Energy Catalyst

Recent Advances in Perovskite–Silicon Tandem Solar Cells: Progress, Challenges, and Pathways to Commercialisation

James Riffat[a],* [ID], Seyed Reza Samaei[b] [ID]

[a]World Society of Sustainable Energy Technologies, Nottingham, NG11 6AA, United Kingdom,
[b]Department of Marine industries, Science and Research Branch, Islamic Azad University, Tehran, Iran.

* Corresponding author:

James Riffat
E-mail: ceo@wsset.org

A B S T R A C T

Perovskite–silicon tandem solar cells are emerging as a credible route beyond the limits of single junction silicon. Pairing a wide bandgap perovskite top cell with a silicon bottom cell broadens spectral harvesting while reducing thermal and transmission losses. This review explains the rationale for tandems and synthesises progress in perovskite materials, interface and passivation strategies, and scalable fabrication on flat and textured silicon, including ambient processing. We examine stability under moisture, oxygen, heat and light, advances in encapsulation and ISOS protocols, and implications for reliability. Techno-economic factors are analysed, including LCOE drivers, yield and throughput constraints, and bankability needs. Although certified efficiencies now exceed 29%, deployment still hinges on durable materials, robust tunnel junctions, uniform large-area coatings and credible end-of-life plans. We conclude with priorities for research and industry that could close the gap between laboratory prototypes and market-ready modules within the next five years.

1. INTRODUCTION

The world energy sector is undergoing a fundamental transformation to reduce carbon emissions and address the increasingly destructive effects of climate change. Among the available renewable sources, photovoltaic systems are among the most scalable and widely used technologies for converting sunlight into electricity. However, traditional single-junction crystalline silicon solar cells are approaching their practical efficiency limit, with current commercially available modules achieving around 26–27 percent [1,2]. To overcome these limitations, tandem solar cells that combine perovskite and silicon materials have emerged as a promising next-generation solar technology. This review highlights recent advances in perovskite–silicon tandem cell development, focusing on key technical and

economic challenges and outlining a roadmap for commercial deployment [3,4]. To split the solar spectrum effectively, tandem devices employ a stacked configuration, typically with a perovskite layer on top of silicon. The perovskite layer absorbs high-energy photons and contributes to the voltage, while lower-energy light that passes through is absorbed by the silicon beneath, generating additional current. The two cells can be optically or electrically connected. As illustrated in Figure 1, this architecture enables better spectral utilization than a single-junction design, thereby allowing efficiencies beyond conventional limits.
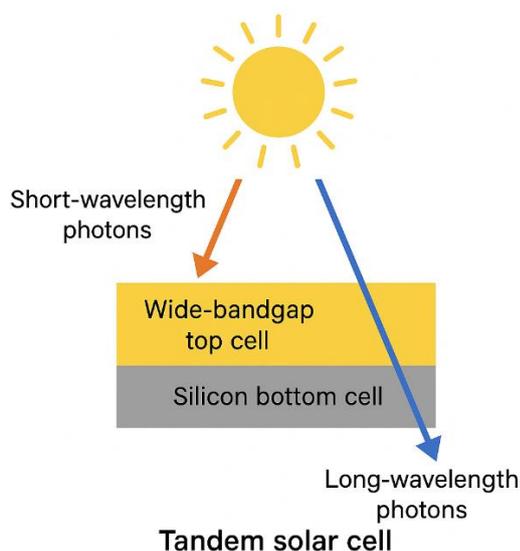

Fig. 1. Tandem solar cell architecture: high-energy (short-wavelength) photons are absorbed in the wide-bandgap perovskite top cell, while lower-energy (long-wavelength) photons transmit to the silicon bottom cell (not to scale).

Tandem solar cells improve efficiency by dividing the incoming spectrum between two layers that absorb different parts of the light. The top cell, usually a wide-bandgap perovskite around 1.65 to 1.75 eV, absorbs the high-energy photons and sets the voltage. Lower-energy photons that pass through are absorbed by the silicon bottom cell, which has a bandgap near 1.1 eV. This design helps limit thermalisation losses in the top layer and reduces the amount of unabsorbed light that would otherwise escape. Figure 2 shows how this spectral division improves utilisation of the AM1.5G spectrum, which is one of the main reasons tandem designs have become a focus in high-efficiency PV research.
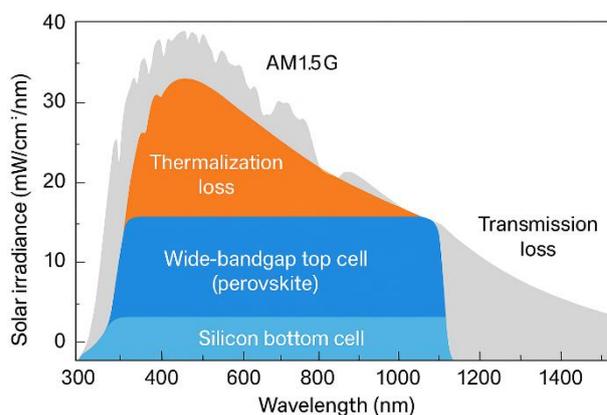

