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Advancing Perovskite Solar Cells: Addressing Stability, Scalability, and Environmental Challenges

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Abstract

PSCs or perovskite solar cells are revolutionizing the whole renewable energy field by possessing low cost of production yet high efficiency. The achievement of perovskite cell efficiencies has reached over 25%, an important milestone for the technology as it was initially introduced into practical light absorbers within photovoltaic devices. Improvements in materials, engineering of interfaces, and techniques of fabrication have led to this development. This study summarises the latest developments in PSC research, emphasizing new developments in material stability, encapsulating techniques, and the creation of lead-free substitutes to improve environmental safety. We also consider scalable manufacturing techniques that address PSCs' environmental impact and enable mass production, such as roll-to-roll printing. The possibility of being integrated with energy storage systems and localized energy solutions makes PSCs important to assist in sustainable energy transitions, especially in underserved areas. Future research in this area is expected to overcome the current issues of stability, scalability, and recycleability, ensuring that PSC technology will be a contributor to meeting the world's energy demands and mitigating climate change.

Keywords: Perovskite solar cells, Renewable energy, Thin-film photovoltaics, Tandem solar cells, Roll-to-roll printing, Environmental impact, Lead-free perovskites, Stability and scalability, Advanced encapsulation techniques

Introduction to Perovskite Solar Cells

Perovskite solar cells (PSCs) have rapidly become one of the most disruptive technologies available in the renewable energy business which challenges conventional photovoltaic functions (ALMORAA, Vaillant-Roca, & Garcia-Belmonte, 2017). PSCs have quickly gained significant improvements in pricing, scalability, and even efficiency since its first announcement in 2009 while breaking all previous records in photovoltaic conversion. A family of crystalline minerals that enable efficient generation of solar energy, "perovskite" refers to a unique and distinct crystal structure. Most of these solar cells are made of hybrid organic-inorganic materials, including methylammonium lead iodide ($MAPbI_3$), which has exceptional light absorption and efficient charge transfer, besides many other highly desirable optoelectronic properties. Because of such properties, PSCs can already reach power conversion efficiencies close to 28%, comparable with the efficiencies of established solar technologies like silicon-based cells, whose theoretical maximum efficiency is around 29.4% (Sahoo, Manoharan, & Sivakumar, 2018).

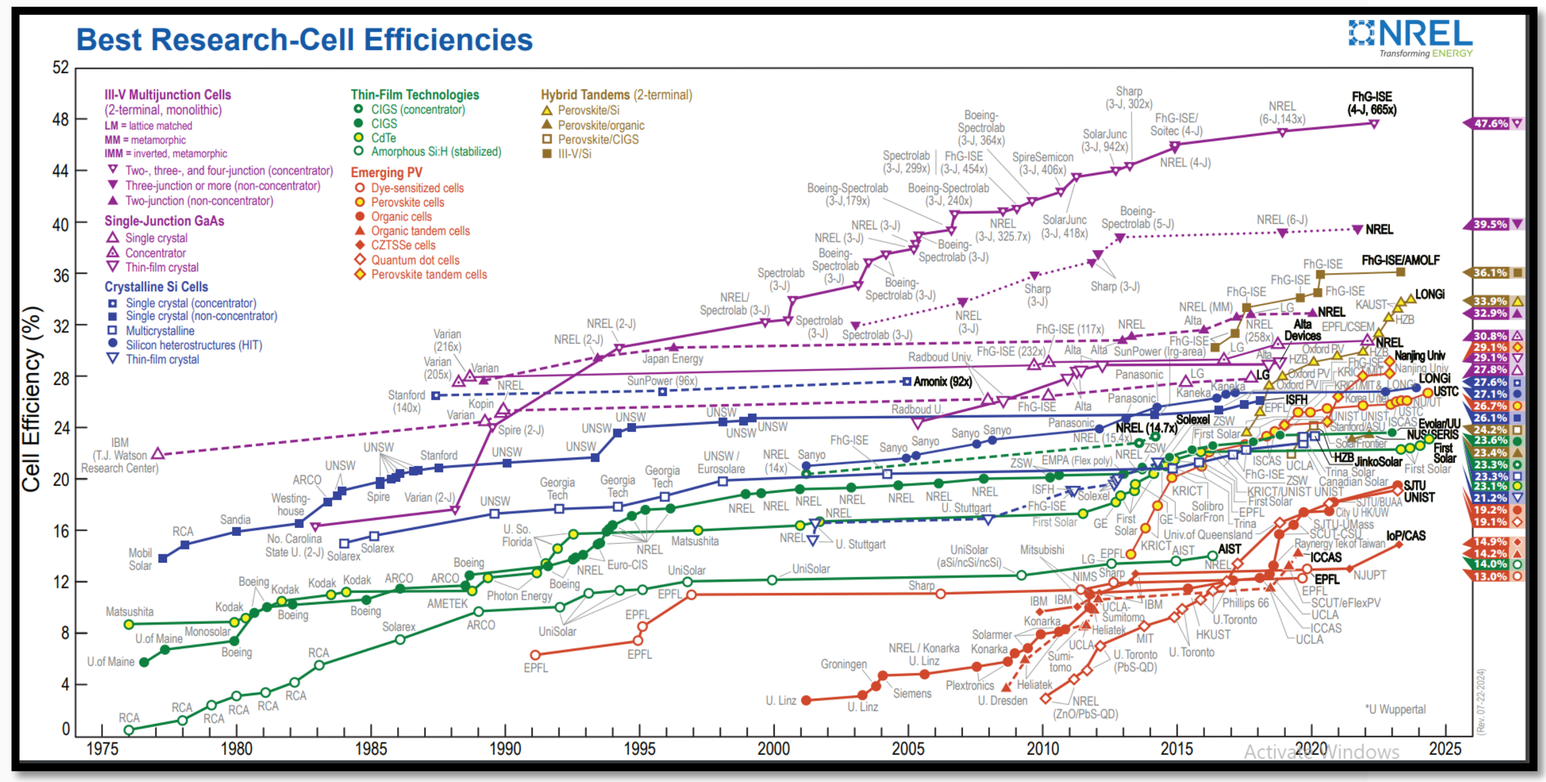


Figure 1: Efficiency Chart (National Renewable Energy Laboratory

Peperovskite materials can be used in the thinnest films that are 300 nanometers due to their excellent absorption ability over a wide range of wavelengths. This feature is very important for several applications, including massive solar farms, portable electronics, and even advanced technologies like building-integrated photovoltaics (BIPV), which allow buildings to generate their electricity. In addition, the PSC manufacturing processes can be used with low-temperature solution processing methods such as spin coating, inkjet printing, and blade coating (Bhattarai et al., 2022; X. Zhao & Park, 2015). These methods allow for high-throughput manufacturing, which is necessary to satisfy the increasing demand for renewable energy solutions globally, while also reducing production costs.

As shown in **Figure 1**, NREL Best Research-Cell Efficiency Chart focused on huge advances in the perovskite material, which now occupies a new front in photovoltaic (PV) research. This chart reported world record efficiency: 33.9 percent by Chinese manufacturer Longi in November, in a perovskite-silicon tandem solar cell. At this point, this milestone could demonstrate potential perovskite material applications when joined with silicon in tandem configuration to boost energy conversion efficiency. (Dale & Scarpulla, 2023) Perovskites have advanced in terms of efficiency rapidly over the last few years. In reality, perovskite inclusion in tandem cell technologies captures their ability to complement established materials such as silicon to push the boundaries of what is possible in PV. Again, the chart drives into the importance of perovskite innovations in terms of future improvements in solar energy technologies (De Angelis, 2024).

