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Review

Perovskite Photovoltaic Glazing Systems: A Pathway to Low/Zero Carbon Buildings

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Abstract: The need to reduce the carbon footprint of the building sector has become a pressing concern in the global effort to mitigate climate change. Photovoltaic (PV) technology has emerged as a promising solution, offering the potential to transform building envelopes into energy-generating systems. One innovative approach in this direction is the development of perovskite-based PV glazing systems, which can provide a pathway towards low or even zero-carbon buildings. Perovskite materials, with their unique properties, have garnered significant attention in the PV research community. Compared to traditional silicon-based solar cells, perovskite PVs offer advantages such as high efficiency, low-cost fabrication, and the ability to be integrated seamlessly into building facades. The incorporation of perovskite PV glazing systems into building design could revolutionise the way we harness solar energy, reducing the reliance on conventional energy sources and contributing to the overall sustainability of the built environment. The integration of PV technology into building facades has been a subject of extensive research. These studies have highlighted the potential benefits of using PV systems as an integral part of building envelopes, such as optimising energy performance, reducing energy consumption, and enhancing the architectural aesthetics of the structure. However, there are still some challenges that need to be addressed, including ensuring the long-term durability and reliability of the PV glazing systems, as well as developing cost-effective and scalable manufacturing processes. This mini review aims to explore the current state of research on perovskite PV glazing systems and their potential to transform the built environment towards a low/zero-carbon future.

***Keywords*:** perovskite photovoltaic glazing, sustainable built environment, low/zero carbon buildings

1. Introduction

Achieving energy efficiency and sustainability in buildings has become a pressing concern in the face of growing global energy demands and environmental challenges [1]. The building sector still constitutes a major contributor to global energy consumption and carbon emissions with almost 40% [2]. This can be attributed to the poor thermal insulation features of the conventional building materials [3] as well as inappropriate design characteristics of building envelopes causing thermal bridges [4] and other heat loss paths [5]. Windows are still responsible for a significant portion of a building's energy loss due to their relatively low thermal resistance compared to opaque building envelope components [6]. In this regard, novel glazing technologies that can enhance the energy efficiency of buildings have been the focus of extensive research [7]. Despite outstanding advancements in novel and smart windows, factors such as cost, performance, durability, sustainability, and social awareness remain obstacles to their widespread adoption [8]. Perovskite PV glazing systems have emerged as a promising solution to address these issues, offering the potential to transform the energy performance of buildings while paving the way towards low or zero-carbon construction [9].

Perovskite solar cells utilise a perovskite-structured compound, usually a hybrid organic-inorganic lead or tin halide-based material, as the light-absorbing active layer [10]. These perovskite materials, including Methylammonium Lead Halides (MALHs) and all-inorganic cesium lead halide, are renowned for their affordable production and straightforward manufacturing process [11]. In contrast to the solar radiation dependence of traditional crystalline silicon PV cells [12], perovskite solar cells have the remarkable potential to deliver higher efficiency levels at notably lower manufacturing costs [13]. The crystal structure of a typical perovskite solar cell and the appearance of a sample are shown in Figure 1.

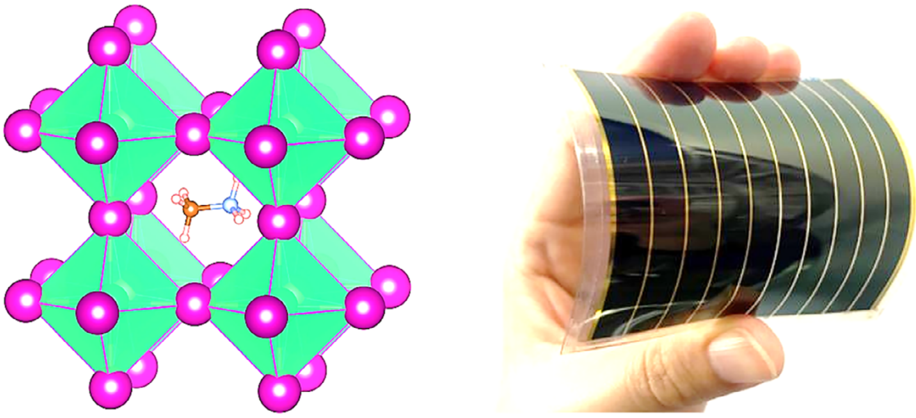
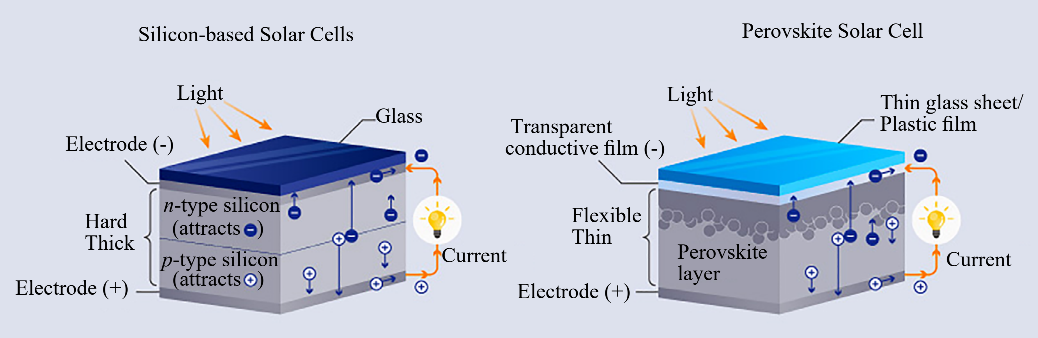


Figure 1. MALHs with a perovskite structure and a typical perovskite solar cell

Solar cell technology has shown remarkable advancements in efficiency figures over the last three decades. The efficiency of laboratory-scale solar cell devices employing perovskite materials has witnessed a remarkable surge in recent years, escalating from 3.8% in 2009 to 25.7% in 2021 [14] for single-junction configurations, and reaching up to 29.8% for silicon-based tandem cells, thus surpassing the maximum efficiency of single-junction silicon solar cells. Perovskite solar cells have been the swiftest-advancing solar technology since 2016. Boasting the potential to attain even greater efficiencies and extremely low production costs, perovskite solar cells have become commercially enticing. However, their short-term and long-term stability remain critical challenges and research priorities [15].

Perovskite solar cells, the emerging generation of solar technology, feature a power-generating layer made of organic material with a perovskite structure measuring around one micrometre in thickness. These solar cells are remarkably thin, lightweight, flexible, and bendable [16]. Thanks to technological advancements, perovskite solar cells have achieved efficiency levels comparable to silicon-based solar cells as shown in Figure 2. These innovative cells can generate electricity even in low-light conditions, like indoor spaces or overcast skies. Moreover, the ease of manufacturing perovskite solar cells through painting or printing the material onto a substrate enables mass production, which is advantageous in lowering manufacturing costs.

Therefore, integrating these systems into windows emerges as a promising solution, leveraging their thin structure to ensure lightweight properties, which not only prevent significant structural loads on buildings but also enhance their earthquake resilience. Lightweight materials and designs play a critical role in reducing the seismic forces acting on a structure during an earthquake, thereby improving the safety and durability of buildings. Additionally, the efficiency advantages of these systems enable buildings to generate their own electricity, potentially reducing or even eliminating reliance on grid energy. However, significant limitations persist regarding the integration of these systems into window applications. The primary challenges lie in the presence of toxic materials, stability issues, and, most notably, the high overall heat transfer coefficient, which hinders thermal performance. Nevertheless, their ability to generate electricity even under low or no sunlight conditions offers a compensatory advantage. In fact, the literature already reports various research efforts aimed at overcoming these limitations, including studies integrating different insulating materials due to the systems' ease of integration. Despite these advancements, the limitations mentioned underscore the urgency of further progress in this field.



20% or more	Conversion efficiency	20% or more
Inflexible	Flexibility	High
Heavy	Weight	Light
High	Cost	Inexpensive
High	Durability	Low

Figure 2. Performance and structural comparison of perovskite solar cells with conventional silicon solar cells [16]

While numerous studies have reviewed perovskite-based PV glazing systems, existing research often focuses on specific aspects, such as efficiency improvements, stability challenges, or integration strategies. However, a comprehensive evaluation encompassing thermal performance, environmental impacts, and operational behaviour under various conditions remains limited. Many critical parameters, including mechanical, optical, and acoustic properties, environmental toxicity concerns, lifespan assessments, cost implications, and comparative analyses with conventional and alternative window technologies, have not been thoroughly examined within a single study. This review aims to fill this gap by providing an in-depth and holistic assessment of window-integrated perovskite PV technologies. It evaluates their thermal resistance in comparison to conventional window solutions while also analysing their mechanical, optical, acoustic, and environmental performance. Additionally, it explores economic feasibility, lifecycle considerations, and the advantages and limitations associated with these systems. By synthesising these diverse aspects, this review seeks to offer valuable insights for researchers, industry professionals, stakeholders, and policymakers, positioning this technology as a promising candidate for future energy-efficient building applications.