Fig. 2. Spectral-loss reduction in perovskite–silicon tandems: high-energy (short-wavelength) photons are absorbed by the wide-bandgap perovskite top cell, while lower-energy (long-wavelength) photons transmit to the silicon bottom cell, reducing thermalization and transmission losses.

This review consolidates recent progress in perovskite–silicon tandem solar cells by linking materials design, interface engineering, scalable manufacturing, and techno-economic analysis. It highlights critical challenges—stability, scalability, and environmental considerations—and provides an integrated perspective to guide both academic research and industrial deployment.

The paper is organized as follows. Section 2 motivates tandems via single-junction efficiency limits. Sections 3–6 cover perovskite materials, interface engineering, scalable fabrication, and stability/degradation. Section 7 analyzes techno-economics, Section 8 surveys commercialization pathways and prototypes, Section 9 discusses challenges and future directions, and Section 10 concludes.

2. EFFICIENCY LIMITS OF SINGLE JUNCTION CELLS

Silicon single-junction photovoltaics have long dominated the industry due to mature processing, material availability, and reliability, yet their efficiency is fundamentally bounded by the Shockley–Queisser limit (≈33% under AM1.5G) [5]. Despite decades of device and manufacturing optimization, state-of-the-art commercial modules remain below ~27% [2]. These bounds arise from intrinsic spectral-loss mechanisms: sub-bandgap photons transmit without absorption, while the excess energy of above-bandgap photons

thermalizes to the band edge, enforcing voltage–current trade-offs. Two-junction tandems alleviate these constraints by spectrally splitting sunlight between complementary bandgaps—typically a wide-bandgap (~1.65–1.8 eV) perovskite top cell harvesting high-energy photons to set a higher Voc, and a ~1.1 eV silicon bottom cell utilizing transmitted longer wavelengths to raise current. This architecture reduces thermalization and transmission losses relative to single absorbers and lifts the detailed-balance ceiling in practice. Monolithic perovskite–silicon tandems that combine suitable wide-bandgap compositions with optimized transport layers and low-temperature processing have already achieved certified efficiencies exceeding 29% [3,6], establishing a credible pathway to practical gains beyond incumbent silicon. Figure 3 illustrates the efficiency landscape from the theoretical Shockley–Queisser limit to laboratory and commercial results for silicon and tandem cells. Commercial silicon modules remain below 27%, whereas monolithic perovskite–silicon laboratory devices have surpassed 29%. Near-term deployment roadmaps project ~30% module-level efficiency as scalable processing and stability improve [2].
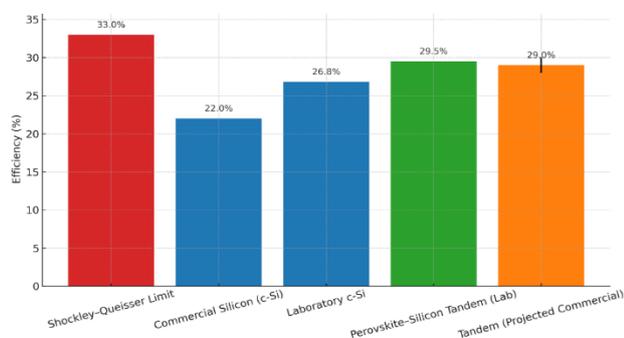

Fig. 3. Certified efficiencies of commercial silicon modules and monolithic perovskite–silicon tandems: tandems have surpassed 29%, while commercial silicon modules remain below 27%; dashed line indicates the single-junction Shockley–Queisser limit (~33%). Data reproduced from [2].

3. PEROVSKITE MATERIALS FOR TANDEM APPLICATIONS

The success of perovskite–silicon tandem solar cells depend heavily on wide-bandgap perovskite absorbers capable of delivering both high photovoltage and long-term stability.

For two-terminal tandems, the top cell generally requires a bandgap in the range of 1.65–1.80 eV, along with stable optical and structural properties under illumination. Low-temperature processing is also critical to avoid damaging the underlying silicon layer. These requirements make precise composition control, defect management, and stable device interfaces essential.