However, there are still several issues with PSC deployment, especially about how stable they are in the face of environmental stresses like heat, moisture, and UV light. The inherent instability of perovskite materials raises questions about their suitability for broad applications and can lead to a degradation of performance over time. Additionally, a lot of the most efficient perovskite materials contain lead, which is hazardous to the environment and human health (Stanyard et al., 2023). The advancement in the long-lasting and environment-friendly aspects of PSC devices has attracted a lot of interest concerning lead-free substitutes and encapsulation methods.

Historical Development of Perovskite Solar Cells

Perovskite solar cells (PSCs) have changed the face of photovoltaic (PV) landscape with the establishment of perovskite materials as efficient light absorbers in photovoltaic devices. This was through the research by Kojima et al. (2009). These early PSCs had efficiencies as low as 3.8% at first, largely due to poor material quality and deficient device architecture that hindered efficient charge transport and light absorption (Kojima, Teshima, Shirai, & Miyasaka, 2009). In solar energy, this introduction generated great attention and led to so much research (Lee, Bae, Kim, & Lee, 2020).

Device engineering and material processing capabilities were evolved with increased research. By 2013, PSCs started reaching efficiencies beyond 15% because of developments in spin-coating methods and sophisticated hole transport materials (WEI Zhang et al., 2013). These breakthroughs had demonstrated the potential of perovskite technology and sparked further studies for enhanced qualities of the material and better device architectures to perform effectively. **Table 1** shows the timeline of key milestones in PSC development.

Table 1: Timeline of Key Milestones in PSC Development

Year	Milestone Description	Reference
2009	Perovskite materials are introduced as light absorbers.	(Kojima et al., 2009)
2012	First gains in efficiency with new material formulas, up to about 10%.	(WEI Zhang et al., 2013)
2013	Efficiency gains above 15% were achieved with new hole transport layers and enhanced deposition techniques.	(Jung et al., 2019)
2016	Mixed-cation and mixed-halide perovskites are introduced to increase stability and efficiency.	(Wenzhe Li et al., 2016)
2019	Creation of tandem solar cells that combine silicon and perovskite solar cells to achieve efficiencies higher than 25%.	(H. Li & Zhang, 2020)
2020	Developments in tin-based materials as non-toxic substitutes for lead-based perovskites.	(Román-Vázquez, Vidyasagar, Muñoz-Flores, & Jiménez-Pérez, 2020)
2023	Efficiency levels in commercial prototypes of perovskite-silicon tandem combinations were reported to be more than 28%.	(Aydin et al., 2024)

2024	Increased PSC durability and stability by improved encapsulation and surface engineering methods for commercial application.	(Alli et al., 2024))

This marked a paradigm shift when the invention of tandem solar cells, combining conventional silicon solar cells with perovskite materials, was realized. Laboratory systems in this design already have achieved efficiency higher than 30% and can collect a broader spectrum of sunlight than single-junction cells (H. Li & Zhang, 2020). Because of these advancements, PSCs are now positioned as alternative options in place of traditional solar technologies. Notably, there has been remarkable progress in material formulation, particularly in mixed-cation and mixed-halide perovskites. It is this incremental improvement that allows for fine-tuned adjustment of the bandgap to optimize light absorption while keeping stability at an acceptable level (Elangovan et al., 2024).

Studies show that this tailored composition diminishes the energy loss and maximizes the efficiency of the solar cell; that is, the efficiency could be optimized depending on various conditions of the environment **(Table 2)**. There have been considerable attempts to mitigate health and environmental issues associated with lead-based perovskite materials (Gong, Darling, & You, 2015; Urbina, 2020; Jingyi Zhang, Gao, Deng, Zha, & Yuan, 2017a). This is because lead toxicity necessitates the development of nontoxic alternatives, like tin-based perovskites, which have the goal of achieving similar efficiency levels without posing health risks (Asghar, Zhang, Wang, & Lund, 2017). The continuation of research will be key to ensuring that PSC technology is sustainable.

Table 2*:* Efficiency Improvements over Time (Wenxiao Zhang et al., 2024)

Solar Cell Type	**Advantages**	**Disadvantages**	**Important Milestones**	**Efficiency Range**	**Applications**	**Environmental Impact**
Silicon Solar Cells	High efficiency, durability, well-established technology	Expensive, rigid, high energy consumption	The first commercial cell was in 1954, efficiency of over 25%	~15–25%	Residential, commercial, utility-scale solar	High carbon footprint in production
Organic Solar Cells	Flexible, low production costs, lightweight	Lower efficiency and stability, degradation under sunlight	Conductive polymers in 1977, an efficiency of around 10%	~3–12%	Wearable electronics, building-integrated photovoltaics (BIPVs)	Lower environmental impact, concerns about long-term waste
Halide Perovskite Solar Cells	High-efficiency potential, broad absorption, tunable	Stability and toxicity concerns, scalability	Introduced in 2009, efficiencies above 25%	Up to 25.5%	Potential for multi-junction solar cells,	Toxicity, particularly from lead

	bandgap	challenges			BIPVs	
CIGS Solar Cells	Good efficiency, flexible applications, less toxic	Complex manufacturing, scarcity of indium, toxicity of selenide	The first report in 1975, efficiencies of over 22%	~10–22%	Portable power, BIPV, space vehicles	Concerns about indium scarcity, selenide toxicity
CdTe Solar Cells	Low-cost production, good efficiency	Toxicity of cadmium, scalability, and disposal issues	Developed in the 1950s, commercialized in the 1980s, efficiencies over 22%	~10–22%	Large-scale solar farms, industrial applications	Cadmium toxicity, recycling challenges
GaAs Solar Cells	Very high efficiency, excellent low-light performance, high radiation resistance	High production cost, manufacturing complexity, niche market application	Invented in 1957, efficiencies over 29%	>29%	Space applications, high-performance electronics	Costly production, and arsenic toxicity concerns

The evolution of PSCs from experimental marvels to prominent contenders in the solar The energy industry is dynamic, and it highlights the potential of the sector to impact sustainable energy solutions (X. Li et al., 2024). Increased collaboration between academia and industry players has facilitated the commercialization path by focusing on durability improvements, scaling up production techniques, and addressing problems with PSC large-scale manufacturing. These collaborations are crucial to delivering PSC breakthroughs to the public as investments in solar technology increase around the world (Suo et al., 2024).

Recent developments make PSC technology increasingly capable. Already by 2023, several research groups reported that commercial prototypes of monolithic perovskite-silicon tandem solar cells had efficiencies above 28% (Liu et al., 2024). Innovations such as optimized surface engineering and better encapsulation techniques have enhanced the stability and endurance of PSCs under real-world conditions in 2024, which is a huge step toward greater implementation in the renewable energy sector (Artuk et al., 2024).

