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Perovskite solar cells: A promising pathway for sustainable development

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Abstract

Perovskite solar cells have emerged as a promising technology for sustainable energy generation, with their high efficiency, low-cost manufacturing, and versatile applications. In this paper, we review the advantages and challenges of perovskite solar cells, highlighting their potential for sustainable development. We discuss their applications in energy generation, as well as other fields such as building-integrated photovoltaics and wearable technology. Additionally, we examine the environmental impact and sustainability of perovskite solar cells through life cycle assessment and comparison with other solar technologies. Finally, we provide recommendations for future research and development to address challenges and promote their equitable adoption. Overall, perovskite solar cells offer a promising solution for sustainable development, and their potential benefits make them a technology worth investing in.

Keywords: Perovskite solar cells, sustainable development, solar energy, environmental impact, energy generation

1. Introduction

The need for sustainable development has become increasingly urgent in the face of climate change and the depletion of natural resources. One key area where sustainable development can make a significant impact is in the field of energy, where the use of renewable sources can help reduce greenhouse gas emissions and promote economic development.

Solar energy is a promising source of renewable energy that has gained increasing attention in recent years due to its abundant availability, low environmental impact, and potential for cost savings. The use of solar energy has the potential to provide clean, reliable energy to people around the world, particularly in remote and underdeveloped areas.

In this paper we will provide an overview of the Perovskite materials, advantages and challenges of perovskite solar cells and their potential applications in sustainable development.

1.1 Perovskite Materials

A perovskite is a material that has a crystal structure characterized by a central cation surrounded by an octahedral arrangement of anions, and a chemical formula of ABX3, where 'A' and 'B' represent cations and X is an anion. It was named after the mineral calcium titanium oxide ($CaTiO_3$) which has the same crystal structure [1]. Cation 'A', which may be cations like CH3NH3+, Ca, Ba, Bi, Cs, and Ge, is typically larger in size compared to cation 'B', which may be cations like Ti, Zr, Pb, and Sn. Perovskite materials used in solar cells are organic-inorganic metal halide compound with the perovskite structure. Halide perovskites are a type of perovskite that contain halide anions as X. Many organic and inorganic cations and halide anions have been investigated to form the perovskite structure, such as Cs+, CH3NH3$^+$ (or MA$^+$), CHN2H4$^+$ (or FA$^+$) for A-site; Pb2+, Sn2+ etc for B-site; Cl−, I−, Br− for X-site.

Organic-inorganic hybrid perovskites (OIHP) are halide perovskites with an organic cation at the A-site position. In addition to methylammonium and formamidinium, several other organic cations like propylammonium, ethylammonium, diethylammonium are also used [2].

The perovskite materials can be used as light-absorbing layer as well as electron/hole transport layer due high extinction coefficient, high charge mobility, long carrier lifetime, and long carrier diffusion distance [3]. Perovskite solar cells are a promising technology for the future of solar energy, as they have the potential to be highly efficient, inexpensive, and versatile.

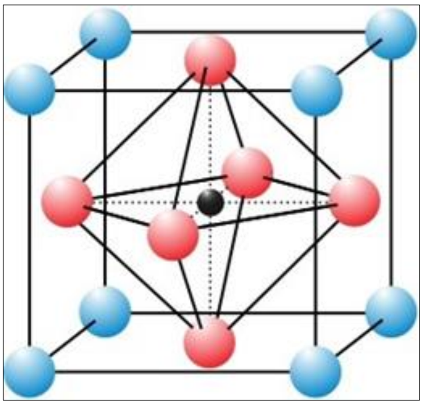

Fig 1: Structure of an oxide perovskite with chemical formula ABO3. (Wikimedia Commons)

1.2 Perovskite solar cells: advantages and challenges

A. Advantages

1. High efficiency: Perovskite solar cells have shown a remarkable increase in efficiency in recent years, with some achieving a conversion efficiency of over 25% [4]. Perovskite solar cells (PSCs) are highly efficient due to a combination of factors such as high optical absorption coefficient, long carrier diffusion length, excellent photoluminescence efficiency, low trap density [5]. Significant progress has been made in increasing the efficiency of perovskite solar cells over the years. The highest efficiency achieved by a monolithic perovskite/silicon tandem cell was reported in 2022 by HZB, with an impressive 32.5% combined efficiency [6] which was certified by the National Renewable Energy Laboratory (NREL). In contrast, the combined efficiency of the first perovskite cells reported by EPFL in 2013 was only 14.1%. The efficiency of perovskite cells has been continuously improving, with many research groups now reporting efficiencies above 20%, and several groups achieving efficiencies above 25%. These improvements in efficiency make perovskite solar cells a promising technology for the future of renewable energy.