3.1 Bandgap Tuning and Halide Composition Strategies

Widening the perovskite bandgap typically involves increasing the bromide content, but this often induces halide segregation under light exposure, leading to phase separation and reduced voltage. To address these issues, several strategies have been explored. For example, a vapour-assisted method was used to create a quasi-2D/3D perovskite containing iodide, bromide, and chloride [7]. This material achieved a 1.78 eV bandgap with an open-circuit voltage (VOC) of 1.32 V and a power conversion efficiency (PCE) of 19.6 %, while maintaining strong stability under continuous illumination. A broader review of wide-bandgap materials reported that mixed-halide and mixed-cation systems can perform well but require surface passivation to suppress non-radiative recombination [8]. However, the authors cautioned that excessive interface modification can hinder charge extraction if not carefully balanced.

3.2 Environmental and Operational Stability

Perovskite materials are highly sensitive to light, heat, moisture, and oxygen, and they often degrade under such conditions. Although laboratory tests may not always replicate real-world stress, some studies have begun to bridge this gap. One report showed that a triple-halide perovskite-maintained stability under long-term illumination, with limited halide migration—likely aided by its layered structure [7]. In addition, perovskite tandems are being evaluated for space applications. Tests of wide-bandgap tandem cells in simulated low Earth orbit conditions, including vacuum, thermal cycling, and radiation, demonstrated that with proper encapsulation the cells performed well, indicating potential for aerospace deployment [9].

3.3 Trade-Offs and Open Questions

A key challenge remains balancing high bandgap, strong voltage output, and long-term durability. Increasing the bandgap by adding more bromide reduces photocurrent and heightens the risk of phase instability. Approaches such as optical confinement or the use of mirror layers can partly mitigate these effects, but careful composition and interface design remain critical for optimal device performance [10]. Table 1 summarises recent progress, including bandgaps, VOC values, efficiencies, and stability metrics for wide-bandgap perovskites. Although laboratory results are promising, most data are still derived from small-area devices, and it remains uncertain whether these materials can be scaled up while maintaining stability under prolonged environmental stress.

Table 1. Summary of Wide-Bandgap Perovskite Systems for Tandem Applications.

Study	Perovskite Composition / Structure	Bandgap (eV)	VOC (V)	PCE (%)	Stability Notes
Cheng et al. [7]	Triple-halide quasi-2D/3D (I/Br/Cl)	1.78	1.32	19.6	Suppressed halide segregation; stable under illumination
Brinkmann et al. [8]	Mixed-halide wide-gap systems (reviewed)	1.68–1.80	~1.30	~16–20	Stability via interfacial passivation and UV tolerance
Yoon et al. [9]	Tandem cells for LEO; wide-bandgap top cell	~1.75 (inferred)	—	~20	Functional under radiation, vacuum, and thermal cycling
Werner et al. [10]	FA/MA/Cs–Br/I compositions	1.65–1.75	~1.2–1.3	~15–20	Summarised bandgap–stability trade-offs
Hou et al. [11]	Broad review of scalable monolithic tandem structures	1.65–1.80	~1.25–1.30	18–25	Highlights commercialisation and encapsulation strategies
Chen et al. [12]	Semi-transparent 1.72 eV perovskite with Ag NW electrode	1.72	1.28	19.0	Stable under 1-sun illumination; compatible with tandems

4. INTERFACE ENGINEERING AND CHARGE TRANSPORT

The efficiency and durability of perovskite–silicon tandem solar cells are strongly influenced by the interfaces between layers. These junctions are critical for charge extraction, suppression of recombination, and overall device stability. Much of the recent progress in tandem device design has resulted from advances in interfacial engineering, including the use of self-assembled monolayers (SAMs), multifunctional transport layers, and improved contact designs.