Materials and Fabrication Techniques

The performance, lifetime, and efficiency of perovskite solar cells (PSCs) are dependent on the materials that make them up (Park & Zhu, 2020). Hybrid organic-inorganic perovskites, such as methylammonium lead iodide, or $MAPbI_3$, owe their remarkable electrical properties and excellent light-absorbing characteristics to broad applications. Organic cations in these compounds, for example, formamidinium (FA) or methylammonium (MA), are tied to the inorganic framework, usually a metal halide like lead iodide (PbI_2) (Berry et al., 2015). Due to this combination, a crystal structure is formed that facilitates both high absorption of visible light and efficient charge transport **(Figure 2)**.

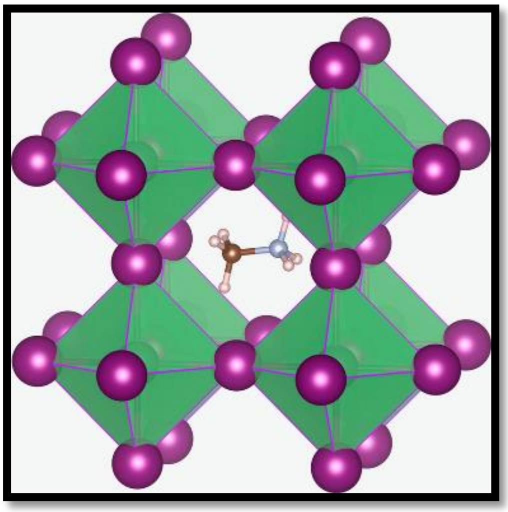


Figure 2: Perovskite structure of $CH_3NH_3PbI_3$. Methylammonium cation (CH_3NH_{3+}) occupies the central A site surrounded by 12 nearest-neighbor iodide ions in corner-sharing PbI_6 octahedra. (Berry et al., 2015)

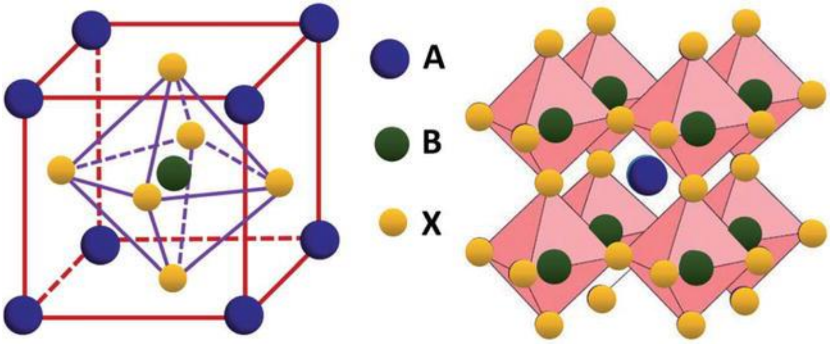


Figure 3: Structure of Hybrid Organic-Inorganic Perovskites (Aslam, Mahmood, & Naeem, 2021)

Recently, the improved thermal stability of all-inorganic perovskites, including cesium lead halides ($CsPbX_3$), has been recognized relative to their hybrid counterparts **(Figure 3)**. These materials address the shortcomings of traditional hybrid PSCs, being best suited for high temperatures and intense solar irradiation. Formamidinium tin iodide ($FASnI_3$) and other tin-based perovskites are gaining popularity as lead-free alternatives. They deliver comparable performance without lead toxicity issues (Zheng & Loh, 2024). **Table 3** shows Comparison of Hybrid and All-Inorganic Perovskites along with their properties and performance metrics.

Some key points are as following:

Hybrid Perovskites: The efficiency and processing techniques of $MAPbI_3$ and similar compounds are well established. However, due to their toxicity and instability, researchers are looking at other materials (Zheng et al., 2024).

All-inorganic perovskites: In high demand applications, $CsPbI_3$ type of material possessing superior thermal stability and resilience to the environmental forces are suitable. However, this still remains in a relatively premature commercialization stage, given their potential (Karimitari et al., 2024).
Tin-Based Perovskites: These materials offer a competitively performing, potentially lead-free alternative. However they suffer from scalability and stability issues (Kashikar et al., 2024).
Table 3: Comparison of Hybrid and All-Inorganic Perovskites: Properties and Performance Metrics

Property/Metric	**Hybrid Perovskites (e.g., $MAPbI_3$)**	**All-Inorganic Perovskites (e.g., $CsPbI_3$)**	**Tin-Based Perovskites (e.g., $FASnI_3$)**
Thermal Stability	Moderate to high (Ferreira, Stroppa, Wang, & Gao, 2020)	High (Ouedraogo et al., 2020)	Moderate to high (Ke, Stoumpos, & Kanatzidis, 2019)
Toxicity	Lead-based, toxic (Egger, Rappe, & Kronik, 2016)	Lead-based, toxic (Liang et al., 2016)	Lead-free, lower toxicity (Cao & Yan, 2021)
Light Absorption	Excellent (Wei Li et al., 2017)	Good (Jingru Zhang, Hodes, Jin, & Liu, 2019)	Moderate to good (Cao & Yan, 2021)
Efficiency (PCE)	~20-25% (Wei et al., 2020)	~18-22% (Ouedraogo et al., 2020)	~12-15% (Cao & Yan, 2021)
Environmental Stability	Sensitive to moisture and heat (Román-Vázquez et al., 2020)	More stable in harsh conditions (Ouedraogo et al., 2020)	Less stable, prone to degradation (Ke et al., 2019)
Fabrication Complexity	Moderate (Wei et al., 2020)	Moderate (Jingru Zhang et al., 2019)	High (Liu et al., 2017)
Bandgap Tunability	High, adjustable via halide composition (Suo et al., 2024)	Moderate, limited to specific compositions (Ouedraogo et al., 2020)	High, but stability issues (Cao & Yan, 2021)
Scalability	High, well-established methods (Urbina, 2020)	Moderate, emerging technologies (Jingru Zhang et al., 2019)	Emerging, with challenges in scalability (Ke et al., 2019)

Manufacturing procedures for perovskite solar cells (PSCs) have dramatically evolved, embracing state-of-the-art techniques aimed at optimizing device performance and material quality. As solution-based methods are facile and scalable, they are widely used to deposit high-quality perovskite films that possess the ideal crystallinity for maximizing device efficiency. Among them, spin coating and blade coating stand out. In particular, blade coating has better crystallinity than spin coating because it allows for the generation of consistent and repeatable film generation over larger areas. Outside of these methods, the advanced vapor deposition techniques, such as CVD and dual-source evaporation, allow for precise composition and thickness control of the deposited films. By allowing for customized material layer deposition under controlled conditions an important step toward optimizing light absorption and charge transport these approaches significantly enhance the repeatability and consistency of PSC performance (Kajal, Ghosh, & Powar, 2018). **Figure 4** shows an example of such perovskite solar cell formation and **Table 4** gives its device parameters (Z. Li et al., 2018).