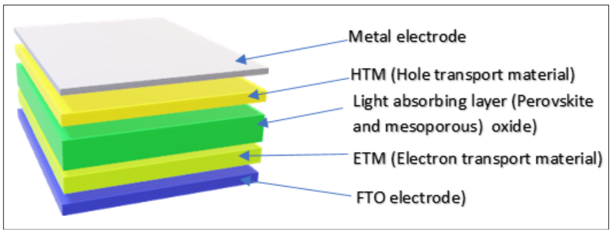

Fig 2: Typical mesoporous PSC layers

Metal halide perovskites have also been emerging as a highly promising material for the third generation of solar cells due to their tuneable bandgap [4], high carrier mobility [5], defect tolerance [6], and solution processability, thus making them the most competitive light-harvesting material currently available. The high efficiency of PSCs has made them an attractive alternative to traditional silicon-based solar cells, especially for applications where cost and flexibility are important factors.

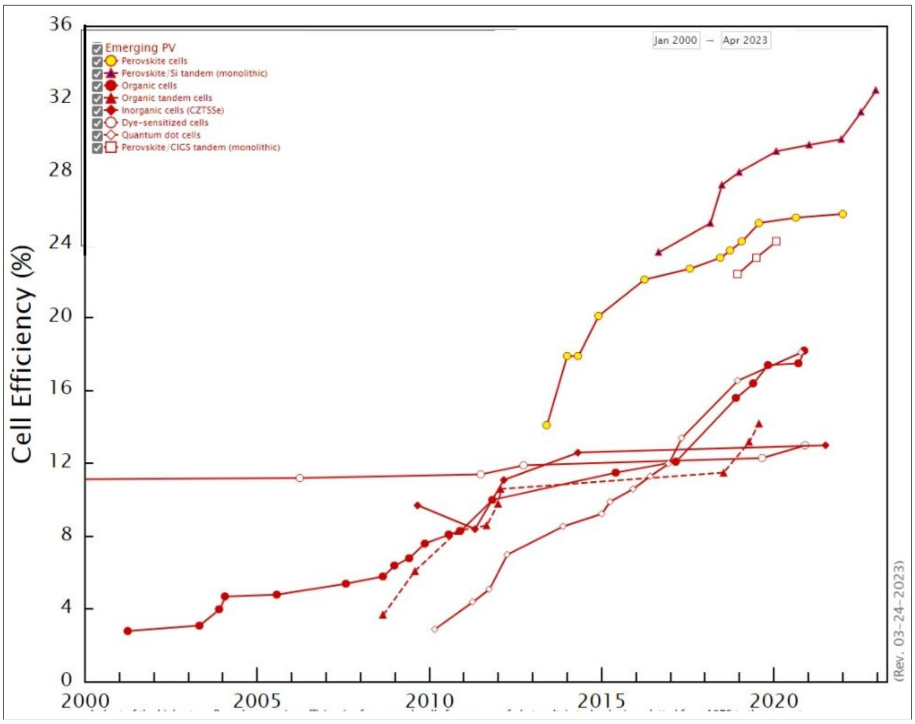

Fig 3: Efficiency chart of emerging PV (NREL)

