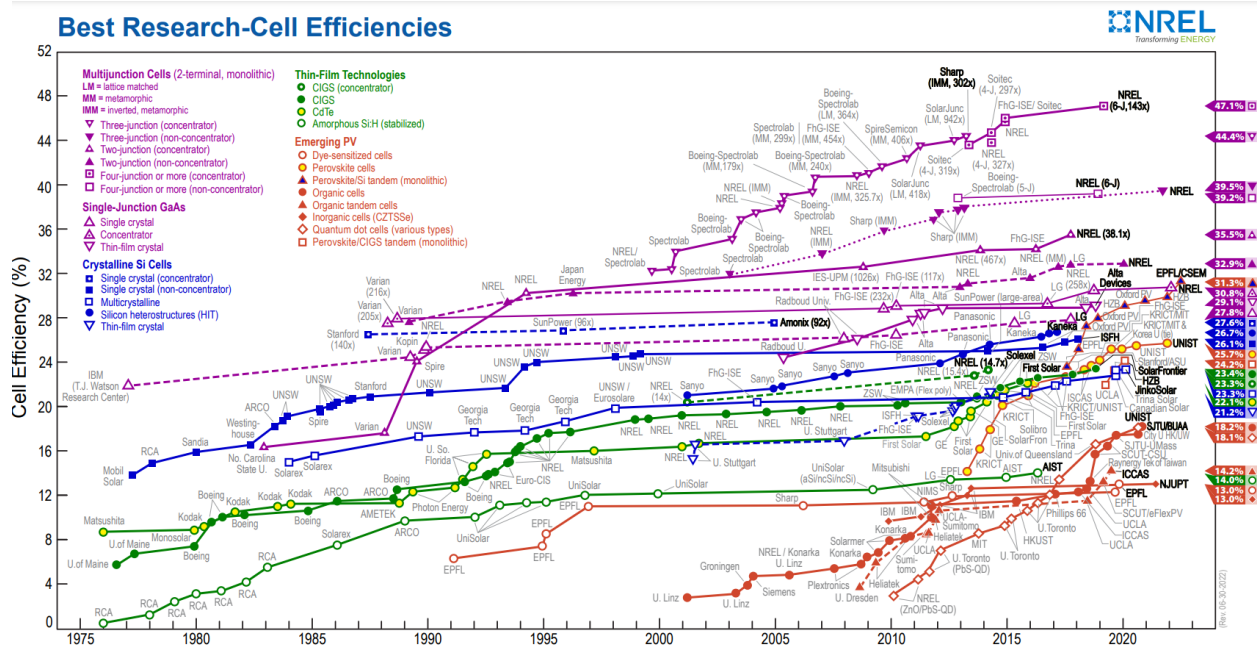


Fig 1, NREL Best Research-Cell Efficiency Chart [2]

II. Perovskite solar cells

1. Structure and working principle

A conventional PSC is made up of an electron transport layer, a perovskite photosensitizer, a hole transport layer, and a metal counter electrode. These layers are used to efficiently separate photogenerated carriers from one another in the perovskite layer after illumination and to enable those carriers’ quick transportation. In the perovskite light absorber layer, the PSCs device absorbs sunlight to produce electron-hole pairs. The conductive electrode surface must receive this electron. Thus, this produced electron is transported to the conductive electrode (FTO) via the electron transport layer, which is composed of transition metal oxides (often TiO₂ or SnO₂). The hole transport material layers (typically spiro-OMeTAD) can collect the hole. In some circumstances, the transferred electron may recombine and affect the PSC devices’ performance. As a result, various compact or buffer layers have been utilized to slow down the recombination process. Any solar cell device’s performance may be assessed using the following metrics: fill factor (FF), power conversion efficiency (PCE), photocurrent density (J_{ph}), and open circuit voltage (V_{oc}).

In PSCs devices, perovskite components served as light absorbers. A typical perovskite structure is represented by the formula ABX₃ (Fig 2a), where X is a halide anion (such as Cl, Br, and I), B is a di-, tri-, or tetravalent metal ion (such as Pb²⁺, Sn²⁺, Sb³⁺, and Ti⁴⁺), and A is a monovalent cation (such as cesium,

methylammonium, and formamidine). However, there is one issue that today's best perovskites include lead, an extremely hazardous metal.