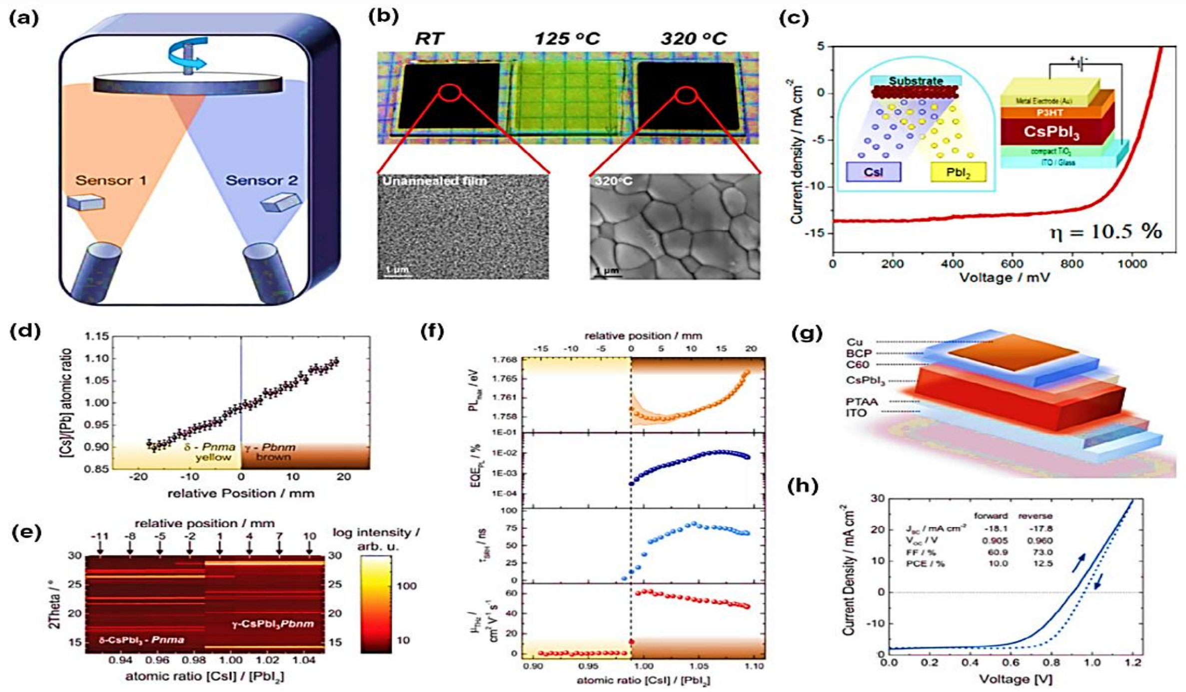


Figure 4: (A) Diagrams showing how a co-evaporation system works to create thin films of perovskites. (b) Images of CsPbI3 thin films made by co-evaporation. (c) The best-performing device's current-voltage characteristics as shown in the movie. Investigation of γ-CsPbI3 perovskite synthesis at low temperatures using high throughput experiments (d–h) (Raman, Thangavelu, Venkataraj, & Krishnamoorthy, 2021).

Table 4: Summary of the device parameters of CsPbI3 PSCs made using vapor deposition (Huang et al., 2021).

PSC Device Configuration	***V_{OC}* (V)**	***J_{SC}* (mA/cm^2)**	**FF (%)**	**PCE (%)**	**Method**	**SPO (%)**	**DOR^a**
Ca/C_{60}/$CsPbI_3$/TAPC/TAPC:MoO_3/Ag	0.98	17.3	56	9.4	CO-E	NA	2017.01

c-TiO_2/$CsPbI_3$/P3HT/Au	1.06	13.8	71.6	10.5	CO-E	NA	2016.12
c-TiO_2/$CsPbI_3$/P3HT/Ag	0.71	12.06	67	5.71	SEQ-E	NA	2017.03
c-TiO_2/$CsPbI_3$/P3HT/Ag	0.79	12.06	72	6.79	SEQ-E	NA	2017.08
SnO_2/$CsPbI_3$/spiro/Ag	1.00	13.0	68	8.8	CO-E	7.8	2017.07
PTAA/$CsPbI_3$/PCBM/Al	1.00	15.5	66	10.2	SEQ-E	NA	2018.05
PTAA/$CsPbI_3$/C_{60}/BCP/Cu	0.96	17.8	73	12.5	CO-E	10.7	2019.04

In addition, advancements in high-end printing technologies, including screen and inkjet printing, have eased the large-scale production of PSCs. Such techniques help in minimizing material losses while producing large-area solar cells, which is indispensable to the economical feasibility of PSC technology. Moreover, these printing processes facilitate the design of complex device structures. That increases the prospects of building-integrated photovoltaics and other applications and aligns with methods of sustainable production (Tu et al., 2021).

Performance Optimization Strategies

PSCs are capable of performing at the highest possible efficiency if important parameters are considered, like efficient light absorption, improved charge carrier dynamics, and overall stability of the device. Light absorption is highly necessary for a good efficiency. Though the absorption coefficient is high in perovskite materials, there is the need for extra techniques for improving light trapping capabilities in such thin-film devices rather than thickening the material. Novel approaches such as surface texturing, nanostructure integration, and photonic crystal application are being explored in detail to improve light absorption **(Table 5)**. To enhance light scattering within the active layer of the perovskite film and increase photon path length and absorption, surface texturing involves creating micro- or nanoscale patterns on the film's surface (Ibrahim, Shoukat, Aslam, & Israr Ur Rehman, 2024). Nanostructures such as nanoparticles or nanorods may provide additional surface area and light-trapping efficiency. Due to periodic dielectric architectures, photonic crystals can also increase light absorption and decrease reflection losses by manipulating light propagation inside the PSC (Godasiaei, 2024).

Table 5: Techniques for Enhancing Light Absorption in PSCs

Technique	**Description**	**Reference**
Surface Texturing	Micro- or nano-scale patterns to scatter light	(Alli et al., 2024; ALMORAA et al., 2017)
Nanostructures	Integration of nanoparticles or nanorods to increase surface area	(Artuk et al., 2024; De Angelis, 2024)
Photonic Crystals	Periodic dielectric structures to manipulate light propagation	(Elangovan et al., 2024; Ibrahim et al., 2024)
Light Scattering Films	Thin films that scatter light to enhance absorption	(Karimitari et al., 2024; Ke et al., 2019)
Metamaterials	Materials engineered to have	(Lee et al., 2020; X. Li et

	properties not found in nature	al., 2024)

Further, the composition of halides may be tweaked to get perovskite materials that precisely tune in the bandgap. This facilitates the capture of a wide light range, especially useful for tandem solar cells. The combined materials having various bandgaps enhance solar spectrum absorption and boost the total efficiency. Combining different band-gap materials into a tandem would increase the power conversion efficiency. This enables the capture of both high and low-energy photons (Si, Zhao, Zhang, Liao, & Zhang, 2024). The building of multi-junction solar cells, which captures an even wider range of the solar spectrum and thereby further enhances efficiency, is enabled by the ability to precisely control the bandgap. Energy losses arising from recombination may be reduced and charge extraction can be maximized by optimizing interfaces between the perovskite layer and the electron and hole transport layers. Recombination losses can be decreased and charge carrier collection can be enhanced through efficient interface designs. It has been shown that the use of interfacial layers or surface modification of the perovskite layer significantly enhances contact quality and allows for efficient charge transfer across interfaces. New interfacial engineering developments, like the invention of new materials for hole and electron transport, have recently been demonstrated to improve PSC stability and performance (Wang, Qin, Li, Zhao, & Liang, 2024).

To ensure efficient charge transport to the electrodes without recombination, it is also important to enhance charge carrier mobility within the perovskite layer. Recent studies have shown that choosing the right transport materials and using passivation methods can significantly increase carrier mobility and reduce trap states in the perovskite layer (Q. Zhao, Li, & Zhang, 2024).