2. Perovskite photovoltaic glazing

Perovskite PV glazing technology exhibits remarkable potential to diminish heat losses through the windows and aligns with the most recent low/zero carbon building standards prevalent in Europe [17]. The integration of perovskite PV technology into building glazing systems presents several advantages. Perovskite-based solar cells have demonstrated remarkable improvements in efficiency, with reported conversion rates exceeding 25%. Additionally, these cells can be engineered to capture a broader spectrum of sunlight, further enhancing their energy generation capabilities. Coupled with their flexibility in design and the ability to be integrated into building facades, perovskite PV glazing systems can contribute significantly to the reduction of a building's energy consumption and greenhouse gas emissions [18].

Building on these advantages, it is essential to explore the multifaceted aspects of perovskite PV glazing technology in greater detail. This section will examine key considerations, including its thermal resistance in comparison with conventional and other window technologies, as well as its mechanical and optical properties. Furthermore, the economic feasibility, recycling, lifespan, and environmental toxicity of this technology will be evaluated. Methods to enhance its performance and stability will also be discussed, highlighting recent advancements in the field. Additionally, the potential for retrofit applications and a balanced assessment of the pros and cons of this technology will be provided in the following sections.

2.1 *Thermal resistance comparison with conventional and advanced window technologies*

Figure 3 illustrates the overall heat transfer coefficients (U-values) of various perovskite PV glazing configurations, showcasing their potential for low/zero carbon buildings. The data highlights the remarkable adaptability of perovskite PV glazing, as its thermal performance is significantly influenced by the glazing type, gas fillings, and additional coatings.

Perovskite PV with a fully sandwiched structure and no air gap demonstrates a relatively high U-value of 5.61 W/(m^2·K), indicating limited thermal insulation performance. However, introducing a 2 mm air gap reduces the U-value to 3.8 W/(m^2·K), demonstrating the beneficial impact of air as a thermal barrier. This improvement becomes more pronounced when using argon (3.4 W/(m^2·K)), krypton (2.8 W/(m^2·K)), and xenon (2.67 W/(m^2·K)) as filler gases, with xenon providing the most effective thermal insulation among the tested configurations [19].

The comparison between uncoated single, double, and triple-glazed perovskite PV systems reveals substantial advancements in thermal insulation as the number of glazing layers increases. For instance, an uncoated single layer exhibits a U-value of 5.608 W/(m^2·K), while the U-value drops to 2.5 W/(m^2·K) and 1.605 W/(m^2·K) for double and triple glazing, respectively. Introducing vacuum-insulated glazing further enhances the thermal performance, achieving a U-value of 2.034 W/(m^2·K) [20]. Adding a Bragg reflector to the perovskite PV glazing offers similar results. A single layer retains the same U-value as uncoated glazing (5.608 W/(m^2·K)), while double and triple layers reduce the U-value to 2.5 W/(m^2·K) and 1.605 W/(m^2·K), respectively. The Bragg reflector combined with vacuum-insulated glazing achieves a U-value of 2.034 W/(m^2·K), highlighting its potential for high-performance glazing systems [20]. Among the configurations, the use of red Low-e coatings stands out as the most effective strategy for improving thermal insulation. For instance, red Low-e-coated single glazing yields a U-value of 3.1 W/(m^2·K), while double and triple layers achieve remarkable reductions to 1.3 W/(m^2·K) and 0.995 W/(m^2·K), respectively. Notably, red Low-e combined with vacuum-insulated glazing and perovskite PV achieves an exceptional U-value of 0.144 W/(m^2·K), which is the best thermal performance among all configurations [20].

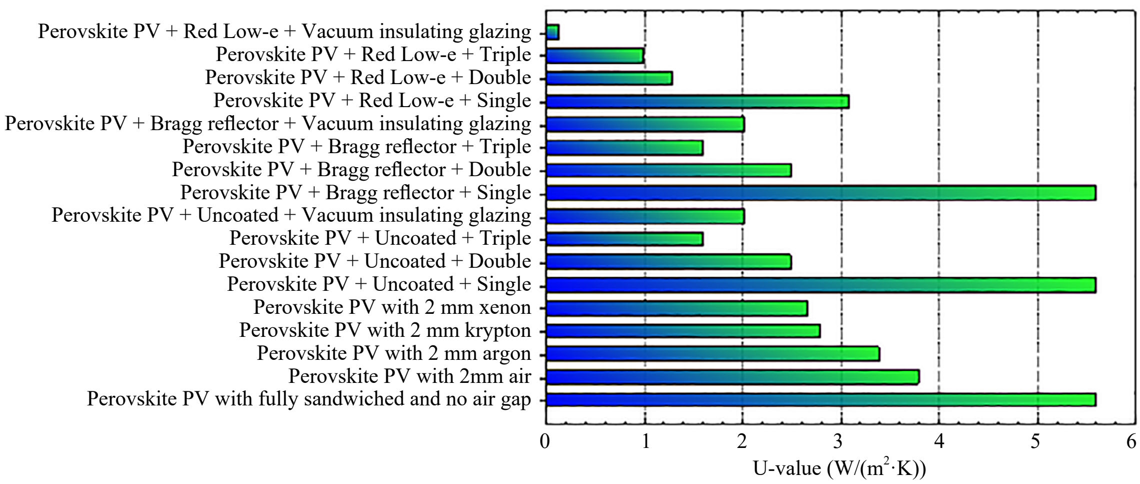


Figure 3. U-values of perovskite PV glazing configurations with the impact of design variations [19-20]

This comprehensive analysis underscores the versatility and adaptability of perovskite PV glazing systems. The findings reveal that careful optimisation of glazing layers, gas fillings, and coatings can result in substantial improvements in thermal insulation, thereby enhancing energy efficiency in buildings. The data also highlights the critical role of advanced materials and technologies, such as vacuum insulation and low-emissivity coatings, in pushing the boundaries of glazing performance.

On the other hand, Figure 4 provides a detailed comparison of the thermal performance of various glazing technologies, using their U-values as a measure of insulation efficiency. These technologies, spanning conventional and advanced systems, play a vital role in reducing energy consumption in buildings and meeting sustainability goals. The analysis highlights significant variations in performance, costs, and feasibility for implementation, which are discussed comprehensively below.

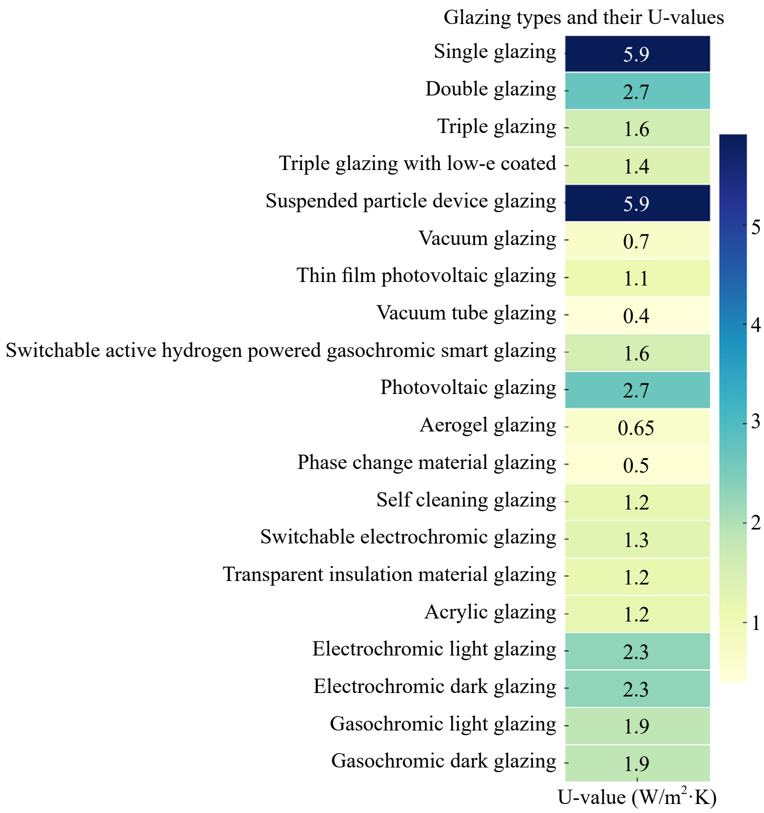


Figure 4. U-values of conventional and advanced glazing technologies for thermal performance comparison [5, 21-33]

Conventional glazing technologies, such as single glazing, exhibit the poorest thermal insulation, with a U-value of 5.9 W/(m^2·K) [21]. While cost-effective, single glazing's high heat transfer rate makes it unsuitable for energy-efficient applications. Double glazing, with a U-value of 2.73 W/(m^2·K), provides better insulation but remains inadequate for modern sustainability standards [21]. A further improvement is observed with triple glazing, which has a U-value of 1.62 W/(m^2·K), offering significant thermal insulation benefits [22]. However, its increased thickness and weight introduce structural challenges, particularly in seismic zones, and raise concerns about cost and aesthetics.