2. Types of Perovskite solar cells

- *Tandem solar cells*: Tandem solar cells are multi-junction solar cells made up of several light absorbers with different band gaps. Si-perovskite, perovskite-perovskite, CIGS-perovskite, and OPC-perovskite are examples of common perovskite tandem solar cells. The current record efficiency of these cells was 31.25%, also shown in Fig 1. The additional perovskite layer on top of silicon solar cells can significantly increase efficiency without radically altering the manufacturing process. These multi-junction solar cells, however, are exceedingly costly when subjected to more intricate manufacturing, which ultimately prevents their usage for terrestrial applications. Solar cell parks will mostly employ this kind of cell.
- *Pure single-junction perovskite cells*: These can be utilized in a variety of applications, including those for windows, garments, construction materials, and automobiles.

Perovskite solar cells are divided into standard n-i-p and inverted p-i-n structures, based on which transport material on the external section of the perovskite solar cell interacts with light first, as demonstrated in Fig 2b. The perovskite absorber layer is sandwiched between an HTL and an Electron Transporting Layer (ETL). In the n-i-p structure, the ETL is deposited first, whereas, in p-i-n structures, the HTL is deposited first. Then, these are separated into:

- + Mesoscopic structures—contain a layer of mesoporous perovskite in the structure. Between ETL and HTL is the mesoporous metal oxide that consists of perovskite. A metallic cap serves as the anode, while the cathode is made of transparent glass.
- + Planar structures—include every planar layer, eliminating the requirement for a mesoporous metal oxide layer and simplifying the design as a whole.