Figure 5 shows general scheme of the charge-carrier dynamics and its importance for the cell. In figure (A) shows Cross-sectional image of a planar PSC with scanning electron microscopy, (B) shows the voltage and current balance limit for the fraction of Shockley-Queisser detailed by record cells is attained; lines representing band gaps used in the S-Q computations based on the uncertainty in the recorded cell's band gap surround the selected data. C and D shows possible charging mechanisms and the characteristic timescale of the cell. E shows the calculated bulk carrier lifetime, interfacial charge extraction and recombination rates, and steady-state photocurrent as functions of these parameters. F represents the Quantum efficiency of charge extraction and collection about interfacial carrier dynamic (Irshad et al., 2024).

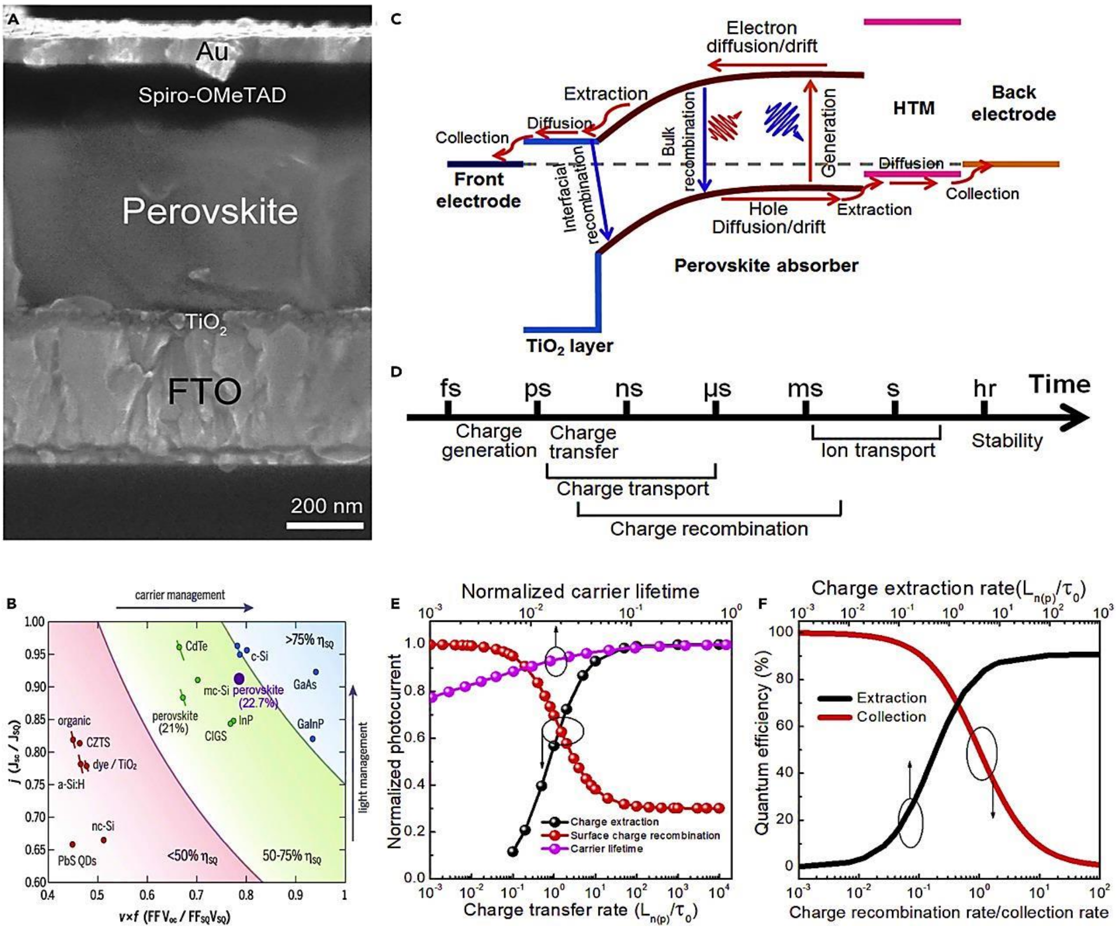


Figure 5 General Scheme of the Charge-Carrier Dynamics and Its Importance for the Cell (Irshad et al., 2024)

To enhance device efficiency, hybrid organic-inorganic materials and state-of-the-art processing techniques have been exploited to enhance carrier mobility and reduce recombination losses. Interface engineering and surface passivation layers have been proved to be used for improving charge carrier dynamics and lowering faults (Kasparavičius, Franckevičius, Driukas, & Gulbinas, 2024).

1 Addressing Stability Challenges

The largest problem facing perovskite solar cells, or PSCs, now as they near commercialization, is stability in real-world settings. Perovskite materials deteriorate due to environmental factors such as heat, moisture, and extended exposure to the sun, which can cause them to degrade and perform at a lower level with reduced lifespan for the device. For instance, moisture penetration can significantly degrade the perovskite layer, considerably reducing the efficiency of a solar cell. Humidity worsens this issue because perovskite materials are more vulnerable to water molecules in these conditions.To overcome these issues, scientists are developing advanced encapsulation techniques that shield perovskite materials from the environment while keeping their essential optical and electrical properties. The moisture-resistant barriers used in these encapsulation approaches, such as fluoropolymer films and multilayered coatings, do not allow water vapor to enter the device. Recent studies have also focused on hybrid encapsulation technologies that incorporate materials such as self-assembled monolayers and polymer matrices **(Table 6)**. These methods combine physical barriers with chemical passivation techniques (Betti, Bosetti, & Malavasi, 2024; Fu et al., 2024; Kerara, Naas, Gueddim, & Meglali, 2024; Popa, Popa, & Goia, 2024).

Table 6: Encapsulation Techniques for Enhancing Stability of PSCs

Encapsulation Technique	Description	Key Benefits	References
Fluoropolymer Films	Layers of fluoropolymer used to prevent moisture intrusion.	High optical transparency and dampness resistance.	(Xiang et al., 2022)
Multilayer Coatings	Protective coatings with oxides and nitrides in multiple layers.	Enhanced oxygen and moisture barrier properties.	(Younas, Kandiel, Rinaldi, Peng, & Al-Saadi, 2021)
Hybrid Encapsulation	Combines SAMs, polymers, and chemical passivation for physical barriers.	Superior resistance to oxygen and moisture.	(Zhu et al., 2023)
Glass Encapsulation	Glass layers fully encapsulate the device.	Excellent protection from external factors.	(Zhou et al., 2023)
UV-Blocking Layers	UV-blocking materials incorporated into the encapsulation.	Prevents photodegradation of perovskite layers.	(B. Yang et al., 2024)
Self-Healing Coatings	Advanced coatings that self-repair minor cracks and damage.	Extends operational life by preventing failures.	(Xiang et al., 2022)

The thermal stability also fundamentally influences the performance of PSCs. At high temperatures, some perovskite materials experience phase transitions that compromise their structural integrity and efficiency. For example, the typical perovskite material methylammonium lead iodide ($MAPbI_3$) undergoes a phase transition at about 85°C, which leads to the degradation of efficiency and crystallinity (Ahmed et al., 2023; L. Li et al., 2022; Zhou et al., 2023). To address this, research is now conducted on altering the chemical makeup of perovskite and incorporating additives that are thermally stable to assist in reducing degradation during its usage. Studies have shown that doping cesium (Karimitari et al.) and formamidinium (FA) into the perovskite framework significantly enhances thermal stability, enabling the solar cells to operate at high temperatures **(Table 7)**.