Table 1: Evolution of perovskite solar cell technology in terms of efficiency

Year	Cell Type	Detailed description	Group(s)	Combined efficiency (%)
2013	Perovskite cells	Thin film, CH3NH3PbI3, perovskite methylammonium triodideplumbate	EPFL	14.1
2013	Perovskite cells	inorganic−organic hybrid thin film materials, based on CH3NH3(□MA)Pb(I1−xBrx)3 perovskites	KRICT	17.9
2014	Perovskite cells	Thin Film	KRICT	17.9
2014	Perovskite cells	Thin Film	KRICT	20.1
2015	Perovskite cells	Thin Film	NIMS	15.0
2015	Perovskite cells	Thin Film	NIMS	15.6
2015	Perovskite cells	MAPbX3 perovskites	KRICT/UNIST	20.1
2016	Perovskite cells	thin film	KRICT/UNIST	22.1
2016	Perovskite cells	Formamidinium lead iodide (FAPbI3) perovskites	KRICT/UNIST	19.7
2016	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic	Stanford/ASU	23.6
2017	Perovskite cells	Thin Film	KRICT	22.7
2017	Perovskite cells	formamidinium lead iodide (FAPbI3) perovskites	KRICT	20.9
2018	Perovskite/Si tandem (monolithic)	Pervoskite/Si, monolithic, 2-term	EPFL	25.2
2018	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic, 2-term	Oxford PV/Oxford/HZB	25.2
2018	Perovskite cells	Thin film, Pb-halide	ISCAS, Beijing	23.3
2018	Perovskite/Si tandem (monolithic)	Pervoskite/Si, monolithic, 2-term	Oxford PV	27.3
2018	Perovskite cells	thin film, Pb-halide	ISCAS, Beijing	23.7
2018	Perovskite/CIGS tandem (monolithic)	Perovskite/CIGS, 2-term	UCLA	22.4
2018	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic, 2-term	Oxford PV	28
2019	Perovskite cells	Perovskite (thin film)	KRICT/MIT	24.2
2019	Perovskite/CIGS tandem (monolithic)	Perovskite/CIGS, 2-term	HZB	23.3
2019	Perovskite cells	Perovskite (cell)	ANU	21.6
2019	Perovskite cells	Perovskite (thin film)	KRICT/MIT (tied w/ Korea U)	25.2
2019	Perovskite cells	Perovskite/perovskite, 2-term	Nanjing Univ	24.2
2020	Perovskite/CIGS tandem (monolithic)	Perovskite/CIGS, 2-term	HZB	24.2
2020	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic, 2-term	HZB	29.15
2020	Perovskite cells	Perovskite (cell)	UNIST	25.5
2020	Perovskite/Si tandem (monolithic)	2-terminal monolithic	Oxford PV	29.5
2021	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic	HZB	29.8
2021	Perovskite cells	Perovskite (cell)	UNIST	25.7
2022	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic, 2-term	EPFL/CSEM	31.3
2022	Perovskite/Si tandem (monolithic)	Perovskite/Si, monolithic, 2-term	HZB	32.5

2. Low-cost manufacturing

Traditional monocrystalline silicon/polycrystalline silicon solar cells that are commonly used in industrial applications are expensive. Dye-sensitized solar cells offer a lower cost and simpler process, but still face challenges such as thick absorbing layers and light bleaching with organic dyes [3]. Perovskite solar cells can be manufactured using simple, low-cost processes such as spin coating, spray coating, drop-casting, ultrasonic spray coating, electrodeposition, slot-die coating, chemical vapour deposition, thermal vapour deposition, vacuum deposition, screen printing, inkjet printing, etc., with various product architectures, which can significantly reduce the cost of production [7]. This makes perovskite solar cells a more affordable option for large-scale deployment than traditional solar cells.

3. Versatility

By changing the composition of perovskite materials by mixing more than one anion or cation, their properties such as band gap, lattice structure, and stability can be altered. So just like extrinsic semiconductors, their band gap can be tuned to light spectrum by changing composition [2]. Perovskite solar cells can be easily customized to fit different applications, including flexible and transparent solar cells. This versatility makes perovskite solar cells a suitable option for a wide range of uses, including building-integrated photovoltaics and portable devices.

B. Challenges

1. Stability: One of the biggest challenges facing perovskite solar cells is their stability over time [8]. The materials used in perovskite solar cells are sensitive to moisture, heat, and light, which can cause degradation over time [9, 10]. The extrinsic stability factors affecting perovskite solar cells (PSCs) include water, moisture, light, and interface materials. Exposure to environmental moisture, either alone or in the presence of oxygen, can hydrate the perovskite, causing structural deformation that weakens the chemical bonds and makes the perovskite more vulnerable to other extrinsic factors [8, 11, 12]. Moisture also induces the degradation of the perovskite film, starting from the grain boundaries. The thermodynamic stability of MAPbI3 can be affected at 85 °C while being kept in an inert atmosphere. Other components in PSCs (Figure 2) [3], such as the hole-transporting material Spiro-OMeTAD, can also be degraded up on heating. Light and interface materials, such as electrode materials and encapsulation materials, can also cause degradation of PSCs [8].