4.1 Energy-Level Alignment and Transport Layers

Misalignment between the energy levels of the perovskite layer and adjacent transport layers can lead to voltage losses, inefficient charge extraction, and reduced fill factors. SAMs have emerged as a promising solution. For example, materials such as MeO-2PACz and PTAA not only align energy levels to enhance hole extraction but also passivate surface defects. Their ultra-thin profiles help maintain optical transparency, which is essential for monolithic tandem cells [13].
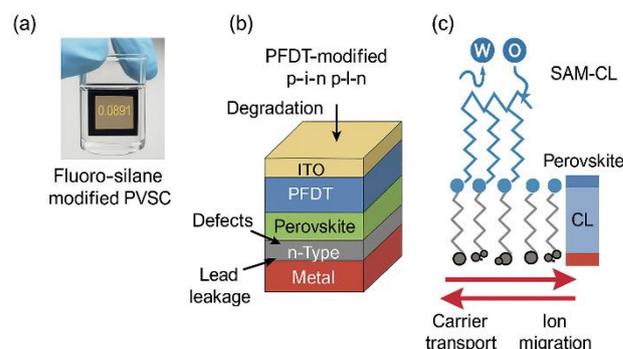

Fig. 4. Role of self-assembled monolayers (SAMs) in enhancing interfacial stability and charge extraction. (a) Fluoro-silane–modified device sustaining photovoltage under direct water exposure. (b) PFDT-modified p–i–n perovskite architecture with reduced degradation, defect suppression, and improved lead containment. (c) Schematic of the SAM–contact layer (CL) interface illustrating improved carrier transport, defect passivation, moisture blocking, and mitigated ion migration via ordered molecular assembly. Abbreviations: SAM, self-assembled monolayer; PFDT, a fluorinated silane; CL, contact layer.

Complementary work using computational modeling has examined how tripodal SAMs—such as 3PATAT-C3—affect surface dipoles and the work function of underlying contacts. These

studies show that subtle variations in molecular orientation and bonding chemistry can significantly influence interfacial energetics, which is crucial for minimizing voltage losses in tandem configurations [14].

4.2 Defect Passivation and Charge Extraction

Good energy alignment is only one part of the picture. Suppressing non-radiative recombination at interfaces is equally important. One study demonstrated that a multifunctional hole transport layer—combining passivating groups with high charge mobility—can significantly increase VOC and enhance stability, even under ambient fabrication conditions. This dual-function strategy is particularly relevant for scalable tandem production, where environmental tolerance and interface robustness are critical [15].

4.3 Mechanical and Interfacial Stability in Stacked Structures

As tandem devices become more complex, mechanical stability between layers is emerging as a key concern. Layer adhesion and elasticity affect not only initial device performance but also long-term reliability under real-world stresses such as thermal cycling and encapsulation. A study on contact mechanics revealed that interface stiffness and contact quality strongly influence stress distribution and the risk of delamination—issues of particular importance in stacked tandem architectures incorporating tunnel junctions and recombination layers [16].
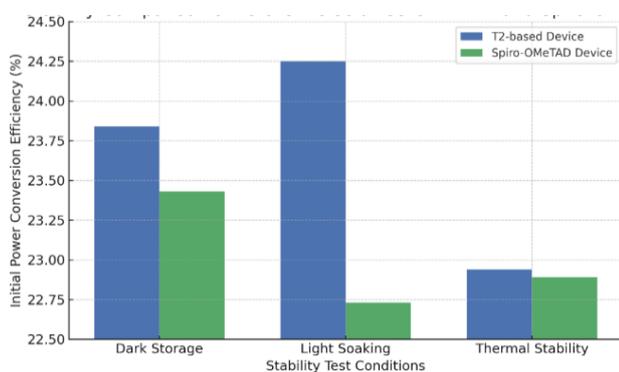

Fig. 5. Initial power conversion efficiency (PCE) of perovskite solar cells with T2-based and Spiro-OMeTAD hole transport layers under stability tests: (a) dark storage (ISOS-D-1; RH ≤ 10%), (b) light soaking (ISOS-L-1; unencapsulated; N_2 atmosphere), and (c) thermal exposure at 60 °C in Ar. Adapted from [15]. Abbreviations: PCE, power conversion efficiency; HTL, hole transport layer; RH, relative humidity.

Interfacial engineering in tandem cells is now about much more than just moving charges efficiently. It involves managing energy-level alignment, minimising defects, ensuring mechanical durability, and enabling scalable processing. As the field moves toward commercial-scale manufacturing, controlling these interfaces will be key to delivering high-performance, long-lasting tandem modules.

5. FABRICATION AND SCALABILITY

Lab-scale tandem solar cells have achieved remarkable efficiencies, but translating these results to commercial production remains a significant challenge. High performance must be maintained across large areas using fabrication methods that are cost-effective, industrially compatible, and reproducible. This section examines how the field is moving beyond spin coating, highlights recent advances in scalable deposition techniques, and considers the broader economic implications.