Table 7: Schematic of Thermal Stability Improvements in Perovskite Solar Cells (PSCs)

Thermal Stability Approach	Description	Key Benefits	References
Incorporation of Cesium (Karimitari et al.) and Rubidium (Rb)	Cs and Rb cations are added to the perovskite structure to improve thermal stability through phase transition reduction.	Enhanced gadget performance and thermal stability at high temperatures.	(Ahmed et al., 2023)
Use of Thermally Stable Additives	To stop heat breakdown, the perovskite layer is filled with polymers or stabilizing chemicals.	Extended device lifetimes and enhanced resilience to heat-induced degradation.	(L. Li et al., 2022)
Advanced Encapsulation Techniques	Innovative encapsulation techniques are used to shield PSCs from heat stress and moisture.	Improved stability and endurance in challenging environmental circumstances.	(Xu et al., 2024)
Optimized Device Architecture	Enhancing heat dissipation and lowering thermal stress on perovskite layers through device structural engineering.	Enhanced operating stability and decreased thermal depreciation.	(Mousavi et al., 2022)

Moreover, effective defenses against light-induced damage demand a basic understanding of the principles behind photodegradation. Photodegradation refers to the degradation process perovskite materials undergo when exposed to light for a long period, particularly UV radiation. Incorporation of UV filters in the structure of solar cells and utilization of stabilizing chemicals such as antioxidants in the perovskite matrix are recent developments. These methods have been shown to reduce the detrimental effects of UV radiation, making PSCs longer-lived in real-world applications (Mousavi et al., 2022; Zhu et al., 2023). By addressing these environmental vulnerabilities with cutting-edge encapsulation techniques and inventive materials engineering, PSCs can become much more stable and approach large-scale deployment in a variety of environmental settings.

2 Environmental and Economic Considerations

2.1 Environmental Impact of Perovskite Solar Cells

As PSCs have much to offer, their widespread use needs careful consideration of environmental impacts. On the positive side, if PSCs substitute fossil fuel-based energy generation, their ability to generate power efficiently allows for considerable reduction in greenhouse gas emissions (Urbina, 2020). The current estimates indicate that integrating PSCs into the already existing energy systems could drastically decrease the carbon footprint linked with the generation of power, thus supporting international efforts toward mitigating climate change. Life cycle studies also indicate that the use of PSCs would result in a lesser environmental burden compared to conventional energy sources. **Table 8** represents degradation rates of perovskite cells compared to silicon cells under various environmental conditions (Hauck, Ligthart, Schaap, Boukris, & Brouwer, 2017).

That aside, the major problem with PSC technology is the toxicity of lead-based compounds. Scientists are focusing on making lead-free alternatives because the risk of lead leaking into the environment is a major health threat to both humans and wildlife. For instance, tin-based perovskites have shown promise in minimizing lead toxicity while achieving similar efficiency. However, they often face problems with stability and scalability during production. Some of the measures to mitigate these risks include robust encapsulation methods that protect perovskite cells from moisture and UV light—two major reasons for material degradation. The life span of PSCs is improved through advances in encapsulation technologies, which ensure that they last for a long period and improve their reliability as a renewable source of energy.

Table 8: Degradation Rates of Perovskite Cells Compared to Silicon Cells under Various Environmental Conditions

Environmental Condition	Degradation Rate of Perovskite Cells (Ghosh et al., 2024)	Degradation Rate of Silicon Cells (Xu et al., 2024)
Humidity (80%)	15% over 6 months	5% over 6 months
UV Exposure (1,000 hours)	25%	10%
Temperature (60°C)	20% over 3 months	5% over 3 months

To guarantee PSC technology's overall sustainability, rigorous environmental studies must coincide with the technology's development and application.

Economic Potential of Perovskite Solar Cells

One of the major reasons for their adoption in the renewable energy market is economic feasibility. The low manufacturing cost of PSCs becomes highly appealing when the demand for greener sources of energy increases with increasing global prices of energy. Due to reduced energy consumption and raw materials usage in streamlined production processes, the present-day estimates for PSC production costs could be around 50% lower compared to that of conventional silicon-based solar cells **(Table 9)**. The applicability of PSCs can also enable their integration into existing solar structures, thereby enhancing overall energy efficiency besides the cost. Hybrid devices, where PSCs are integrated with more traditional silicon-based technologies, further optimize energy harvesting for longer periods of sunlight. As such, tandem solar cells can significantly increase the harvested amount of energy on the same rooftop space, which achieves a 30% efficiency value in the literature. Here is a table that contrasts the efficiencies and cost structures of PSCs with those of conventional silicon solar cells (Stasiulionis, 2015).

Table 9: Comparison Table of Perovskite Solar Cells and Traditional Silicon Solar Cells

Parameter	**Perovskite Solar Cells**	**Traditional Silicon Solar Cells**
Manufacturing Cost	~$0.20 - $0.30 per Wp (NRECA, 2022)	~$0.60 - $0.70 per Wp (Ahmed et al., 2023)
Power Conversion Efficiency	Up to 28% (He et al., 2016)	Up to 26% (Mousavi et al., 2022)
Materials Used	Hybrid organic-inorganic (Yang et al., 2020)	Crystalline silicon (Li, 2024 #16)
Average Lifespan	10 - 15 years (Machín & Márquez, 2024; Sahoo et al., 2018)	25 years (Honsberg & Cugnet, 2024)
Environmental Impact	Potentially toxic (lead) (Sahoo et al., 2018)	Less toxic, but energy-intensive (Roussel & Li, 2024)
Flexibility	Flexible and lightweight (Stasiulionis, 2015)	Rigid and heavy (Y. Zhang & Chen, 2024)
Applications	BIPV, electronics, wearables (Jingyi Zhang, Gao, Deng, Zha, & Yuan, 2017b)	Rooftop, utility-scale installations (Y. Zhang & Chen, 2024)

Furthermore, governments globally have enacted various legislations that encourage the consumption of renewable power through incentives. For many firms and households wanting to achieve energy autonomy, in addition to the quest towards reducing carbon footprints, favorable rules promote the implementation of a product like PSC. With the growth of the solar energy industry new opportunities for investment and the creation of employment in the manufacturing, installation, and maintenance industries are introduced as the financial landscape is changing rapidly (Jingyi Zhang et al., 2017b).

Applications and Market Potential of Perovskite Solar Cells

Building-Integrated Photovoltaics (BIPV) Utilizing Perovskite Solar Cells Since 2024

In 2024, several trends emerge in the application of BIPV, such as those concerning the introduction of PSCs to architectural designs. The incorporation of BIPV technologies for achieving net-zero energy buildings is becoming essential for many urban areas where sustainability and energy efficiency top the agendas. PSCs are the essential component for BIPV applications due to their high power conversion efficiencies and diverse optical characteristics. One of the significant milestones in commercialization is the stabilization of PSC technology (Rossi et al., 2024). Due to novel encapsulation techniques, which protect PSCs from environmental degradation, their lifetime and reliability in real applications have improved. These techniques allow PSCs to tolerate moisture, temperature shifts, and UV exposure. These upgrades have increased the application of BIPV technologies in architecturally designed and constructed buildings (Chen et al., 2024).