Advanced glazing technologies, by contrast, showcase superior performance. For example, triple glazing with low-e coating, with a U-value of 1.4 W/(m^2·K), reduces radiant heat transfer and strikes a balance between thermal performance and feasibility [22]. Vacuum glazing, with a U-value of 0.7 W/(m^2·K), eliminates conductive and convective heat transfer through its vacuum layer [23]. This technology is highly effective but requires advanced manufacturing processes and high costs, which limit its widespread adoption. Further advancements are seen in vacuum tube glazing, which achieves an unparalleled U-value of 0.4 W/(m^2·K) [24]. This technology is ideal for extreme climates but is constrained by its complexity and cost. Similarly, aerogel glazing, with a U-value of 0.65 W/(m^2·K), offers lightweight, high-performance insulation, making it an attractive option for energy-efficient designs [25]. Suspended particle device glazing, with a U-value of 5.9 W/(m^2·K), provides dynamic control over light transmission by suspending particles within a film that respond to an applied electric field [26]. While the U-value does not reflect significant thermal insulation, its ability to regulate visible and infrared light makes it a valuable option for improving indoor comfort and reducing cooling loads in hot climates. PV glazing is a multifunctional solution, combining thermal insulation with energy generation. Its U-value of 2.67 W/(m^2·K) is modest compared to other advanced technologies, but the ability to generate renewable electricity makes it highly appealing for sustainable building designs [27]. When integrated into facades or roofs, this technology supports net-zero energy goals while maintaining sufficient insulation performance. Acrylic glazing, with a U-value of 1.2 W/(m^2·K), offers a lightweight and durable alternative to traditional glass [28]. Its low density reduces structural loads, making it particularly suitable for applications in seismic zones or lightweight building systems. Additionally, acrylic glazing provides good thermal insulation and design flexibility, although it may be less durable over long periods compared to more advanced options. Dynamic technologies such as phase change material glazing (U-value: 1.17 W/(m^2·K)) and transparent insulation material glazing (U-value: 0.5 W/(m^2·K)) further enhance energy efficiency by adapting to environmental conditions [5, 29]. Phase change material glazing stores and releases heat based on temperature fluctuations, while transparent insulation material glazing optimises daylight penetration without compromising insulation. Switchable technologies, including electrochromic glazing (U-values ranging from 1.3 W/(m^2·K) to 2.3 W/(m^2·K)) and gasochromic glazing (U-value: 1.86 W/(m^2·K)), enable dynamic control over solar heat gain and light transmission [30-31]. These systems enhance thermal comfort while reducing cooling and heating demands. The advanced hydrogen-powered gasochromic glazing, with a 1.56 W/(m^2·K) of , further improves insulation whilst retaining switchable properties [32]. Lastly, self-cleaning glazing, with a U-value of 1.2 W/(m^2·K), integrates a photocatalytic layer that reduces maintenance needs, particularly in urban or high-pollution environments [33]. While its insulation performance is moderate, the reduced cleaning costs and extended durability add significant value to building facades.

2.2 *Mechanical and optical properties*

Perovskite solar panels are renowned for their outstanding mechanical and compression properties [34]. For instance, Li et al. [35] achieve the highest recorded efficiency of flexible perovskite solar cells, reaching 24.08%, by employing-Cyano (CN) additives to control molecular dipoles, effectively minimising grain boundary defects and mitigating stress. Additionally, Park et al. [36] identify that perovskite materials have a low elastic modulus of approximately 13.5 GPa and a high yield stress of around 17.3 MPa. These properties highlight their remarkable flexibility and durability, which present significant potential for the development of flexible batteries in PV integration. Flexible and lightweight solar cells are particularly suited for building integration, as they exert minimal stress on structures. The lightness of these devices is typically measured by their specific power, defined as watts per kilogram. Transparent flexible perovskite solar cells require transparent, flexible electrodes with high conductivity and mechanical stability. Kang et al. [37] address this challenge by developing an ultrathin, lightweight, and flexible device using a silver nanowire network, achieving an efficiency of 15.2% and a specific power of 29.4 W/g. Durability remains a critical factor in the practical deployment of perovskite solar cells. Significant progress has been made in developing cells that pass the International Electrotechnical Commission 61215 accelerated testing standards. In this context, glass-glass encapsulation methods, combined with butyl rubber edge sealants and encapsulants such as ethylene-vinyl acetate or polyolefin, stand out as effective solutions [38-40]. Furthermore, ultraviolet-cured epoxy and moisture-absorbing desiccants enable resistance to damp heat for 1,000 hours, with only an eight percent efficiency loss [41]. Low-temperature polymer-free direct glass-glass bonding techniques are also emerging as promising options for building integration and general PV applications [42]. Perovskite PV cells are exposed to significant mechanical stresses, leading to stress intensity factors and strain energy release rates. Recent research has strongly established a relationship between the operational stability and mechanical reliability of these materials [43]. Beyond operation, these materials are also expected to maintain their mechanical integrity during manufacturing, installation, and maintenance. Consequently, mechanical reliability is considered a key technical barrier to the successful commercialisation of this technology. Direct measurements of the elastic modulus for halide perovskites remain limited. For instance, the elastic modulus values for methylammonium lead iodide and methylammonium lead iodide-bromide are reported as 5.5 and 4.5 GPa, respectively [44], whilst single-crystal methylammonium lead iodide and methylammonium lead bromide exhibit elastic modulus values along the direction of 10.6 ± 1.0 and 13.1 ± 1.3 GPa [45]. However, the effects of grain boundaries and microcracks in polycrystalline thin films on the elastic modulus are not yet fully understood. Emerging micro testing techniques provide valuable opportunities to measure these properties. The hardness of halide perovskites is also studied using surface-sensitive methods such as nanoindentation. For instance, Vickers microhardness tests yield hardness values of 0.76 ± 0.05 and 0.54 ± 0.02 GPa for methylammonium lead iodide and methylammonium lead bromide single crystals, respectively [45]. However, hardness measurements for thin films often produce artificially high results due to indenter size effects. The interplay between plasticity-related mechanisms and their impact on optoelectronic properties remains an area of active investigation. Fracture toughness is another fundamental mechanical property of halide perovskites, with reported values of 0.18 ± 0.03 and 0.20 ± 0.03 MPad$\cdot\sqrt{m}$ for methylammonium lead iodide and methylammonium lead bromide, respectively [45]. However, the grain boundary toughness of polycrystalline films is likely to be significantly lower. Double-cantilever beam tests also provide critical insights into adhesion toughness, and extending these tests to the full cell and module levels could offer valuable information on the mechanical durability of perovskite solar cells.

Perovskite materials have garnered significant attention in PV research due to their highly adaptable bandgap, which spans from 1.2 to 2.3 eV, detailed in Table 1.

Table 1. Comparison of metal halide perovskite types with bandgap range [46]

Perovskite types	Bandgap (eV)
Methylammonium tin iodide	1.2-1.4
Formamidinium tin iodide	1.41
Formamidinium lead iodide	1.47
Methylammonium lead iodide	1.55
Cesium-formamidinium-methylammonium lead iodide-bromide	1.57
Cesium lead iodide	1.72
Cesium lead iodide bromide	1.9
Cesium lead iodide dibromide	2.1
Methylammonium lead bromide	2.3

This unique characteristic enables the customisation of solar cells to suit specific requirements, optimising performance across various lighting and environmental conditions. Tailoring the bandgap to approximately 2 eV enhances energy conversion efficiency under low-light scenarios, making perovskite solar cells particularly advantageous for regions with limited sunlight or indoor PV applications where conventional technologies fall short [47]. Beyond efficiency improvements, the adjustable bandgap of perovskites opens doors to novel applications, particularly in architectural glass for building-integrated PVs. By manipulating their optical attributes, perovskites can be designed to exhibit a wide range of colours or achieve semi-transparency, harmonising energy generation with aesthetics. The aesthetic appeal makes colourful perovskite solar cells highly sought after for building-integrated PVs, where the colour of perovskite films can be influenced by their light absorption characteristics and bandgap properties. Noh et al. [48] pioneered the chemical adjustment of $MAPb(I_{1-x}\,Br_x)_3$ perovskites to achieve vibrant colours, shifting the absorption onset significantly. This customisation not only results in colourful perovskite solar cells but also enables advancements in device efficiency, such as those demonstrated by Zhang et al. [49], who incorporated porous photonic structures to achieve tunable colours. Additionally, the incorporation of microcavity electrodes and dielectric mirrors has allowed for the manipulation of perovskite solar cell colours while enhancing light absorption efficiency, yielding power conversion efficiencies of up to 18.9% [50]. The transparency of perovskite solar cells plays a pivotal role in determining their power conversion efficiency and is crucial for energy harvesting applications when integrated into windows and roofs of buildings. The amount of sunlight passing through these transparent or semi-transparent structures significantly impacts the visual comfort of occupants. Factors such as average visible transmittance, correlated colour temperature, and colour rendering index must be optimised. For window applications, an average visible transmittance within the 20%-30% range is generally required, but this necessitates a delicate balance between transparency and efficiency, as increasing transparency can lead to reduced absorption and lower power generation capacity [51-52]. Research indicates that transparency can be enhanced by limiting the coverage of the perovskite absorber, but this often results in perovskite solar cells that appear brownish [53]. Therefore, striking a balance between optical properties and efficiency remains a significant challenge for the adoption of perovskite technology in building applications.