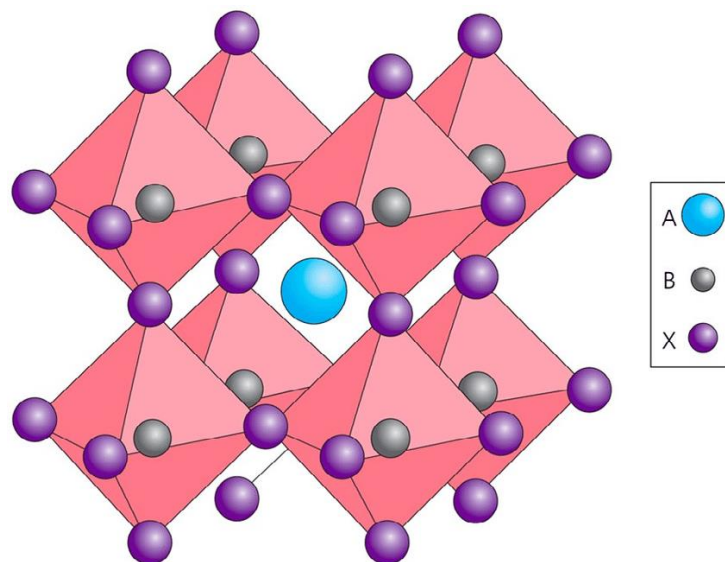


Fig 2a. Perovskite structure

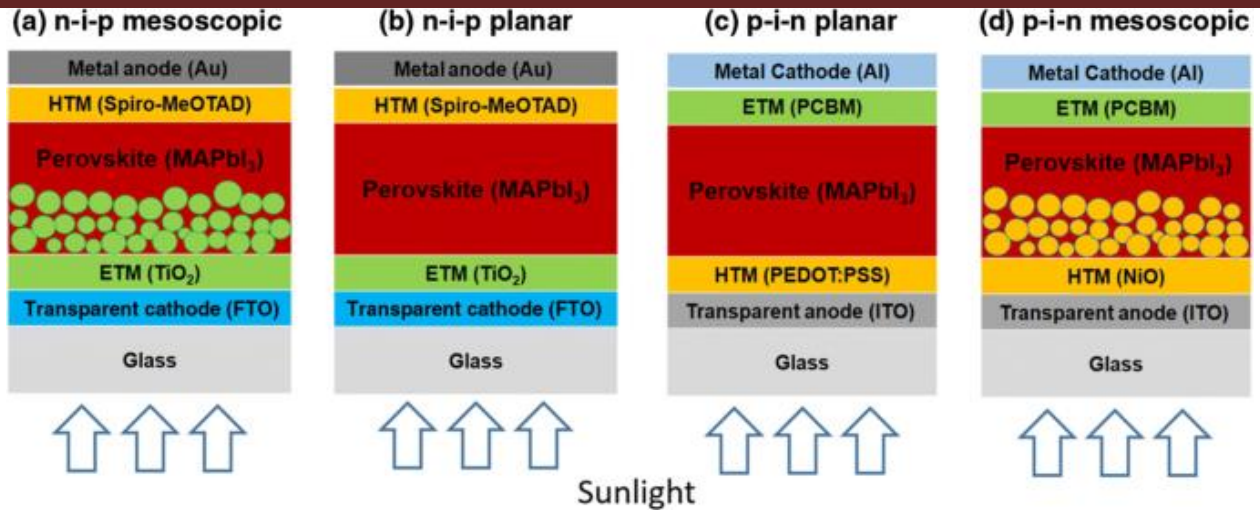


Fig 2b. Types of PSCs

III. Advantages and Disadvantages of PSCs

1. Advantages

Perovskite solar cells' advantages derive from some of their unique properties:

- *Band gap tuning*

The band gap essentially stands for the minimal energy needed to excite an electron up to a state in the conduction band where it may engage in conduction. Perovskites' ability to have their band gap modified by making minor compositional changes or adjusting the doping level makes them appealing for use in photovoltaics. Thanks to their versatility, perovskites may be used in tandem solar cells. Compared to silicon's 1.1 eV band gap, the majority of the perovskite materials applied in the highest-performing solar cells have band gaps between 1.48–1.62 eV. To absorb the most photons from the sun's energy, the ideal band gap for solar cells is 1.4 eV. Therefore, it remains important to find lower band gap materials to collect a larger range of the solar spectrum.

- *High absorption coefficient reducing fabrication cost*

The absorption coefficient defines the amount of light that a material with a specific thickness absorbs. A substance that absorbs more light per thickness has a higher absorption coefficient. For instance, the visible MAPbI₃ area has an absorption coefficient greater than $3.0 \times 10^4 \text{ cm}^{-1}$ [3], over 10 times more than that of silicon, suggesting that perovskites' absorption layer is significantly thinner crystalline silicon's. Compared to crystalline silicon, which is confined to absorbing wavelengths greater or equal to 1,100 nm, perovskites may be tailored to absorb varier colors in the spectrum. As a result, PSCs possess a high light-absorption coefficient and should be cheaper to produce.

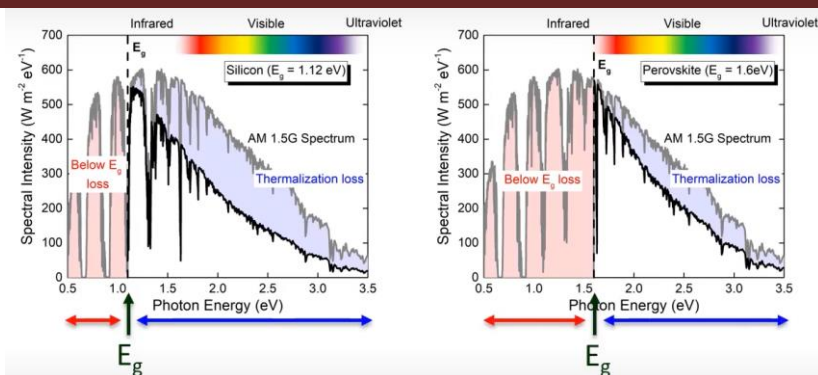


Fig 3. Silicon single-junction cells bandgap (left) vs Perovskite single-junction cells bandgap (right)

- *High carrier mobility leading to higher efficiency*

The relationship between the carrier's speed and the strength of the electric field applied is known as carrier mobility—one of the important parameters determining cell performance since the movement of carriers from the absorber to the charge transport layer and their collection by electrodes are crucial processes that determine the efficiency of the cell. Perovskite crystal carrier mobility and diffusion length have both surpassed hundreds of $\text{cm}^2/\text{V}\cdot\text{s}$ and hundreds of μm , respectively.

- *Long charge carrier diffusion length for high efficiency*

The diffusion length of a carrier in a substance is the typical distance traveled by an excited carrier before recombination. With over 1-micron diffusion length, MAPbI₃ and MAPbI₃-XCIX both contributed to the perovskite solar device's high efficiency. Moreover, if the perovskite absorber is thicker than the carrier diffusion length, the produced carriers will recombine before reaching the electron transport layer (ETL). This is why Mesoporous TiO₂ is placed over the hole-blocking layer to prevent recombination. The photogenerated electrons can move through the mesoporous TiO₂'s expanded network and eventually get to the anode before they recombine.