The cost of PSCs has also been reduced as a result of innovation in production methods, making BIPV solutions more competitive in comparison to conventional energy resources. Roll-to-roll printing processes, which were first initiated in 2024, have enabled the mass manufacture of flexible, thin, and lightweight PSCs in large quantities at lower costs while maintaining quality. This has led to the integration of solar technology in more applications of building materials such as roofing systems and facades. Architectural landscape has been open to aesthetic potential through PSCs. Buildings now appear more aesthetically due to the availability of semi-transparent and colored solar cells through the improvement of the perovskite material's tunability. Because they can now integrate solar technology without compromising architectural integrity, architects and builders like the BIPV solutions with integrated PSCs more. Integrated BIPV systems, especially those utilizing PSCs, can help significantly reduce building energy demands as urban planners increasingly focus on climate resilience. Energy-generating roofing and facades promote decentralization of energy systems, increase local energy production, and reduce reliance on conventional grid infrastructures. Nevertheless, there remain challenges in scale-up production and ensuring widespread availability of high-quality PSCs for BIPV applications. Hybrid perovskites and formulation techniques with better development offer promising progressions; further research is, therefore required to enhance the stability and efficiency of perovskite materials (Rossi et al., 2024; X. Yang et al., 2024).

Wearable and Portable Electronics

Perovskite solar cells (PSCs) are flexible, thin, and lightweight. Consequently, PSCs offer a number of exciting opportunities for customers and wearable technology with their excellent energy conversion efficiency **(Table 10)**. PSCs are ideal for driving small, portable devices like smartphones and smart watches. Moreover, due to the requirement of wearable technology for dependable power source under lowlighting conditions, the excellent lowlight performance makes them an appropriate choice for this application as well. Lastly, novel progress has provided flexible and stable PSCs, that can be directly embedded onto textile substrates or in electronic device surfaces (Posar & Griffith, 2024).

Table 10: Energy efficiency and weight of traditional solar cells versus PSCs for wearable applications

Parameter	**Traditional Solar Cells**	**Perovskite Solar Cells**	**References**
Energy Conversion Efficiency	15-20%	Up to 25%	(Goje et al., 2024)
Weight	Heavier (1-2 kg/m²)	Lighter (<1 kg/m²)	(Tan, 2024 #23
Flexibility	Rigid	Flexible	(Hauck et al., 2017; L. Li et al., 2022)
Durability	Moderate	Higher potential with protective coatings	(Machín & Márquez, 2024; Mousavi et al., 2022)
Cost	Higher production costs	Lower production costs expected	(Rossi, 2024 #19;Tan, 2024 #23)

Solar-Powered Vehicles

The automotive industry is increasingly focusing on the integration of solar technologies into cars to make them more sustainable and energy-efficient. Being highly flexible and efficient, perovskite solar cells are an excellent candidate for being integrated into multiple vehicle surfaces such as windows and roofs. PSCs can be used for powering electric car auxiliary systems, such as entertainment and lighting, recent studies have found (Zhou et al., 2023). This may increase the range of the vehicle and reduce the necessity of frequently recharging the vehicle externally. An increasing interest in utilizing solar energy for transportation is realized through the integration of PSCs by companies, such as Light year an (Qamar et al., 2024)d Toyota.

Figure 6 illustrates the possible application areas of ST-PSCs based on their transparency in different regions of the solar spectrum. ST-PSCs with high visible transparency could be utilized in building-integrated photovoltaics (BIPV) systems or automotive applications, such as power-generating transparent car roofs. Meanwhile, NIR-transparent PSCs are suitable for integration as top cells in tandem photovoltaic systems (Naseri, Araghi, Razeghi, & Noorollahi, 2024).

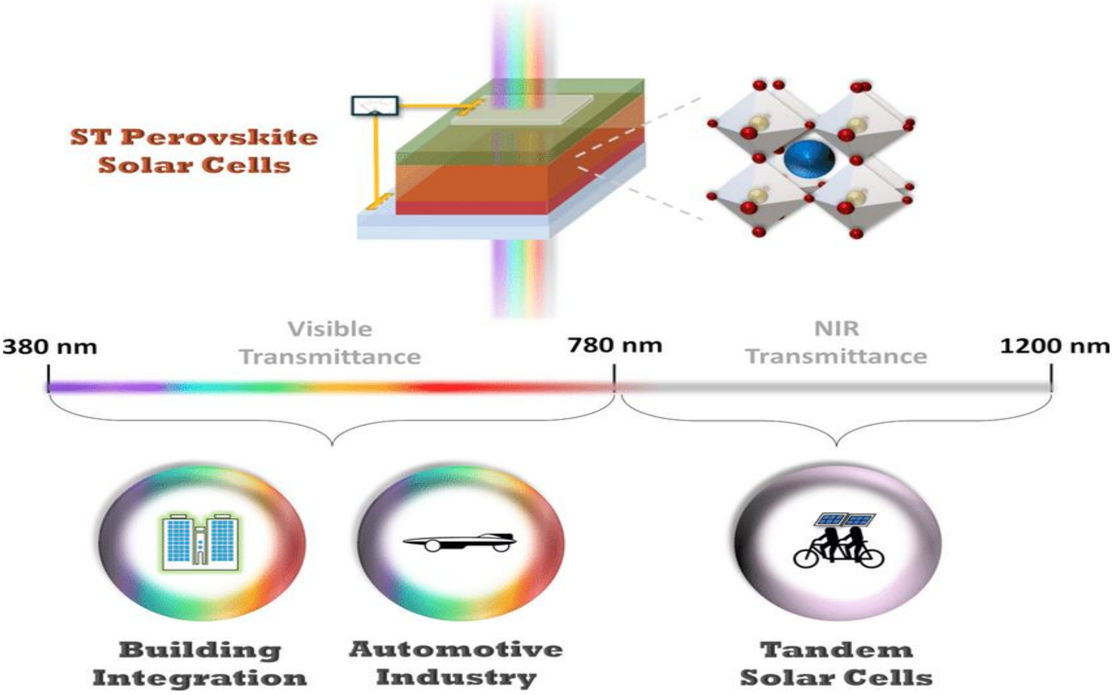
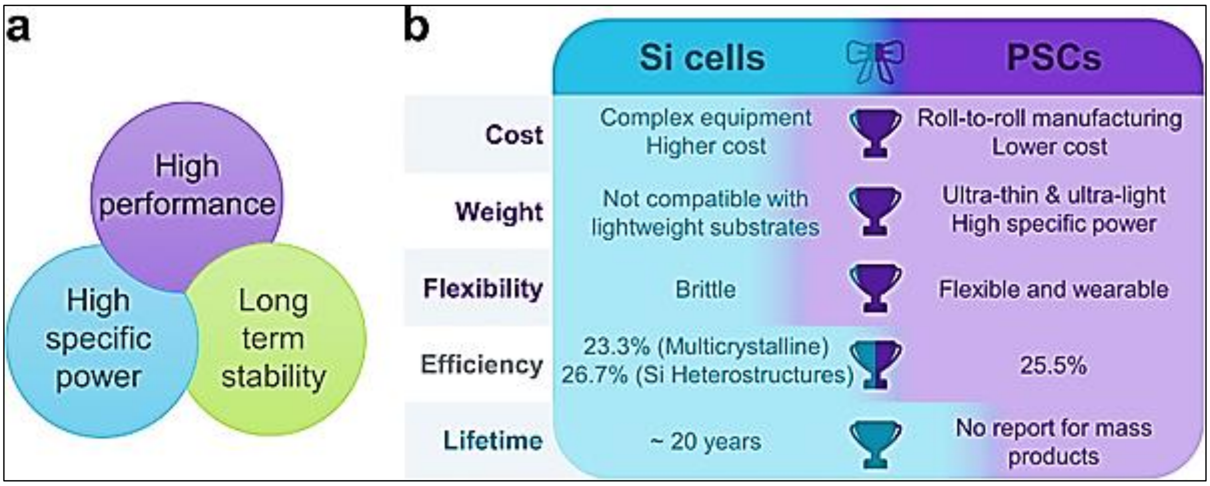