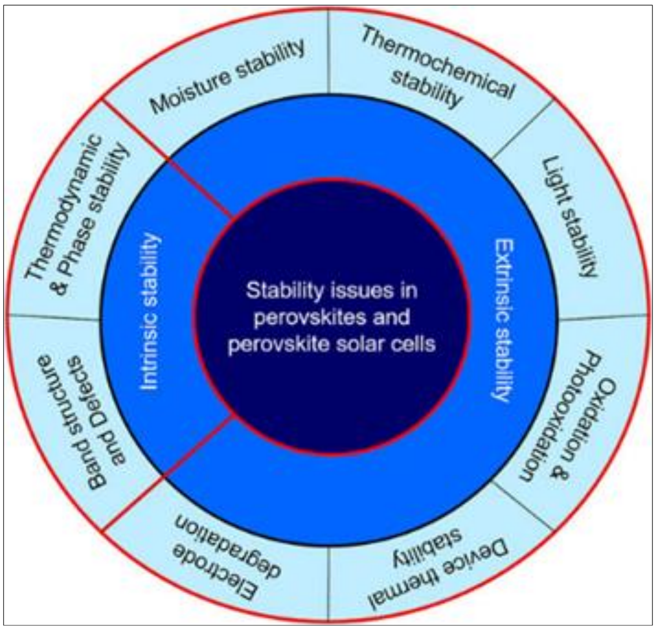

Fig 4: Various stability issues in perovskites and perovskite solar cells. (Mazumdar, Zhao, & Zhang, 2021) [8]

Significant research are going on for improving the stability of perovskite solar cells to make them more durable and reliable. Research on strategies such as charge-transporting layer optimization, composition engineering, additive engineering, surface modification etc. have been reported in many research papers. Charge-transporting layer optimization is usually done using well-matched energy levels and high mobility charge-transporting materials and introducing an additional layer or physical deposition by high vacuum methods to improve stability. Perovskite composition engineering is usually employed by changing the A-site cation, inorganic species, alloying perovskites, post-treatment with FAI solution, partial substitution of X-site iodide by other halides, and bulky cations to enhance thermodynamic stability and operational stability in ambient conditions. Additive engineering can be done using Lewis acids, organic molecules such as fullerene derivatives, and multifunctional additives to passivate defects and ameliorate instability issues. Surface modification can be done using fullerene derivatives, ILs, V2O5, Cs-based perovskite quantum dots, inorganic salts, luminescent perovskite nanoparticles, and polymers to improve efficiency, stability, and durability, and using alternative electrode materials and effective barrier layers to prevent electrode-induced degradation.

1. Toxicity

The highly efficient solar cell the most efficient perovskite devices utilize Pb2+ for their B site metal cation [13, 14, 15]. Lead is a toxic material that poses a risk to human health and the environment if not handled properly [16]. The most efficient perovskite devices utilize Pb2+ for their B site metal cation. Researchers are exploring alternative materials to replace lead in perovskite solar cells [17-20]. For instance, tin perovskite solar cells (TPSCs) have been emerging as a high-efficiency lead-free PSCs [5]. Other options work on different techniques for minimizing the risk of lead exposure during the manufacturing and disposal process is also going on [21-22].

2. Scalability: Perovskite solar cells are still in the early stages of development, and scaling up production to meet the demands of large-scale deployment is a challenge. Researchers are working on improving the manufacturing process and finding ways to make perovskite solar cells more scalable and cost- effective [23, 24].

Despite these challenges, perovskite solar cells hold great promise for the future of sustainable development. Their high efficiency and low-cost manufacturing make them a viable alternative to traditional solar cells, and their versatility and customization options make them suitable for a wide range of applications. Ongoing research and development are necessary to overcome the challenges and realize the full potential of perovskite solar cells for sustainable development.

3. Applications of perovskite solar cells in sustainable development

A. Energy generation

Solar panels for households and businesses: Perovskite solar cells can be used to manufacture solar panels for homes and businesses, providing a clean and affordable source of energy. The low cost of production makes perovskite solar panels an attractive option for households and businesses looking to reduce their energy costs and carbon footprint.

Off-grid applications

Perovskite solar cells can also be used in off-grid applications such as rural electrification, providing electricity to remote areas without access to the traditional power grid. The high efficiency of perovskite solar cells makes them an ideal choice for off-grid applications where space is limited, and the cost of installation and maintenance is a significant factor.

Large-scale solar farms

Perovskite solar cells can also be used in large-scale solar farms, providing a renewable source of energy to power cities and towns. The low cost of production and high efficiency of perovskite solar cells make them an attractive option for large-scale deployment, reducing the cost of electricity generation and promoting sustainable development.