The performance of window glazing systems is crucial to optimising energy efficiency, particularly in terms of thermal comfort and energy conservation. In assessing energy-efficient windows, two critical parameters are the solar heat gain coefficient and visible light transparency. These parameters play a pivotal role in determining how windows interact with solar radiation, impacting both heat retention in the colder months and mitigating unwanted heat gain in the warmer seasons. The solar heat gain coefficient of window systems refers to the fraction of solar radiation transmitted through a window, whilst visible light transparency pertains to the percentage of visible light that passes through the glazing. Typical single- and double-glazed windows with air-filled spaces have solar heat gain coefficient values of 0.885 and 0.775, respectively, while their visible light transparency values are 0.901 and 0.817 [54]. These windows allow a significant amount of natural light to enter the space, which can reduce the need for artificial lighting. However, the high solar heat gain coefficient may also lead to overheating in warmer climates, increasing cooling demands. To address overheating and glare issues, especially in hot climates, various glazing technologies have been developed. These technologies include reflective coatings, solar control low-e coatings, and tinted glass, which can be available in several colours, including bronze, green, and grey. The colour of the tinted glass is determined by the metallic colorants added during the manufacturing process. The solar heat gain coefficient for tinted glass can range from 0.45 to 0.68, depending on the colour and thickness of the glass [55]. Although these glazing technologies are designed to reduce solar heat gain coefficient and visible light transmittance in order to prevent glare and overheating, certain window systems are intentionally optimised to increase solar heat gain coefficient, particularly in colder climates, to harness solar energy for heating. Passive low-e coatings and anti-reflective coatings are often used to achieve higher solar heat gain coefficient values. For instance, single-glazed windows with anti-reflective coatings can reach solar heat gain coefficient values as high as 0.90, but such windows also exhibit high visible light transparency, which may lead to glare, with visible transmittance values of up to 0.98 [56].

Even though the above glazing technologies are promoted in terms of solar heat gain coefficient and visible light transparency based on single-/double-glazed systems, their properties cannot adapt to the changing weather conditions. In addition to conventional window technologies, smart glazing has emerged as a highly promising solution for improving energy efficiency by adjusting the optical properties of windows in response to external stimuli such as temperature or electrical fields. Passive smart windows, such as thermochromic, photochromic, and Phase Change Materials (PCMs) based windows, change their optical properties naturally under varying thermal conditions. For example, thermochromic glazing can transition from a solar heat gain coefficient of 0.29 and a visible light transparency of 0.50 at 25 °C to 0.13 and 0.12 at 65 °C [55], effectively reducing solar heat gain during peak heat hours. On the other hand, active smart windows, such as electrochromic and gasochromic windows, adjust their properties when subjected to an external stimulus like an electric field or heat, offering high flexibility in managing solar heat gain and visible light transmittance. Electrochromic windows, for instance, can switch between a clear state with a solar heat gain coefficient of 0.47 and a visible light transparency of 0.62, and a fully tinted state with a solar heat gain coefficient of 0.09 and a visible light transparency of 0.02 [57]. Additionally, windows can also be employed to harvest energy, as seen in PV glazing technologies. Commercial thin-film PV glazing has a range of solar heat gain coefficient values from 0.123 (double-glazed unit with a-Si) to 0.413 (single-glazing laminate with μc-Si), although the visible transmittance is quite low (5%-8%) [58]. Furthermore, studies on photothermal and semi-transparent PVs show varying solar heat gain coefficients, from 0.58 to 0.67 for photothermal windows [59] to 0.42 for Photovoltaic-Vacuum (VPV) glazing [60]. Moreover, advanced glazing systems such as ventilated PV double-skin facades and semi-transparent perovskite solar cells also contribute to energy efficiency. The solar heat gain coefficients of ventilated PV double-skin facades range from 0.1 to 0.12 [61], while semi-transparent perovskite solar cells offer a peak visible transmittance of 77% and a power conversion efficiency of 12.7% [59]. These technologies not only contribute to reducing heat gain but also enable windows to generate power, thus contributing to the overall energy performance of a building. The potential of semi-transparent perovskite-based solar cells is further explored by Cannavale et al. [62], who investigated the integration of these cells into building facades. They found that perovskite-based PV windows offer a high visible light transparency of 42.4%, which enhances visual comfort by improving useful daylight illuminance and reducing daylight glare probability. These windows also maintain comparable energy production levels to that of artificial lighting consumption, while minimising the impact of varying solar heat gain across different climates. Furthermore, the development of perovskite-based photovoltachromic cells, which combine PV and electrochromic functionalities, has shown great promise in self-adjusting transparency. These devices, which change from a neutral semi-transparent state to a dark blue colour upon exposure to sunlight, provide both energy generation and self-adaptive optical control. The average visible light transparency of these devices can reach 26%, while their light power conversion efficiency can achieve up to 5.5%. When activated, these devices exhibit a reduced average visible light transparency of 8.4%, making them suitable for dynamic energy-efficient building applications [63]. This ongoing research into advanced glazing technologies, particularly those incorporating visible light transparency and solar heat gain coefficient, is crucial to improving the overall energy efficiency of buildings. By integrating both passive and active smart glazing solutions, architects and engineers can design buildings that are not only more energy-efficient but also adaptable to changing environmental conditions, contributing to long-term sustainability. In conclusion, the future of energy-efficient window glazing systems lies in the combination of multiple innovative technologies. The interplay between visible light transmission, solar heat gain coefficient, and active/passive adjustment systems such as thermochromic, electrochromic, and PV-glazing technologies, alongside new materials like perovskites, offers an exciting range of solutions for sustainable building design. As the demand for energy-efficient buildings grows, these technologies will play an increasingly significant role in reducing the energy consumption of buildings, enhancing visual comfort, and improving the overall performance of building-integrated systems.

2.3 *Economic feasibility, recycling, lifespan, and environmental toxicity*

Efforts to enhance the efficiency of perovskite-based building-integrated PVs largely depend on the use of lead-based materials [64-66]. However, these materials present significant challenges, particularly regarding the stability of perovskite solar cells under high temperatures and humidity, which cause rapid degradation of the perovskite layer [67]. This degradation represents a major obstacle to the integration of PVs into buildings. Additionally, the environmental and health concerns associated with lead in perovskite materials make it necessary to reduce or eliminate lead content while improving the optoelectronic performance and stability of these devices. Various strategies have been proposed to improve the performance of building-integrated PVs, including selecting suitable PV materials, managing temperature, optimising solar irradiation, and minimising mechanical strain [68]. External factors such as moisture and oxygen accelerate the degradation of the perovskite layer [67, 69], while mechanical stability is compromised by the accumulation of stress and compatibility issues between materials, such as mismatched electrodes and substrates [70]. Although perovskite solar cells contain lead, the amount is relatively low and is comparable to the lead content found in a layer of natural soil beneath the module. Perovskite solar cells typically contain less than one gram per square metre of lead, which is significantly lower than the approximately seven point three grams per square metre found in a standard sixty-cell silicon solar module [46]. Nevertheless, the presence of soluble lead remains a significant obstacle to the adoption of perovskite technology in consumer and building-integrated PV applications. Current research focuses on developing lead-free or reduced-lead perovskites by substituting lead with tin or germanium in the perovskite crystal structure [71]. These approaches aim to achieve comparable levels of ambient stability and power conversion efficiency. Innovative methods to mitigate lead leakage are receiving increasing attention. Jiang et al. [72] identify epoxy resin as an effective encapsulation material, which reduces lead leakage to zero point zero eight milligrams per hour per square metre after mechanical impacts such as hail. Similarly, Xiao et al. [73] achieve an almost totally reduction in lead leakage by using ionogel in combination with polyolefin for encapsulation, although the long-term stability of this method is not yet certain. Other approaches include coating glass substrates with lead-absorbing materials or integrating cation-exchange resins into carbon electrodes [74]. Wu et al. [75] demonstrate the effectiveness of thiol-functionalised two-dimensional metal-organic frameworks as electron-extraction layers that capture lead ions, while Lee et al. [76] develop a hole transport layer that chelates lead ions without compromising the integrity of the perovskite lattice. Furthermore, Niu et al. [77] incorporate polymer additives into perovskite precursors to form hydrogels that capture lead ions effectively, whilst Chen et al. [78] propose a low-cost mesoporous resin scaffold that significantly reduces lead contamination from damaged modules. However, concerns persist regarding the potential toxicity of tin and its possible environmental leakage. Moreover, the environmental stability of encapsulation materials is crucial, as they must provide long-term protection for cells while being removable or thermally decomposable without generating harmful by-products. The design of PV modules also plays an essential role in their recyclability and material recovery at the end of their lifecycle. A comprehensive recycling process for perovskite solar cells involves delamination to access active layers, with various methods available to achieve this. Substrates such as titanium dioxide can be reused for the fabrication of new perovskite solar cells, but careful consideration is required to ensure that lead-containing materials do not interfere with recycling procedures. In summary, although perovskite technology offers significant potential for advancements in PV efficiency, it is essential to address challenges related to lead content, environmental stability, and recyclability at the end of the product lifecycle to ensure economic viability and wider acceptance in the market.