Figure 6: Potential integration of semitransparent perovskite solar cells (ST-PSCs) into various surfaces of a vehicle.

Space Applications

Perovskite solar cells are viable alternatives for traditional solar technology in the exploration of space, weighing and efficiency being the principal concerns. PSCs can be used to power the satellites and spacecraft due to their high power output and being light. The versatility of PSCs enables them to be adapted to fit intricate shapes of spacecraft, thus enabling maximum utilization in confined space **(Figure 7)** (G. Zhao et al., 2024).



	Si cells	PSCs
Cost	Complex equipment Higher cost	Roll-to-roll manufacturing Lower cost
Weight	Not compatible with lightweight substrates	Ultra-thin & ultra-light High specific power
Flexibility	Brittle	Flexible and wearable
Efficiency	23.3% (Multicrystalline) 26.7% (Si Heterostructures)	25.5%
Lifetime	~ 20 years	No report for mass products

Figure 7: (a) Specific requirements for space solar cells, and (b) a comparison between silicon (Si) cells and perovskite solar cells (PSCs) (Tu et al., 2021)

To offer reliable operation in space environment, the latest advancement of space-grade PSCs focuses on their resistance to radiation and extreme temperatures. To capitalize on the advantages of PSCs for long-duration missions into space, NASA, as well as other space agencies, are currently researching to implement them in future missions **(Table 11)** (G. Zhao et al., 2024).

Table 11: Comparison of Perovskite Solar Cells and Traditional Solar Cells for Space Applications

Parameter	**Perovskite Solar Cells (PSCs)**	**Traditional Solar Cells**
Weight	Much lighter than conventional cells—roughly 0.5 kg/m² (Leijtens et al., 2017).	Crystalline silicon typically weighs between 20 and 25 kg/m² (Mousavi et al., 2022)
Efficiency	Reported 26.1% efficiency in laboratory settings (Wong et al., 2018).	For conventional silicon cells, this typically falls between 15 and 22% (Siow & Chindamanee, 2024)
Cost	$20–30 per watt is the estimated cost of production (Wong et al., 2018).	High-efficiency modules range in price from $100 to $150 per watt (Goje et al., 2024)
Temperature and Stability	Reaches 85°C without losing efficiency, and stability keeps getting better (Wong et al., 2018).	Generally, proven stability functions best in challenging environments (Ahmed et al., 2023)
Flexibility	Enables the creation of distinctive designs when manufactured on flexible substrates (Jung et al., 2019).	Stiff design with little room for creative integration (Zhu et al., 2023)

Internet of Things (De Rossi et al.) Devices

With the rapid proliferation of the Internet of Things, the growing number of connected devices necessitates efficient power solutions. Because perovskite solar cells are small in size, light in weight, and capable of operating under low-light conditions, they are suitable for this application (Chen et al., 2024). All of these Internet of Things (De Rossi et al.) devices, including smart meters, cameras, and sensors, can be mounted with PSCs which provide a long-term power source that eliminates frequent battery change **(Table 12)**. This integration is specifically helpful for the devices in remote or outdoor locations for which conventional power sources are impractical (L. Li et al., 2022). The results of the developments have demonstrated that PSCs can be applied to power environmental sensors and smart street lights. Infrastructure thus gets smarter and energy-efficient (Uršič, Pirc, Jošt, Topič, & Jankovec, 2024).

Table 12: Potential IoT applications powered by PSCs and their corresponding energy requirements.

IoT Application	Description	Energy Requirement	References
Smart Streetlights	Solar-powered lamps that illuminate streets at night	~50-100 W	(Siow & Chindamanee, 2024)
Environmental Sensors	Devices monitoring soil moisture and temperature	~1-5 W	(Kang et al., 2024)
Wearable Health Monitors	Fitness trackers that monitor physiological parameters	~2-3 W	(Shi et al., 2024)
Smart Agriculture Equipment	Devices for monitoring crop health and water levels	~10-15 W	(Uršič et al., 2024)
Connected Vehicles	Solar panels integrated into vehicles for auxiliary power	~200-500 W	(Qamar et al., 2024)

Conclusion and Future Outlook

Hence, the development of perovskite solar cells in the period from their very invention in 2000 to the breakthroughs through by 2024 marks one of the most important periods so far in photovoltaic technologies. The use of the halide perovskites in solar cells only became possible through early experiments that produced initial power conversion efficiencies of about 3.8% (Sahoo, Manoharan, & Sivakumar, 2018). PSC efficiency has since increased to well over 26% under laboratory conditions due to swift developments, which has also put them in the running for a competitive alternative to silicon-based solar systems (Noman et al., 2024). However, stability concerns and environmental issues remain prevalent. Curiously, developments into lead-free alternatives like tin-based and other hybrid perovskites have been prompted by the fact that lead-based perovskites, although so effective, pose serious toxicity issues. These materials aim to achieve similar efficiency values but concurrently tackle health and environmental issues (Elangovan et al., 2024). Furthermore, the ongoing developments in stability-improving methods and encapsulation techniques have been shown to be promising enough to enhance the working lifetimes of PSCs (Noman et al., 2024; Jan et al., 2024). One innovative strategy for enhancing energy conversion efficiency is tandem solar cells. Researchers are looking to break the constraints of single-junction cells by matching PSCs with silicon and other materials to gather more sunlight in a broader spectrum.

Charge transport layers, which are crucial in improving charge collection and overall device performance, must still be developed (Noman et al., 2024).

Scalability in PSC production is still vital in the future. With roll-to-roll printing and other cost-effective manufacturing procedures, mass production is becoming viable for real-world applications (Jan et al., 2024). It will also be important to develop extensive recycling programs and green manufacturing techniques to foster use worldwide (Raza et al., 2024). PSCs have advantages in terms of weight and versatility, making them an option for off-grid energy use, especially with the need that is rising for energy throughout the world, particularly for unconnected and underserved groups. Their ability to present solutions for regional energy solutions is going to assist such groups in economic development and, therefore, energy availability (Noman et al., 2024). Continued innovation and research are all set to further brighten up the future of perovskite solar cells: in short, more and more efficient with greater sustainability as it would significantly support world energy transitions. In development, PSC technology stands ready to make an effective contribution toward the battle of climate change and forwardness of a sustainable energy environment.

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