5.1 From Lab-Scale to Scalable Coating

Spin coating has long been the standard in early perovskite research, yet it is unsuitable for large-scale manufacturing because it wastes material and struggles to maintain uniformity on large substrates. To address these limitations, scalable methods such as slot-die coating, blade coating, and hybrid evaporation are being adopted to deposit wide-bandgap perovskites for tandem applications. One study demonstrated that slot-die coating can reliably produce triple-halide perovskite films with bandgaps around 1.68 eV.
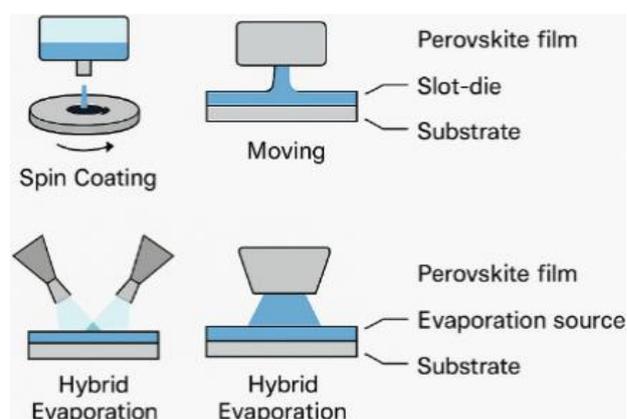

Fig. 6. Comparison of perovskite deposition methods for the production of tandem solar cells.

The resulting devices exhibited excellent layer uniformity and strong performance when integrated into monolithic tandems, supporting slot-die as a manufacturing-ready alternative [17]. A more recent development introduced a solvent system based on n-butanol that enables perovskite layers to be deposited in ambient air. Using this approach, researchers achieved a certified efficiency of 28.7 % over a 16 cm² area without the need for gloveboxes—a major step toward roll-to-roll compatible processing [18].

5.2 Hybrid and Textured Surface Strategies

For tandem cells to scale, deposition methods must also function effectively on the textured surfaces typical of silicon bottom cells. One study addressed this challenge using a two-step process that combined thermal evaporation with blade coating. Their method worked well on fully textured silicon, achieving efficiencies above 28 %, with low defect density and excellent repeatability [19]. At the module level, interconnection design is equally important. Another study proposed a shingled architecture for heterojunction-based tandems that improved edge passivation and reduced resistance losses. This approach simplifies the integration of large-area devices while maintaining current continuity across the module [20].

5.3 Techno-Economic Considerations

Even with strong laboratory performance, cost remains one of the main barriers to the adoption of tandem photovoltaics. A detailed techno-economic analysis indicated that tandem modules could achieve near-term manufacturing costs of approximately $0.43 per watt DC [21]. Their model identified module efficiency, coating throughput, and uniform film quality as the most critical factors for lowering both capital expenditures and the levelized cost of electricity (LCOE). The field is rapidly advancing from laboratory demonstrations to early indicators of industrial readiness. Scalable deposition methods such as slot-die and blade coating, combined with surface engineering and improved interconnection strategies, are making commercial tandem modules increasingly feasible. As these techniques mature and economic models continue to validate their potential, tandem photovoltaic technology may soon emerge as a serious competitor to conventional silicon.

6. STABILITY AND DEGRADATION

Long-term stability remains one of the major obstacles to bringing perovskite–silicon tandem solar cells to market. Although wide-bandgap perovskites (1.65–1.80 eV) are essential for achieving high efficiencies in tandem architectures, they are also more susceptible to environmental and operational degradation. This section outlines the key stability challenges—including moisture and oxygen exposure, halide segregation, and ion migration—and highlights recent efforts to mitigate them. It also emphasizes progress in encapsulation and the adoption of standardized testing protocols as essential steps toward commercial readiness.

6.1 Moisture, Oxygen, and Thermal Sensitivity

Wide-bandgap perovskites are especially vulnerable to ambient moisture and oxygen; the high Br content that enables 1.65–1.80 eV bandgaps also increase hygroscopicity and chemical reactivity. Under ambient exposure, Br-rich films can degrade rapidly: study [22] reported noticeable Voc losses within ~100 h in unencapsulated devices, attributed to material decomposition and trap formation at grain boundaries.
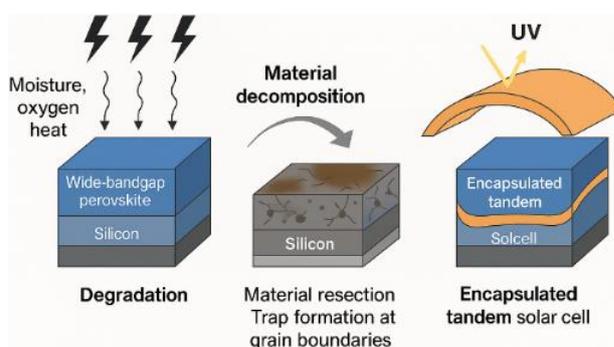
Fig. 7. Environmental degradation and encapsulation strategies for wide-bandgap perovskite solar cells.