The rapid advancement and anticipated extensive deployment of perovskite solar cells have raised substantial concerns regarding their management at the end of their operational life and recycling processes. Due to their relatively shorter lifespan compared to well-established PV technologies, significant quantities of these panels, both encapsulated and unencapsulated, will require recycling in the near future. A major challenge involves recovering lead from the methylammonium halide active layer, as the potential release of this toxic element into the environment poses serious risks [79]. To address this issue, innovative recycling methods have been developed to recover all key components of perovskite solar cells without compromising their efficiency. For instance, Chen et al. [80] successfully fabricated perovskite solar cells using lead reclaimed from recycled car batteries, achieving power conversion efficiencies comparable to those achieved with commercial lead iodide. Additionally, techniques employing deep eutectic solvents have demonstrated recovery rates as high as nearly 100% for lead in perovskite solar cells, offering a promising path for large-scale recycling [81]. These advancements suggest that lead, often cited as a major concern in perovskite solar cells, can be effectively reclaimed and reused, thus reducing its environmental impact. Furthermore, studies assessing the entire life cycle of these technologies indicate that there is limited data available on the environmental effects of lead-based perovskite solar cells after they are decommissioned. Concerns are frequently raised about the risks associated with improper disposal, such as landfill waste. Comparatively, while silicon-based and cadmium telluride solar panels are also recyclable, their recycling processes are often energy-intensive and less economically viable due to reductions in precious metal content over time [82]. In contrast, perovskite solar cells can be dismantled more easily, as selective solvents allow the dissolution of individual layers at room temperature without affecting other layers. This straightforward delamination process enables the recovery of key materials, such as glass coated with fluorine-doped tin oxide, lead iodide, and other valuable metals, without significant loss of efficiency in cells produced with recycled components. Unlike the energy-intensive treatments required for the recycling of silicon-based and cadmium telluride solar panels, perovskite solar cell recycling methods significantly reduce energy demand, making the process both environmentally and economically attractive [82]. While the environmental risks posed by lead leakage from perovskite solar cells are valid, it is essential to put these concerns into context. For instance, the coal industry emits an estimated eighty thousand metric tons of lead annually, along with other hazardous metals such as cadmium and mercury, due to the presence of trace elements in coal. In comparison, a global solar installation with a capacity of one terawatt based on 20% efficient perovskite solar cells would require approximately twenty thousand metric tons of lead, which would remain immobilised within the panels under normal conditions. Even in extreme cases of encapsulation failure, such as those caused by fire, hail, or earthquakes, the release of lead would contribute far less to soil contamination than historically emitted amounts from other industrial sources, such as leaded gasoline. Moreover, the natural concentration of lead in the soil already averages 36 mg/kg, while the legal threshold for agricultural soil in China is as high as 250 mg/kg [83]. These figures suggest that substituting perovskite solar cells for fossil fuels could significantly reduce global lead emissions. Additionally, recycling lead from alternative sources presents clear advantages. With advancements in battery technologies, such as lithium-air and lithium-sulphur systems, an increasing number of lead-acid batteries will no longer be recycled into new ones. This shift creates an opportunity to repurpose lead from these batteries for the production of perovskite solar cells. Notably, a single car battery can yield sufficient lead to manufacture approximately seven hundred square metres of perovskite solar cell panels. Using recycled lead not only reduces reliance on primary lead ores but also prevents unused lead from contributing to environmental pollution [80]. As perovskite solar cell technology advances, recycling initiatives are becoming increasingly critical, not only to mitigate environmental harm but also to conserve valuable resources and stabilise costs, particularly for scarce materials.

The PV sector can draw inspiration from well-established recycling systems for cadmium telluride solar panels, such as those employed by First Solar, which achieve recovery rates of up to 95% for semiconductors and 90% for glass [84]. These models highlight the potential for similar approaches in perovskite solar cell recycling as the market continues to expand. Overall, the integration of innovative recycling strategies and regulatory frameworks underscores the long-term sustainability of perovskite solar cells within the solar energy industry. By addressing challenges associated with the end of their operational life, these efforts not only reduce material waste but also align with circular economy principles, contributing to the broader goal of sustainable energy production.

The economic potential of perovskite solar cells has attracted considerable attention, given their capacity to revolutionise the solar energy sector. Renowned for their remarkable efficiency, low manufacturing costs, and adaptability to lightweight and flexible designs, these cells are poised to become a pivotal component in renewable energy solutions. Nevertheless, the path to commercial viability necessitates overcoming several key challenges, including scalability, long-term stability, cost efficiency, and widespread public acceptance. Expanding manufacturing capabilities is essential to meet the increasing global demand for solar energy. Current efforts are focused on refining scalable fabrication techniques, such as roll-to-roll processing and advanced printing methods, to facilitate high-volume production [85]. Simultaneously, establishing a dependable supply chain for raw materials and developing cost-efficient production methods are critical milestones in achieving large-scale deployment [86]. Another pressing concern is ensuring the stability and durability of perovskite solar cells, which are expected to function reliably over a 25-year operational lifespan [87]. Research is advancing in the areas of material improvement and the development of robust encapsulation technologies to safeguard cells against environmental stressors like humidity, temperature fluctuations, and Ultraviolet (UV) exposure. These improvements are fundamental to bolstering consumer confidence and encouraging broader market adoption. Maintaining cost competitiveness remains a core priority. Perovskite solar cells stand out due to their reduced material requirements, lower energy consumption during production, and streamlined fabrication processes. Incorporating perovskite technology into existing silicon-based solar cell manufacturing lines offers a promising opportunity to harness economies of scale. Studies indicate that the production costs of perovskite solar modules range from \$31.7/m^2 to \$147/m^2, contingent on production techniques and scale. Furthermore, applications such as semi-transparent PV glass exhibit manageable incremental costs, resulting in acceptable payback periods of 13 years or less when additional cost-saving measures are factored in [88-89]. Perovskite solar cells also offer significant environmental advantages, including lower energy requirements during production and efficient material usage, further enhancing their economic feasibility. For instance, transitioning from mini modules to sub modules leads to a notable reduction in production costs, from €0.086/cm^2 to €0.034/cm^2, owing to improved material management during upscaling. Moreover, the environmental impact of antisolvent use remains negligible, contributing only minimally to overall production costs [90]. Finally, public awareness and market acceptance are integral to the successful adoption of perovskite solar cells. Promoting their unique attributes, such as high efficiency, lightweight structures, and versatile aesthetic applications, is crucial. Collaborative initiatives involving industry stakeholders, governmental bodies, and academic institutions can play a pivotal role in fostering public engagement. Educational campaigns and policy support can emphasise the transformative potential of perovskite solar cells in achieving sustainable energy goals, ultimately enhancing demand and creating favourable market conditions [91].