- *Crystalline structure*

A high crystalline perovskite film is integral to achieving a superior performance of PSCs. The enlargement of perovskite grain prolongs diffusion length, thus remarkably improving Perovskite photovoltaics performance.

With their properties, Perovskite solar cells offer high efficiency, low cost, and an easy manufacturing process with low energy consumption. We can obtain very high values of V_{oc} (open-circuit voltage)—the highest voltage a solar cell can generate for an external circuit. Perovskite solar cells can be prepared in solutions with a low process temperature of about 100 °C, compared to over 600 °C of crystalline silicon cells, and 250 °C of other thin-film cells. Although crystalline silicon is an established technology with years of cost-reduction research, perovskite solar cells are now produced at a cost equivalent to the cheapest c-Si solar cells, thanks to the abundant raw materials, cheap vacuum equipment, and aforementioned high absorption coefficient. The easy manufacturing process and fewer materials made Perovskite solar cells a viable option for developing countries such as South East Asia and Latin countries without existing infrastructure for processing silicon. For this reason, Perovskite solar cells are vital in the global transition to renewable energy. Last but not least, the high optical transparency, lightweight and excellent flexibility make Perovskite solar cells potential for wide applications. Low dimensional metal halide Perovskite can be used on windows, paints, electronic devices, screens, drones, etc.

2. Disadvantages

- *Instability of Perovskite solar cells*

The short life span of PSCs can be attributed to the deterioration of the light-harvesting interface (extrinsic factors) and the instability of the perovskite material itself (intrinsic factors).

The degradation of PSCs' structural integrity can be caused by the layers around the perovskite. Some of the extrinsic factors causing the degradation of PSCs:

- + UV: TiO₂ has photocatalytic properties, which can catalyze the decomposition reaction of perovskite materials under ultraviolet irradiation. Although Ultraviolet rays affected PSCs most significantly when combined with other factors such as humidity and oxygen, MAPbI₃ can still degrade to PbI₂ under UV light without humidity or oxygen present.
- + Moisture: Moisture leads to irreversible degradation. Conventional perovskite cells have a very short lifespan in an environment with high water and oxygen content. Perovskite films, especially MAPbI₃, can quickly deteriorate in the presence of ambient humidity. The commonly used organic materials in the hole transport layer decompose rapidly when they meet water. The fundamental underlying mechanism is an evaporation-like process of the organic component in the hybrid organic-inorganic perovskite. Because the organic cations in the hybrid organic-inorganic perovskite are relatively hygroscopic—that is, they form weak hydrogen bonds with water molecules—the integrity of the crystal is undermined. The inorganic solid residue that was left after the procedure, although still mainly intact, is useless for light absorption.
- + Temperature: Ionic bonding essentially holds perovskite compounds together. Although this makes it simple to create highly crystalline films at low temperatures, it also leads to a breakdown at low temperatures, making these substances inherently less thermally resilient than silicon. Since MAPbI₃ may turn into PbI₂ at high temperatures, exposure to these conditions can lead to deterioration. Without air or moisture, the process advanced more slowly than when they were present.
- + Oxygen-rich environment: The perovskite film develops substantial PbI₂ structures under these circumstances.

Some of the intrinsic factors causing the degradation of PSCs:

- + Defects, vacancies in the perovskite structure during perovskite film formation, can facilitate ion migration across the perovskite film. Ion migration inside the perovskite layer might cause a PV device's performance to be poor or inconsistent.
- + This ion migration may also result in the creation of an electric field at the interface of the perovskite layer, which may deprotonate the organic cations and ultimately damage the perovskite solar cell.
- + The perovskite layer may be affected by ion migration from conductive connections, which might result in the creation of reverse channels for electrons that would shorten the solar cell's circuit and lower its efficiency.

- *Environmental problems regarding lead (PbI₂)*

Lead is the common material of high-efficient PSCs these days. Natural phenomena like heavy rain, strong winds, and wildfires may erode the damaged perovskite solar cells, releasing poisonous lead. High lead levels in the environment result in reduced development and reproduction in plants and animals, as well as neurological consequences in vertebrates. Last but not least, when contacting our bodies, it disrupts enzymes and harms our brains by obstructing brain cells' connection and information transmission to others.