Thermal stress accelerates these pathways and can couple to defect growth and interfacial degradation, further reducing operational stability. Given these sensitivities, robust encapsulation is essential. The review in [23] surveys scalable approaches—polymer bilayers, atomic-layer-deposited (ALD) barriers, and flexible glass laminates. ALD layers such as Al2O3 offer excellent moisture blocking but face throughput/scale challenges,

whereas hybrid multilayer laminates (inorganic/organic stacks with UV filters and desiccants) provide a practical balance of barrier performance, transparency, and mechanical compliance for early tandem prototypes.

6.2 Ion Migration and Halide Phase Segregation

Ion migration, especially the motion of halide ions, is a major instability pathway in wide-bandgap perovskites. Under illumination or electrical bias, mobile species can drive light-induced halide phase segregation and local composition changes that produce sub-bandgap emission and progressive losses in open-circuit voltage (VOC) [24]. The issue is particularly acute in Br-rich mixed-halide absorbers used for 1.65 to 1.80 eV top cells. Several mitigation strategies focus on compositional and interfacial control. Co-doping with small monovalent cations together with defect-passivating additives can stiffen the lattice and suppress ion mobility [25]. In addition, process control that limits or optimizes residual PbI_2 formation during fabrication has been shown to enhance photostability and slow VOC decay under continuous illumination [26].

6.3 Encapsulation and Environmental Protection

Encapsulation not only serves as a physical barrier but also contributes to the stabilization of reactive interfacial layers. Studies have shown that encapsulated devices exhibit delayed hysteresis and maintain high fill factors during thermal cycling [23]. Multilayer barrier films that combine inorganic and organic components offer a strong balance of flexibility, optical transparency, and environmental resistance. Additional emerging strategies include incorporating UV filters, using non-volatile interfacial dopants, and engineering perovskite layers with compositional gradients to minimize strain and improve compatibility with encapsulation.

6.4 Stability Testing Protocols and Results

As research increasingly targets long-term device performance, standardized testing has become essential. The ISOS protocols are now widely adopted to benchmark how perovskite devices withstand different environmental conditions. For example, one study [27] operated inverted perovskite cells under the ISOS-D-1 protocol, which involves dry-air aging for 1,000 hours. Unprotected devices degraded noticeably, whereas those incorporating both passivation and encapsulation retained over 90 % of their initial efficiency. In another case, researchers [22] examined perovskite–organic tandem devices under simulated sunlight for 500 hours and found that unencapsulated cells maintained about 85 % of their initial performance. While these results demonstrate the significant impact of protective measures, they also highlight that laboratory conditions do not always translate directly to real-world outdoor performance. Wide-bandgap perovskites are critical for achieving high-efficiency tandem solar cells, yet they introduce added complexity in terms of durability. Moisture, heat, oxygen, and mobile ions all contribute to performance loss, and these effects are often amplified in Br-rich compositions used for top cells. Researchers are addressing these challenges through composition and interface modifications, improved passivation, and advanced encapsulation. These approaches have yielded measurable gains in stability, particularly under controlled testing conditions. Standard protocols such as ISOS are proving valuable for comparing results across different laboratories and device architectures. Nevertheless, the long-term stability challenge remains unresolved. Tandem devices continue to face open questions about degradation under realistic outdoor exposure and during scale-up. At present, stability remains one of the primary constraints to the commercial deployment of perovskite–silicon tandem solar cells.

7. TECHNO-ECONOMIC OUTLOOK

7.1 Levelized Cost of Electricity (LCOE)

The levelized cost of electricity (LCOE) remains the primary benchmark for evaluating the commercial viability of new photovoltaic (PV) technologies. Tandem devices, particularly perovskite–silicon modules, benefit from higher efficiencies that can lower system and land-related costs, even if the cells themselves are more expensive to manufacture. One study

ran projections for both two-terminal (2T) and four-terminal (4T) tandem modules at gigawatt-scale production and estimated LCOE values between €0.025 and €0.035 per kWh, depending heavily on the achieved efficiency and long-term stability of the modules [28]. Another analysis compared different architectures and concluded that 2T tandems could deliver better cost performance than either single-junction silicon or 4T tandems, provided they reach efficiencies above 28 % and maintain lifetimes exceeding 20 years [29].