2.4 *Methods to enhance its performance and stability*

Localised heating has significant potential for addressing defects and relieving stress in perovskite materials. It is suggested that cast perovskite initially exists in a metastable state containing complex intermediate phases. The transition from a wet film to a stable perovskite phase requires severe thermal procedures [92]. However, these processes can lead to the formation of voids and defects in both the perovskite material's core and exterior layer, ultimately restricting device efficiency. Kim et al. [93] introduce a rapid laser crystallisation method that achieves the perovskite state alteration by utilising laser-induced thermal effects. Nonetheless, these thermal annealing techniques often fail to sufficiently minimise nanoscale defects and voids. Recent studies show that plasmonic nanoparticles not only enhance light absorption but also have the ability to rectify defects and relieve stress via localized heating effects [94]. Plasmonic metal nanostructures are regarded among the leading efficient techniques for photon management in the solar energy sector for several reasons: i) localized near-field effects; ii) light scattering that increases broadband optical absorption; iii) energy exchange from metallic nanoscale structures to the operational layer [95]. Plasmonic nanostructures can be positioned at various locations within devices to enhance light absorption. Firstly, metallic nanoparticles with an average diameter exceeding 50 nanometres can be placed on the surface of the solar cell to couple incoming light to the operational film. Secondly, nanoparticles made of metal within diametric measurements ranging from 5 to 20 nanometres function as antennas to augment the effective light capture surface of operational layer film by merging the plasmonic near field with the semiconductor. Thirdly, periodic lattice arrays are integrated into the backside of the active layer, significantly improving optical absorption in the working film by coupling incident light to surface plasmon polariton modes at the metal/semiconductor interface. Collectively, they primarily augment solar cell performance by boosting optical capture across a broad wavelength spectrum [96]. Carretero-Palacios et al. [97] simulate the electric field distribution based on plasmonic metal materials at a stimulation wavelength of 750 nanometres. The increase in the electric field for silver is found to be considerably higher than that of gold or aluminium particles. The broadening of resonance spectrum of plasmonic waves represents a reliable technique to enhancing light collection performance as well as maximising solar cell performance. Photonic nanostructures not only enhance the solar cells' photonic-electronic characteristics, however, might also be employed to control thermal distributions by merging solar cells along with radiation cooling devices. The potential efficiency threshold of monojunction solar cells is approximately 33%, indicating that considerable share of sunlight received by solar cells converts into undesirable heat within the device [98]. Thermal effects are detrimental to the capability as well as robustness of PV devices. Over the past period, nanophotonics-based non active radiation cooling system has gained considerable interest due to its ability to reflect sunlight and dissipate heat into ultra-cold space, effectively cooling PV devices without electrical input [98]. Fan et al. [99] propose a polydimethylsiloxane photonic structure to be utilised as a cooling layer for heat dissipation to diminish the operating temperature of PV devices and enhance their efficiency. The integration of the radiative cooling layer significantly boosts the emission of solar cells in the range of 8 to 25 micrometres. Simultaneously, the surface temperature of the solar cells decreases by approximately 11.5 degrees Celsius compared to conditions without a cooling layer, leading to substantial efficiency improvements across various types of solar cells. However, further investigations are required regarding the enhancement of perovskite solar cell efficiency and stability through radiative cooling [100]. In summary, radiative cooling technology has the potential to reduce surface temperatures in perovskite solar cells and other PV devices, thereby enhancing their effectiveness as well as prolonged performance reliability. Considering aesthetic aspects and practical applications, it is widely employed so as to build adaptable solar power systems for diverse applications, including coloured and semi-transparent solar cells. In [101], coloured perovskite solar cells featuring adjustable red, green, and blue colours are developed by incorporating liquid crystal cholesteric reflector films. Compared to opaque perovskite solar cells, coloured perovskites containing red, green, and blue cholesteric reflector films exhibit power conversion efficiency values like approximately 16%, 18%, and 20%, associated with reductions in power conversion efficiency of 17%, 13%, and 9%, respectively. In particular, semi-transparent solar cells generate increasing interest for upcoming uses like windows embedded in buildings facades and vehicles. However, achieving a trade-off between solar cell performance as well as optical clarity requires careful consideration. In conclusion, micro-spaces that create ideal shades for semi-transparent perovskite solar cells can be applied to most metals with low reflectivity in both visible and ultraviolet light wavelengths. Surface and interface passivation techniques also enhance the overall efficiency of cells by minimising non-radiative recombination losses. All these advancements contribute significantly to improving the performance and longevity of perovskite solar cells.

2.5 *Pros and cons*

Perovskite solar cells have emerged as a promising technology within the field of PVs. Figure 5 provides a comprehensive overview of their key advantages and disadvantages. Among the advantages, these cells demonstrate excellent shade tolerance, allowing them to maintain performance under partial shading conditions [102]. They also offer flexible design options and versatile production methods, making them adaptable to various applications [103]. Their lightweight nature and high efficiency make them attractive compared to conventional solar cells [104]. Additionally, perovskite materials enable spectral and colour control, bandgap tunability, and semi-transparency, which support innovative and aesthetic applications [105]. The low production costs and their ability to perform well in low-light conditions further enhance their appeal [106]. However, perovskite solar cells face several challenges. One major drawback is their stability issues, as they still struggle to achieve long-term durability [107]. Scaling up production for commercial applications remains a significant challenge [108]. There is also a trade-off between efficiency and transparency, complicating their optimisation for specific uses. Concerns about the toxicity of some of the materials used raise environmental and health-related questions [109].

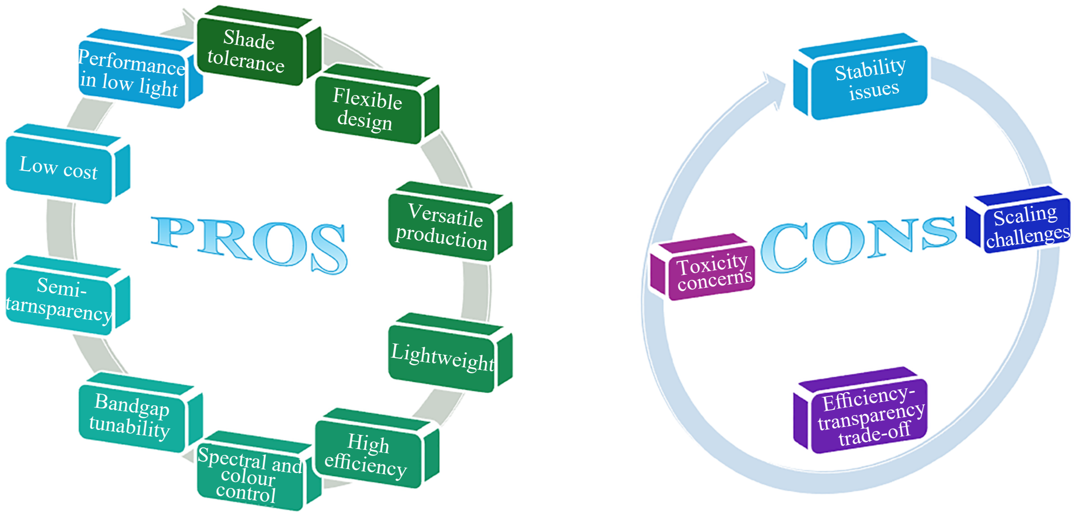


Figure 5. Pros and cons of utilising perovskite solar cells

However, current research on perovskite solar cells presents notable gaps that warrant further exploration. For instance, while stability remains a critical issue, studies on the long-term degradation of perovskite cells under real world conditions are still limited. Many laboratory conditions do not account for the varied environmental factors, such as humidity, UV exposure, and temperature fluctuations, that can significantly degrade their performance over time. Therefore, future research should focus on enhancing material stability and longevity, specifically targeting moisture resistance and UV degradation. Studies aimed at improving encapsulation techniques to protect perovskite materials from external environmental factors will be crucial for advancing their commercial viability. Another area requiring more attention is the scalability of perovskite solar cell production. Although significant progress has been made in laboratory settings, transferring these successes to large-scale manufacturing remains a challenge. Current production methods struggle to maintain uniformity and efficiency across large-area modules, which is a critical aspect for their mass deployment. Research should therefore be directed towards developing more cost-effective and efficient production methods, including roll-to-roll processing and high-throughput deposition techniques. These methods could enable the mass production of perovskite solar cells at a competitive cost, essential for their adoption in large-scale applications. Finally, the environmental and health concerns related to the use of lead in perovskite formulations must not be overlooked. Despite the high efficiency of lead-based perovskite cells, the toxicity of lead raises significant concerns. Consequently, there is a growing demand for lead-free perovskite alternatives. While some promising materials are being developed, more research is needed to identify non-toxic, high-performance alternatives that can maintain the remarkable efficiency levels of lead-based perovskite cells. Future research should explore alternative materials that can replace lead without compromising the performance of the cells. The integration of these diverse PV technologies into building envelopes not only enhances energy generation but also influences daylighting, thermal comfort, and architectural aesthetics. While crystalline silicon may reduce natural light penetration, amorphous silicon and perovskite technologies can be customised to balance transparency and energy performance. Similarly, cadmium telluride and copper indium gallium selenide modules impact solar heat gain, with potential benefits for cooling in summer but challenges for winter heating efficiency. The varying environmental implications of these technologies also warrant careful consideration, as material toxicity and resource constraints may impact long-term sustainability. Among these technologies, perovskite solar cells remain the most promising for future applications, particularly due to their unique combination of high efficiency, low production costs, and flexibility. Unlike rigid crystalline silicon, perovskite cells can be manufactured in transparent and coloured variants, allowing for greater integration into windows, facades, and even historic building retrofits. Their ability to function effectively in diffused and artificial lighting conditions further enhances their appeal for urban environments. However, challenges remain, particularly concerning stability and durability. Perovskite materials are susceptible to moisture, temperature fluctuations, and UV degradation, factors that limit their commercial viability at present. Moreover, the presence of lead in most perovskite formulations raises environmental and health concerns. Encouragingly, ongoing research is making strides towards enhanced encapsulation techniques and lead-free alternatives, which could significantly improve their lifespan and sustainability. Despite these hurdles, perovskite solar cells stand as a transformative force in the PV sector, bridging the gap between efficiency and aesthetic adaptability. Their potential to reshape urban energy landscapes is vast, provided that material innovations continue to address their stability issues. As research progresses, perovskite technology could outpace conventional silicon-based PV, ushering in a new era of sustainable and visually harmonious energy solutions. If these challenges are overcome, perovskite solar cells could revolutionize the future of energy-efficient architecture.