IV. Current methods for improving Power Conversion Efficiency and Stability

There have been many attempts to improve stability and PCE, extend longevity, and switch hazardous lead elements to safer alternatives. The most stable PSCs nowadays have low efficiency, whereas the most efficient ones frequently have durability issues. These are significant obstacles that hinder PSCs' manufacture and future commercialization, and countless types of research have been and are done to find solutions for the ultimate eco-friendly PSCs with high efficiency and high stability. Past research efforts have been mostly devoted to improving PCE, while some concentrated on increasing stability.

- *Progress in lead-free perovskite solar cells:*

Globally, researchers are working to find eco-friendly metallic ions that can substitute the poisonous lead in cells without reducing the PCE. Tin (Sn)-based PSCs are becoming more and more popular because of their great photovoltaic performance, appropriate bandgap, low manufacturing cost, and environmental friendliness. In contrast to their lead equivalent, tin-based PSCs are still in the research stage and have received less attention. Due to the divalent Sn's oxidative properties, tin-based PSCs perform worse than lead-based PSCs. There is a high possibility that Sn²⁺ in CH₃NH₃SnI₃ oxidizes to the volatile Sn⁴⁺, which results in a process known as self-doping in which the Sn⁴⁺ functions as a p-dopant and lowers PCE. However, since the beginning of the tin-based PSCs era in 2014, there has been substantial advancement in the sector. From a PCE of 5.73%, recent demonstrations of PCE have exceeded 15%. These eco-friendly PSCs will become a prominent movement in the future with more studies and funding invested in this area.

- *Preparation and processing methods of PSCs:*

Scalable deposition requires effective preparation methods. Vacuum deposition, one-step solution deposition, two-step sequential deposition, and vapor-assisted deposition are a few of the processing methods to create high-quality perovskite films. While solution-processed spin-coating has previously been used to create organic perovskite films because of the rapid replication, refinement, and experimental advancement, it is unscalable for PV manufacture. Other methods that could find application for PSC thin film fabrication in the near future include electrospray deposition, the sol-gel technique, and the molecular precursor method (MPM). These three methods are relatively new compared to the other methods discussed earlier. MPM is the most promising of the three considering that it can be readily integrated with established fabrication methods such as spin coating and spray coating. Furthermore, MPM thin films of metal oxides require low annealing temperatures compared to the sol-gel method and have been shown to have much finer crystals with better uniformity. As shown in Fig 4, the graphical chronology of fabrication techniques for hybrid organic-inorganic halide perovskites demonstrates that throughout the preceding five years, most solution-based techniques have been used by researchers to create PSCs. With the capability of solution-based methods to ensure the scalability and uniformity of deposits across the device, the future focus should be on solution-based methods. Additionally, the complete encapsulation of the devices, which shields them from external deterioration factors like ambient moisture or UV radiation, is another method for enhancing the durability of PSCs. In certain experiments, moisture is absorbed before it can enter the perovskite layer using a hygroscopic material. All of the aforementioned techniques greatly boost the stability of solar cells.