7.2 Capital and Process Costs

Much of the cost in tandem module production arises not from raw materials but from manufacturing processes. One study demonstrated that replacing vacuum-based interlayers with printable, low-temperature alternatives could reduce module costs by more than 30 %, although certain expenses—such as high-purity precursors and the maintenance of dry-room environments—are not easily scaled down [30]. Another investigation compared crystallization in spin-coated and slot-die-coated $MAPbI_3$ films, finding that while slot-die coating is more scalable, it produces slower and less uniform film formation. Such variability is critical at industrial scale, where throughput and yield directly influence the cost per watt [31].

7.3 Yield, Degradation, and Warranty Assumptions

Many LCOE models assume optimistic values for module lifetime and annual degradation, which can lead to overly favorable cost projections. One analysis argued that even small decreases in the annual performance ratio—for example, from 1.0 to 0.95—can significantly extend payback periods, particularly for emerging technologies. This highlights the importance of warranties. The current industry standard is a 20–25-year product life with less than 1 % annual degradation [32]. For tandem modules to compete, they will need to approach this benchmark, especially in utility-scale and investor-driven markets. As discussed in Section 6, achieving such durability will depend largely on improving the long-term stability of wide-bandgap perovskites.

7.4 Market Readiness and Industrial Roadmaps

Some manufacturers are already moving tandems closer to commercialization. Oxford PV, for instance, has established a pilot line producing 2T modules with 28 % efficiency and aims to reach 30 % by 2026. Other groups, including Meyer Burger and CSEM, are exploring industrial-scale approaches to interconnection and coating. One study outlined a roadmap identifying three key hurdles: scalable deposition of high-quality perovskite layers, reliable tunnel junctions for stacked architectures, and proven long-term outdoor durability [33]. The analysis suggests that with continued progress in these areas, first-generation tandem modules could become commercially available within the next five years, provided stability and cost targets are met.
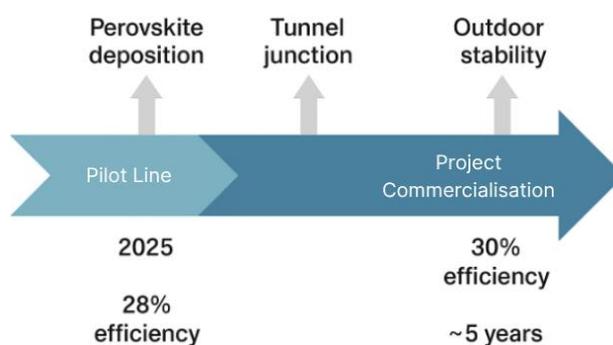

Fig. 8. Industrial roadmap for perovskite–silicon tandem solar cell commercialisation.

Tandem solar cells are starting to look commercially viable on paper. Projected LCOE values are coming close to what silicon and thin-film panels can offer, and higher efficiencies help offset some of the cost challenges. That said, the technology isn't there yet. Scalability, stability, and process compatibility still need to catch up. If efficiency gains hold and degradation can be brought under control, tandems could be a competitive option not just in niche markets, but in large-scale deployments.

8. COMMERCIALISATION LANDSCAPE AND INDUSTRIAL PROTOTYPES

Commercial interest in perovskite–silicon tandem photovoltaics has grown quickly. Several pilot lines are now producing modules with certified efficiencies close to 30%, and many groups are preparing for limited deployment.

This section looks at who's building what, how performance is being validated, and where things stand in terms of getting these technologies to market.

8.1 Industrial Actors and Pre-Commercial Modules

Oxford PV is one of the most visible companies working on commercial tandems. They're using silicon heterojunction (SHJ) cells as the base and adding a wide-bandgap perovskite layer on top. Their pilot line in Freiberg has produced two-terminal tandem modules with a certified efficiency of 28%, and they're aiming for 30% soon [34]. These modules are built on standard silicon formats and use existing encapsulation methods, which could help with scaling. Meyer Burger is also exploring tandem integration alongside its existing SHJ production. On the research side, institutions like CSEM and Helmholtz Zentrum Berlin are focused on process development and interlayer design, particularly tunnel junctions, which are still a limiting factor in monolithic tandems. Not all tandem developments are silicon-based. A 29.9% efficiency has been demonstrated in a perovskite–CIGS configuration, offering potential benefits for flexible and lightweight applications [35]. While different in architecture, it shows that tandem concepts are attracting attention beyond the silicon platform.