Table 2. Characteristics, challenges, and applications of various PV technologies in building integration [110]

Technology	Key characteristics	Challenges	Effect on building performance	Benefits	Drawbacks	Typical applications
Crystalline silicon	-Most established PV technology -High energy conversion efficiency -Durable and long-lasting	-Rigid and thick, limiting integration into glazing -Efficiency is influenced by temperature fluctuations and shading -Energy-intensive manufacturing process	-Reduces natural light penetration, affecting interior illumination -Alters solar heat gain, which can improve cooling but reduce winter heating	-Proven long-term performance -Well-established supply chain and recycling options	-Heavier and more brittle than alternative technologies -Fully opaque, restricting design flexibility	-Rooftop installations -Large-scale commercial solar projects
Amorphous silicon	-Thin, lightweight, and flexible -Can be manufactured with varying degrees of transparency -Lower production costs for large-scale use	-Lower efficiency than conventional silicon cells -Degradation over time can reduce power output -Transparency and efficiency must be carefully balanced	-More even daylight distribution indoors -Helps reduce cooling demand in summer but may increase heating costs in winter	-Performs better under shading than crystalline silicon -Cost-effective with a short energy payback period	-Requires more surface area to achieve comparable energy output -Gradual efficiency loss over time	-Semi-transparent BIPV glazing -Curved or flexible facade installations
Cadmium telluride	-High efficiency among thin-film technologies -Cost-effective with a short energy payback time -Performs well at high temperatures	-Contains cadmium, a toxic element with environmental concerns -Limited options for transparent or aesthetically adaptable designs	-Dark appearance can impact the building's daylighting strategy -Reduces solar heat gain, potentially lowering heating demand	-Efficient energy generation with minimal material usage -Can be produced at a lower cost than many alternatives	-Environmental concerns due to toxic components -Dark-coloured panels may not suit all architectural designs	-Utility-scale solar farms -Industrial and commercial building facades
Copper indium gallium selenide	-High-performance thin-film technology -Lightweight and flexible, suitable for diverse applications -Performs well under low light conditions	-More expensive than other thin-film options -Limited availability of indium and gallium may constrain scalability	-Suitable for irregular and curved surfaces -Aesthetically versatile for architectural applications	-Among the highest efficiencies in the thin-film category -Resilient to partial shading and low-light conditions	-Higher production costs compared to other thin films -Dependence on scarce raw materials	-Portable solar panels -Flexible and lightweight BIPV solutions
Dye-sensitized solar cells	-Available in a variety of colours and transparency levels -Works efficiently in diffused and indoor lighting conditions -Simple and cost-effective manufacturing process	-Lower power output compared to other PV types -Electrolyte solutions can degrade over time, leading to leakage	-Ideal for aesthetic applications where design is a priority -Can generate electricity even in low-light environments	-Aesthetic customisation possibilities -Can harness energy from artificial lighting sources	-Limited lifespan due to electrolyte stability issues -Susceptible to high temperatures and humidity	-Decorative architectural glazing -Smart windows and interior applications
Perovskite solar cells	-High efficiency potential with tunable bandgap -Customisable transparency and colour -Low-cost manufacturing and easy deposition processes	-Degradation due to moisture, UV exposure, and temperature shifts -Lead content raises environmental and health concerns	-Allows natural light transmission while generating energy -Offers an adaptable solution for modern architectural needs	-Promising efficiency gains with ongoing research -Can be produced at a fraction of the cost of silicon cells	-Stability and longevity remain key challenges -Requires the development of safer, lead-free alternatives	-Transparent and semi-transparent PV glazing -Historicbuilding retrofits and energy-efficient facades

PV technologies have emerged as a cornerstone of modern sustainable architecture, offering a range of energy-efficient solutions tailored to diverse building applications. Table 2 presents a comparative analysis of six leading PV technologies, highlighting their key characteristics, challenges, and effects on building performance [110]. Crystalline silicon, the most established PV option, delivers high efficiency and durability but remains rigid and opaque, limiting its integration into glazing. In contrast, amorphous silicon offers flexibility and transparency, making it a viable choice for semi-transparent building-integrated PV applications, albeit at the cost of lower efficiency and gradual degradation over time. Cadmium telluride technology stands out for its high efficiency and cost-effectiveness, yet its reliance on toxic cadmium poses significant environmental concerns. Copper indium gallium selenide films, known for their flexibility and superior low-light performance, face scalability issues due to the limited availability of indium and gallium. Dye-sensitised solar cells, with their aesthetic appeal and ability to function in low-light conditions, introduce new possibilities for decorative architectural glazing but suffer from electrolyte degradation and limited lifespan. Meanwhile, perovskite solar cells represent a promising frontier in PV development, offering high efficiency and design flexibility, though stability, longevity, and lead content remain key challenges. The integration of these diverse PV technologies into building envelopes not only enhances energy generation but also influences daylighting, thermal comfort, and architectural aesthetics. While crystalline silicon may reduce natural light penetration, amorphous silicon and perovskite technologies can be customised to balance transparency and energy performance. Similarly, cadmium telluride and Copper indium gallium selenide modules impact solar heat gain, with potential benefits for cooling in summer but challenges for winter heating efficiency. The varying environmental implications of these technologies also warrant careful consideration, as material toxicity and resource constraints may impact long-term sustainability. Among these technologies, perovskite solar cells emerge as the most viable option for the future. They offer a unique combination of high efficiency, low production costs, and flexibility, making them highly suitable for modern architectural applications. Unlike rigid crystalline silicon, perovskite cells can be manufactured in transparent and coloured variants, allowing for greater integration into windows, facades, and even historic building retrofits. Their ability to function effectively in diffused and artificial lighting conditions further enhances their appeal for urban environments. However, challenges remain, particularly concerning stability and durability. Perovskite materials are susceptible to moisture, temperature fluctuations, and UV degradation, factors that limit their commercial viability at present. Moreover, the presence of lead in most perovskite formulations raises environmental and health concerns. Encouragingly, ongoing research is making strides towards enhanced encapsulation techniques and lead-free alternatives, which could significantly improve their lifespan and sustainability. Despite these hurdles, perovskite solar cells stand as a transformative force in the PV sector, bridging the gap between efficiency and aesthetic adaptability. Their potential to reshape urban energy landscapes is vast, provided that material innovations continue to address their stability issues. As research progresses, perovskite technology could outpace conventional silicon-based PV, ushering in a new era of sustainable and visually harmonious energy solutions. If these challenges are overcome, perovskite solar cells could revolutionise the future of energy-efficient architecture.