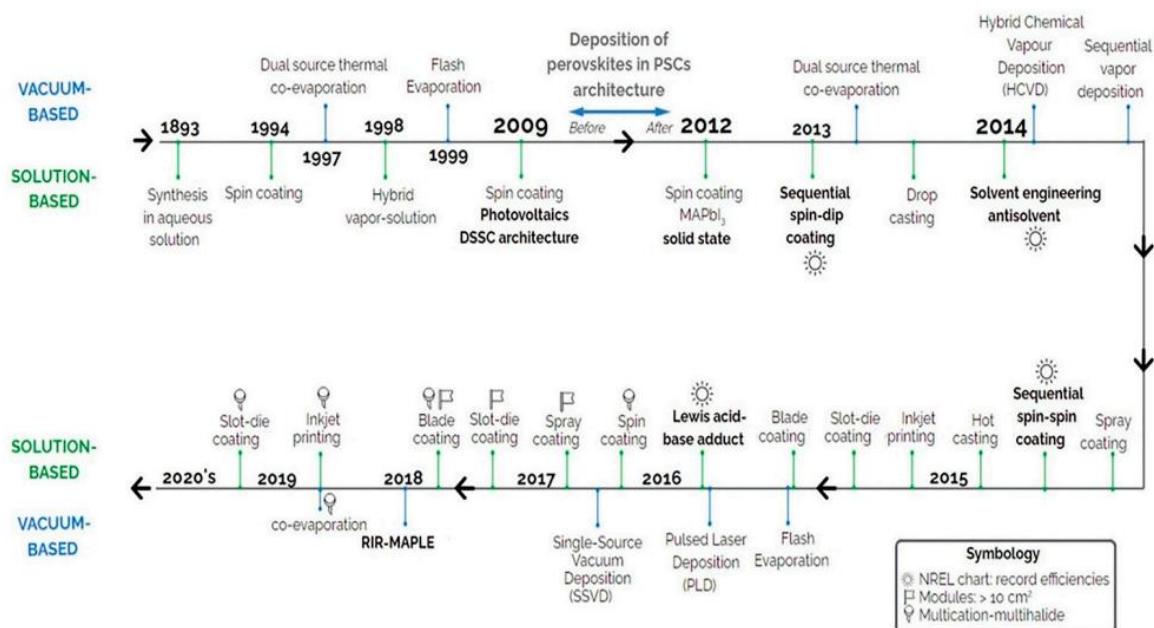


Fig 4. Timeline for application of vacuum deposition methods vs solution processing methods in the fabrication of inorganic and mixed halide perovskites. The symbology legend defines fabrication methods used; reported National Renewable Energy Laboratory (NREL) record efficiencies, modules, and multi-cation/multi-halide compositions [4]. Copyright 2020 American Institute of Physics.

- *Modification strategies to improve PCE and stability:*

Compositional and interfacial engineering are attractive approaches to maximize PSCs' performances given the benefits of directly modifying various intrinsic properties of materials, which results in better-performing perovskite. Given the benefits of directly modifying various intrinsic properties of materials, compositional and interfacial engineering are appealing methods to maximize PSCs' performances. This results in better-performing perovskites with improved solar capabilities. To reach optimal and durable PSCs, these strategies improve interface interaction, reduce charge carrier recombination, and increase carrier capture. The incorporation of dopants to enhance the electrochemical properties of perovskite have been covered in a large collection of studies. Doping is the technique of injecting particular chemical components into a semiconductor to alter its conductivity. Although certain element doping will boost the electron transport rate, it won't always enhance the efficiency of PSCs. This is because the performance will drop when certain ions do not fit the perovskite's lattice. Therefore, finding complementary components for this strategy is crucial. One example is co-doped MAPbI₃ film with 1% Bi and 1% Sn for higher efficiency of 10.03%, resulting from the low recombination rate. Co-doping 1% Bi and 1% Sn to MAPbI₃ film increased grain size (80.3nm) and Voc (1.18 V), Jsc (9.71 mA cm⁻²), FF (0.609) and η (6.98%) [5]. Fe and Ta doping into TiO₂ also increased incident light absorption to 81.7% and 81.2%, respectively, compared to 79.5% of the pure TiO₂ [6]. Meanwhile, Quan Li et al. found that TiO₂ nanotubes and TiO₂ nanosheets incorporated into the TiO₂ porous layer of perovskite solar cells outperformed pure TiO₂ cells with higher Voc (1.06 V), PCE (15.58%), short-circuit current (Jsc) and fill factor (FF). These performance improvements stem from the better properties of modulated TiO₂, including better optical transmission properties, faster electron transfer rate, and higher electron lifetime [7]. Apart from doping, passivation is also critical to solar cells. Passivation involves neutralizing the impacts of under-coordinated ions, lingering defects at grain boundaries, and pinholes at surfaces. In simple

terms, the material is coated so it becomes "passive" - less readily affected or corroded by the environment. One demonstration is that the energy modulation and interface passivation caused by 2FEABr decrease the nonradiative recombination loss. The charge transport and stability of the perovskite film are improved by the atomic-scale details on the partial substitution of the I sites by the Br anions, the limited motion of the partial MA⁺ cations, and the framed perovskite lattices in the 2FEABr treated perovskites. These findings significantly increased the PCE of the p-i-n structured device from 19.44 to 21.06%, along with exceptional stability [8]. As defects may be properly passivated and nonradiative recombination is subsequently decreased, interfacial engineering is among the finest techniques to create stable and efficient PSCs.