B. Other applications

Building-integrated photovoltaics

Perovskite solar cells can be incorporated into building materials such as windows [25], roofing, and façades, providing a sustainable source of energy to buildings [26-27]. This can help reduce the energy consumption of buildings and promote sustainable development in the construction industry.

Wearable technology

Perovskite solar cells can also be used in wearable technology such as smart watches, fitness trackers, and other portable devices. The flexibility and versatility of perovskite solar cells make them an ideal choice for wearable technology, providing a sustainable source of energy to power these devices [28-29].

Portable devices

Flexible Perovskite solar cells can be used in a variety of portable devices such as smartphones, tablets, and laptops, providing a sustainable source of energy to power these devices because of their flexibility, light weight, portability, and compatibility with curved surfaces [30]. This can help reduce the reliance on traditional batteries and promote sustainable development in the electronics industry.

In conclusion, perovskite solar cells hold great promise for the future of sustainable development, with their high efficiency, low-cost manufacturing, and versatility making them a viable alternative to traditional solar cells. Their applications in energy generation, building-integrated photovoltaics, wearable technology, and portable devices offer a range of possibilities for promoting sustainable development in various industries. However, ongoing research and development are necessary to overcome the challenges facing perovskite solar cells and realize their full potential for sustainable development.

4. Environmental impact and sustainability of perovskite solar cells

A. Life cycle assessment

Manufacturing

The manufacturing process for perovskite solar cells involves the use of hazardous chemicals such as lead and other toxic materials. This can lead to environmental pollution and negative health impacts for workers involved in the manufacturing process. However, recent advancements have been made in developing less toxic and more sustainable manufacturing processes for perovskite solar cells.

Installation

The installation of perovskite solar cells has a lower environmental impact compared to other solar technologies, as they require less space and materials to generate the same amount of electricity. Additionally, perovskite solar cells can be installed on existing structures, reducing the need for land use and minimizing the environmental impact.

End-of-life management

Proper end-of-life management of perovskite solar cells is crucial to prevent environmental pollution and negative health impacts. Recycling of materials used in the manufacturing of perovskite solar cells can reduce waste and minimize environmental impact.

B. Comparison with other solar technologies

Perovskite solar cells have a lower environmental impact compared to other solar technologies such as silicon-based solar cells, as they require less energy to manufacture and have a shorter energy payback time. Additionally, perovskite solar cells can be manufactured using less toxic materials, making them a more sustainable option.

C. Environmental and social implications

The widespread use of perovskite solar cells has the potential to significantly reduce carbon emissions and mitigate climate change. However, there are also potential negative social implications associated with the use of perovskite solar cells, such as the displacement of communities due to the construction of large-scale solar farms. It is important to consider these social implications and ensure that the benefits of perovskite solar cells are shared equitably across society.

In conclusion, perovskite solar cells offer a promising pathway towards sustainable development, with their low environmental impact and potential for reducing carbon emissions. However, it is important to address the environmental and social implications associated with the manufacturing, installation, and end-of-life management of perovskite solar cells to ensure their sustainability. Ongoing research and development, as well as collaboration across industries and sectors, are necessary to further improve the sustainability of perovskite solar cells and promote their widespread adoption for sustainable development.

5. Conclusion

1. Summary of main points

Perovskite solar cells offer a promising pathway towards sustainable development, with their high efficiency, low-cost manufacturing, versatility, and potential applications in energy generation and other fields. However, they also face challenges such as stability, toxicity, and scalability. Proper life cycle assessment and management are crucial to ensuring the environmental sustainability of perovskite solar cells.

2. Implications for sustainable development:

Perovskite solar cells have the potential to significantly contribute to sustainable development by reducing carbon emissions and promoting the use of renewable energy. They can be used in a variety of applications, from solar panels for households and businesses to portable devices and building-integrated photovoltaics. However, it is important to consider the social and environmental implications associated with their manufacturing and installation and ensure that the benefits of perovskite solar cells are shared equitably across society.

3. Recommendations for future research and development

Further research and development are necessary to address the challenges associated with perovskite solar cells and improve their sustainability. This includes developing more stable and less toxic materials, improving scalability, and advancing recycling and end-of-life management. Collaboration across industries and sectors is also important to promote the widespread adoption of perovskite solar cells and their integration into sustainable development strategies.

In conclusion, perovskite solar cells offer a promising solution for sustainable development, and their potential benefits for society and the environment make them a technology worth investing in. By addressing the challenges associated with their manufacturing and use, and promoting their equitable adoption, perovskite solar cells can play a significant role in promoting a more sustainable future.

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