2.6 *The potential for retrofit applications*

Retrofitting existing buildings with advanced technologies offers a promising pathway to enhance energy efficiency and sustainability without necessitating extensive structural alterations. Building-integrated PV play a crucial role in this transformation, seamlessly merging energy generation with architectural elements to achieve net-zero energy goals. Perovskite PV glazing systems present a particularly advantageous solution for retrofit applications due to their unique properties, including lightweight design, high efficiency, and ease of integration into existing window systems. These attributes not only facilitate direct replacement of traditional glazing but also enable integration into facade elements, skylights, and curtain walls, expanding their functionality beyond conventional window applications. As a result, they are suitable for a wide range of building types, from historical structures to modern high-rise buildings. The integration of perovskite PV glazing into retrofit projects can address several critical challenges associated with energy efficiency in older buildings. Traditional windows are often a major source of heat loss, contributing significantly to energy consumption for heating and cooling. By replacing or augmenting these windows with PV glazing, it is possible to reduce thermal losses while simultaneously generating renewable energy on-site. This dual functionality not only minimises reliance on grid electricity but also aligns with global objectives for reducing carbon emissions in the built environment. Furthermore, compliance with building energy codes and performance standards is a key consideration in retrofit projects. Perovskite PV glazing can contribute to meeting stringent energy efficiency requirements while maintaining daylighting and thermal comfort within interior spaces. One of the key advantages of perovskite PV glazing in retrofit scenarios is its adaptability to different architectural styles and constraints. These systems can be customised in terms of transparency, colour, and size, allowing them to blend seamlessly with the aesthetic and functional requirements of existing structures. For instance, semi-transparent and colour-tunable perovskite PV glazing can be tailored to meet the design preferences of architects while ensuring optimal energy performance. This is particularly relevant for heritage buildings, where maintaining historical authenticity is essential. Furthermore, the lightweight nature of perovskite materials reduces the structural load on buildings, making them particularly suitable for retrofitting projects in regions prone to seismic activity. This characteristic enhances the resilience of buildings without necessitating extensive reinforcement, which can be both costly and disruptive. Additionally, the flexibility of these systems allows for innovative applications, such as the integration of PV layers onto curved or irregularly shaped windows, expanding their potential use cases in retrofit projects. Economic feasibility is another critical factor driving the adoption of perovskite PV glazing in retrofit applications. The relatively low cost of manufacturing and installation, coupled with the potential for significant energy savings, offers an attractive payback period for building owners and investors. Moreover, advancements in manufacturing techniques, such as roll-to-roll processing, are expected to further reduce costs, making these systems increasingly accessible for large-scale deployment. Additionally, regulatory incentives for Building-Integrated Photovoltaics (BIPV) adoption, such as tax credits and green building certifications, enhance the financial viability of these technologies for retrofit applications. Despite these advantages, certain challenges must be addressed to fully realise the potential of perovskite PV glazing in retrofit applications. Long-term durability and stability remain critical concerns, particularly in environments with high humidity or temperature fluctuations. Research into advanced encapsulation materials and methods is essential to mitigate these issues and ensure reliable performance over the lifespan of the systems. Additionally, the presence of toxic materials, such as lead, in some perovskite compositions necessitates the development of safer alternatives or effective recycling strategies to minimise environmental and health risks. Furthermore, ensuring compliance with fire safety regulations and material durability standards is essential for the widespread acceptance of perovskite PV glazing within the construction sector. In conclusion, perovskite PV glazing systems represent a transformative technology for retrofitting applications, offering a sustainable and cost-effective solution to enhance the energy performance of existing buildings. By reinforcing their role within BIPV frameworks and addressing regulatory and aesthetic considerations, these systems can be effectively deployed in various architectural contexts. By addressing the current challenges related to stability, scalability, and environmental impact, these systems have the potential to play a pivotal role in the global transition towards low-carbon and energy-efficient built environments.

2.7 *Carbon reduction potential of perovskite*

Perovskite Solar Cells (PSCs) have emerged as a promising technology for reducing carbon emissions in the energy sector. Their potential for carbon reduction is primarily assessed through Life Cycle Assessments (LCAs), which evaluate Energy Payback Time (EPBT) and greenhouse gas emissions over their entire lifespan. PSCs represent not only a technological breakthrough but also a significant environmental opportunity. One of the most compelling indicators of their potential is their greenhouse gas emission factor and EPBT. Recent studies show that carbon-electrode-based scalable PSCs can generate electricity at a low cost (3-6 €/kWh), with the lowest EPBT (0.6-0.8 years) and greenhouse gas emissions (15-25 g CO_2 eq./kWh) when compared to grid-connected PV alternatives. These results are based on realistic annual energy yield calculations, assuming a 25 year lifetime, expected reductions in PV system costs, and the recycling and refurbishment of PSC modules. The analysis covers the full lifecycle of PSCs, both at the module and system levels (residential and utility-scale), benchmarking them against dominant technologies like crystalline silicon (c-Si) PVs and Copper-Indium-Gallium-Selenide (CIGS) thin-film PVs. This comprehensive evaluation confirms that PSCs offer a significant reduction in both cost and environmental impact [111]. A recent study of 21 LCAs of solar PV systems provides further insight into the environmental performance of PSCs relative to other technologies. Out of these, 13 LCAs were subjected to statistical analysis based on key indicators such as Energy Return On Investment (EROI), Cumulative Energy Demand (CED), net CED (nr-CED), and Carbon Footprint (CF). The cradle-to-grave EROI of PSCs is notably lower at 3.08, in contrast to the range of 9.4 to 13.17 for silicon-based solar cells. The values for CED, nr-CED, and CF vary considerably depending on cell type, system boundaries, manufacturing processes, and other assumptions; however, PSCs typically require less energy during production. For instance, the cradle-to-gate CED for PSCs ranges between 0.03 MJ and 8.75 MJ per kWh, with one extreme case showing a CED of 213 MJ per kWh for lab-scale PSCs. Similarly, the cradle-to-gate CF for PSCs falls between 0.0025 kg CO_2 eq. and 0.03 kg CO_2 eq. per kWh, though exceptional cases have been recorded as high as 0.38 kg CO_2 eq. for PSCs produced using the antisolvent method. This data underscores that PSCs generally have a lower carbon footprint compared to other PV technologies. The comprehensive lifecycle analysis of PSCs covers both the module and system levels, allowing for direct comparison with other leading technologies like c-Si PVs and CIGS thin-film PVs. The analysis affirms that PSCs deliver a considerable reduction in both cost and environmental impact, particularly with respect to energy demand and CO_2 emissions [112]. Looking forward, the potential of perovskite technology is even more impressive. Projections suggest that by 2060, perovskite-based BIPV could achieve carbon footprint reductions as low as 14 kg CO_2 per MWh. When deployed in urban settings, these systems could significantly lower the carbon intensity of the built environment, helping regions to meet their net-zero emission targets. In conclusion, PSCs not only represent a major technological advancement, but also a strategic solution for reducing global greenhouse gas emissions. Their scalability, rapid energy return, and low carbon intensity position them as a powerful tool in the transition towards a more sustainable energy future.

3. Conclusion

This study thoroughly evaluates perovskite PV glazing systems, highlighting their transformative potential for reducing energy consumption and supporting low/zero-carbon building initiatives. These systems combine energy generation with enhanced thermal performance and aesthetic versatility, offering innovative solutions to modern building challenges. By examining their thermal, mechanical, optical, economic, and environmental properties, this review sheds light on their current capabilities and identifies pathways for further advancements. Key findings and recommendations for future work are summarised below:

• Perovskite PV glazing systems achieve conversion efficiencies exceeding 25%, which positions them as a highly effective technology for building-integrated PV applications. Their lightweight and flexible nature reduces structural load, particularly in seismic zones.

• Thermal insulation performance varies based on system configurations within perovskite PV. For instance, uncoated single-layer glazing has a U-value of 5.608 W/(m^2·K), offering limited insulation [20]. By incorporating gas fillers like xenon, the U-value decreases to 2.67 W/(m^2·K), resulting in a significant improvement. Advanced triple-glazing systems with red Low-e coatings and vacuum insulation achieve an outstanding U-value of 0.144 W/(m^2·K), showcasing exceptional thermal efficiency [19-20].

• Perovskite materials allow adjustable transparency and vibrant colours, enabling seamless integration into building facades without compromising architectural aesthetics.

• Cost-efficient production techniques, including roll-to-roll processing, and manageable payback periods (≤ 13 years) make these systems economically attractive for widespread implementation [88-89].

• Although lead remains a challenge, innovative encapsulation and recycling techniques minimise environmental risks, supporting sustainable deployment.

• Long-term stability under fluctuating environmental conditions, such as high humidity and temperature variations, is an ongoing area for development.

• The lightweight, adaptable design of perovskite PV glazing makes it ideal for retrofitting older buildings and 2030-2050 building configurations, reducing thermal losses and simultaneously generating on-site renewable energy.

• Emerging methods enable the recovery of critical materials like lead and glass, aligning with circular economy principles and reducing waste.

• Integrating passive radiative cooling layers decreases operating temperatures, improving system efficiency and longevity.

• Research is advancing towards lead-free perovskite compositions and robust encapsulation materials, minimising toxicity concerns and environmental risks.

• Further investigations should focus on improving scalability, enhancing optical properties to balance transparency and efficiency, and developing multifunctional glazing solutions for a broader range of applications.

In conclusion, perovskite PV glazing systems are reshaping the future of energy-efficient architecture. With continued advancements in durability, scalability, and environmental safety, these systems hold immense potential to play a pivotal role in achieving global sustainability and low-carbon building goals.

Conflict of interest

The authors declare that they has no conflicts of interest to disclose.

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