Solvent engineering is regarded as the most prevalent method applied in one-step deposition processes. It has been extensively applied to regulate grain development and crystallization in hybrid halide PSCs throughout the film formation process. In 2021, Li et al. synthesized WS₂ QDs by pulsed laser irradiation in the green anti-solvent ethyl acetate as additives to the perovskite layer. This method is faster than conventional methods, giving extremely high-purity QDs and facilitating charge transfer. The maximum PCE obtained was 16.85% while the stability of Perovskite quantum dots was maintained [9]. Wang et al. utilized a one-step anti-solvent deposition method utilizing diisopropyl ether as a dripping solvent to produce highly uniform and crystalline CH₃NH₃PbI₃ perovskite films. PSCs produced through the antisolvent deposition method with diisopropyl ether solvent had an average PCE of 17.67% and the highest PCE of 19.07% [10], outperforming perovskite films fabricated using toluene, chlorobenzene, or chloroform. Therefore, diisopropyl ether is the most appropriate solvent for the antisolvent deposition method. These works show how solvent engineering can be applied in the development, amelioration, and scale-up of novel solar cell technologies.

- *Studies on new materials:*

Scientists have been making different types of combinations of perovskite materials to test the efficiency of those materials and how the material is giving the different types of efficiency. Practical photovoltaic panels cannot employ the conventional methylammonium lead iodide (MAPbI₃) because of its high-temperature sensitivity. Due to its comparable size to methylammonium, formamidinium (FA) has been employed as a substitute. As a result of decreased trap state densities and photogenerated carrier recombination rate, CsFA-based PSCs showed improved efficiency and stability. ST-PSCs fabricated with 100–400 nm thick CsFA-based perovskite films achieved high PCE between 4.2% and 15.4% and also showed improved long-term stability under continuous UV exposure, retaining 85% of their original PCE after 1000h [11]. For inverted planar PSCs, Ni₃(HITP)₂ provides PSCs with a suitable valence band edge and excellent hole mobility. The outcome is the Ni₃(HITP)₂-based inverted planar cells attain the peak PCE of 10.3%. [12]. For tin PSCs, Cu₂O-based HTL demonstrated high hole mobility, better power alignment with CH₃NH₃PbI₃, and a longer lifespan of photo-generated charge carriers [13]. More future research should be done to synthesize new materials for PSCs. For long-term stability goals, inorganic materials prove to be more suitable thanks to their chemical inertness and low cost and hence should be focused on. Also, more studies on metal oxides, which deliver stability and higher efficiency in PSCs, are needed.

V. The future of perovskite solar cells

For the next decade, in addition to greater PCE toward the Shockley-Queisser limit and durability, For commercialization, the discoveries and technology from the small-area PSCs must be converted into qualified large-area products and tandem solar cells. Additionally, new materials for stable and reproducible PSCs ought to be researched.

For over 30% PCE target for single-junction PSCs, the Voc and FF need to be improved. In order to gain insights into the cause of recombination and develop appropriate interfacial engineering techniques, studies on interfaces and grain boundaries are necessary. Recent articles have emphasized interface engineering in this area. Various interfacial engineering methods were put forth, but they all demonstrated common results in Voc and/or FF. Observed data still revealed a difference between theoretical Voc (1.33 V) and FF (0.91) despite study attempts. For the target of over 30% PCE from single-junction perovskite solar cells, research on the advancement of the ETL, reduction of defect loss associated with non-radiative recombination, and improvement of light-harvester are needed, along with new methods being sought.

Long durability and stability: A robust encapsulation may be the best option for durable and stable PSCs, despite Ma-based perovskite's thermochemical instability remaining a problem. To increase stability against light irradiation, moisture, and temperature, it is necessary to gain insights into material sciences, compositional engineering, and interfacial science. Next, interfacial engineering frequently displayed improved stability combined with better performance. It has been demonstrated that a 2D/3D hybrid concept exhibits greater stability than the 3D alone. Furthermore, the chemistry and physics of the defects in perovskites are still poorly understood, although it is believed that they have energies near or inside the energy bands. Future studies on defects are required. The current generation of perovskite solar cells has become significantly more stable thanks to ion replacement, enhanced contact materials, and proper encapsulation. Yet, in order to make the technology profitable, it is important to have a good level of certainty that the product will last 25 years.

Large-Area Coating: It may not be possible to apply the spin-coating technique typically used for surfaces with tiny areas (2.5*2.5 cm). For large-area coating, new coating solutions should be devised without centripetal force. The perovskite solution is typically coated on a large-area substrate (>100 cm²) using a blade, slot-die, spray, or inkjet. The PCE of PSCs and the perovskite film quality prove to be higher with improvements in the process of these manufacturing techniques. For instance, improvements in inkjet printing factors like velocity and the distance between the ink and the substrate have led to successful small-area PSCs at the laboratory scale. If these achievements can be applied to large-area PSCs and the stability and toxicity problems with halide perovskites are resolved, PSCs will be universally commercialized. Lastly, there haven't been many investigations on coating options for large-area FAPbI₃ or FA-based mixed cation and/or mixed anion perovskites, making this field of study challenging.

Perovskite tandem cells: By using multi-junction principles, improved efficiencies can be attained in the near future. Expanding the absorption spectrum range by combining a perovskite film with perovskite itself or other substances like silicon can enhance the amount of solar radiation that is converted into electricity and the voltage at which solar photons are transformed into electrical potential energy. Currently, only Perovskite-Si tandem cells have outperformed single-junction perovskite cells in terms of performance. Still, it is anticipated that perovskite-perovskite, perovskite-CIGS, and perovskite-OPV tandem cells will soon follow. Si or CIGS can combine vertically with perovskite, where current matching is crucial. Therefore, the efficiency of the tandem device must thus be maximized by material design for the optimum bandgap. In addition, to enhance photovoltaic characteristics in the final tandem structure, investigations on optical and electrical control should be conducted. The type of semiconducting Si determines whether the perovskite top cell has a normal or inverted shape in tandem devices. According to simulation data, triple-junction cells with a bottom 1.1eV silicon layer, and a middle and a top

perovskite layer with 1.44eV and 1.95eV, respectively, can result in a PCE of 39%. [14]. There will be further advancements, and triple-junction tandems will be presented very soon.

In the coming decades, perovskite solar cells are anticipated to become commercially viable and usurp silicon cells as the standard generation of solar cells. The manufacturing cost of PSCs is estimated to be only half of silicon solar cells. In 2021, the market for perovskite solar cells was valued at USD 0.17 billion. By 2029, it is anticipated to grow to USD 6.29 billion, achieving a CAGR of 34.50% [15]. However, there are still many barriers to widespread commercialization, and various technical problems must be quickly resolved. Leading companies in the field such as Oxford PV, Tandem PV Inc., Energy Materials Corp, Swift Solar, and WonderSolar, who have already tested and manufactured perovskite devices, will play a critical role in making the commercialization of PSCs a reality. In around 3 years, the technical requirements for flexible large-area perovskite solar photovoltaic cells will be achieved. After that, Perovskite-Si tandem cells with a warranty of 25 years might be launched in the market. It is expected that perovskite solar cells will soon dominate the photovoltaic industry, and perovskite-based clean and sustainable devices will significantly advance humankind.

VI. Conclusions

- Solar energy is vital to transitioning from fossil fuels to renewable energy. As the fastest-growing solar technology, Perovskite solar cells are the front-runner to succeed crystalline silicon solar cells in the next era of photovoltaics. With their crystalline structure, tunable band gap, high carrier mobility, and long carrier diffusion length, PSCs offer high power conversion efficiency. Meanwhile, the abundant materials and easy fabrication process along with the high absorption coefficient of perovskite allow perovskite solar cells to be manufactured at low cost. Although the most efficient PSCs nowadays still suffer from fast degradation, various methods have been applied to enhance their stability, such as encapsulating the device with hygroscopic substances, solvent engineering, doping, and passivation. New materials combinations have been studied in order to achieve higher efficiency of perovskite solar cells. In addition, more and more research is being done to find eco-friendly alternatives for toxic lead.
- In terms of future directions, more focus should be on interfacial engineering, the electron transport layer, and light harvesting near the band edge to improve the open-circuit voltage and fill factor for higher power conversion efficiency. Next, studies on compositional engineering, interfacial engineering, encapsulation methods, and the understanding of defects should be conducted. For future commercialization, appropriate large-area coating solutions are critical. Lastly, apart from single-junction PSCs, double-junction and triple-junction tandems should also be developed. Hopefully, then, perovskite devices will enter the market and greatly impact our lives.

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