8.2 Quality Assurance and Certification

For large-scale deployment, tandem modules must meet established quality and safety standards. Several studies have highlighted remaining challenges, including layer uniformity, contact resistance, and encapsulation reliability [36]. Standard IEC protocols such as 61215 and 61730 are currently used to assess these devices, although they were not originally designed for perovskite-based systems. A major limitation remains the lack of long-term outdoor performance data. Most existing certifications are still derived from short-term laboratory tests involving thermal cycling, UV exposure, and damp-heat conditions, all of which strongly influence perovskite stability [37]. Some manufacturers have started publishing ISOS-compliant stability data, with devices passing 500 hours or more, but broader adoption of third-party testing is still needed.

8.3 Market Readiness and Outlook

Tandem modules aren't quite ready for mass deployment, but some may enter the market soon, likely in smaller rooftop or high-performance utility projects. Efficiencies exceeding 30%, combined with strong durability and high manufacturing yield, could reduce the levelized cost of electricity to below €0.03/kWh in high-irradiance regions [34]. Further modelling efforts have evaluated the energy yield of tandem systems under real-world operating conditions [38,39]. Their work shows that even modest efficiency gains, when applied to large-scale or bifacial systems, can lead to meaningful improvements in total energy output and cost per kilowatt-hour. The main hurdles at this point are stability, large-scale process control, and getting through full certification. Work is ongoing in all of these areas, but exactly when tandems will be ready for full commercial rollout depends on how fast these pieces come together. Perovskite–silicon tandems are no longer just a lab experiment. Companies like Oxford PV are shipping pilot modules, and other groups are moving in the same direction. Certification and long-term reliability are still in progress, but the technology is getting close to market in some segments. If current progress holds, we may see the first real deployments before the end of the decade.

9. CHALLENGES AND FUTURE OUTLOOK

Perovskite–silicon tandem solar cells have made impressive gains in the lab and are now edging into pilot production. But the path to wide-scale deployment is still complicated. Key challenges remain — not just in how the cells perform, but in how they're made, certified, and integrated into existing solar markets.

9.1 Technical Barriers

Efficiencies exceeding 29 % have now been certified for perovskite–silicon tandem cells, but most of these results come from small-area devices tested under carefully controlled laboratory conditions. Replicating such performance at scale—across full-size commercial modules—remains challenging. Achieving uniform coating on textured silicon, ensuring reliable tunnel junctions, and maintaining consistent monolithic integration

are all difficult at industrial throughput [34]. Long-term stability is an even greater concern. Wide-bandgap perovskites, which are essential for high-efficiency tandems, remain susceptible to ion drift, halide segregation, and UV-induced degradation. As noted in previous studies, these degradation pathways are especially problematic under International Electrotechnical Commission (IEC) testing standards. Although encapsulation techniques have improved, meeting the 25-year warranty standard typical of silicon modules remains beyond the reach of most tandem prototypes [40].

9.2 Economic and Bankability Risks

Even if tandem modules can be manufactured at a competitive cost, their bankability depends on more than price alone. Project developers and investors require reliable performance guarantees, third-party certification, and long-term field data. As highlighted in recent analyses, ISOS-based tests are useful but not yet universally adopted, and real-world deployment data remain scarce—making it difficult to justify large-scale, utility-level investment [37]. Manufacturing scale is another critical hurdle. While pilot production lines are successfully fabricating working modules, very few have demonstrated the yield or process control needed at the gigawatt scale. Equipment costs, tight process tolerances, and the need for consistent quality still render high-volume tandem manufacturing a risky proposition.

9.3 Environmental Sustainability

Lead content remains a significant environmental concern. Most high-efficiency perovskite formulations still rely on lead-based chemistry, and although the absolute quantities are small, the potential for lead leaching from damaged modules cannot be overlooked. Experts argue that future tandem designs should integrate circular-design principles from the outset to facilitate safe recovery and recycling. At present, however, no established recycling pathway exists for perovskite modules [41, 11]. As production volumes grow, this gap will become increasingly visible. Emerging standards such as IEC 63397, along with industry initiatives like PV CYCLE, may help define best practices, but their implementation is still in the early stages.

9.4 Research and Industry Pathways

Several areas are likely to determine how quickly tandems reach full market readiness:

- Long-term testing: Standardised, third-party data from ISOS-D, -L, and -T protocols

- Material innovation: Lead-free alternatives and more stable wide-bandgap formulations

- Process integration: Flexible encapsulation, scalable coating [12], and tunnel junction reliability

- Policy support: Public funding or incentives for high-risk, high-efficiency PV technologies

Cross-sector collaboration, particularly between research labs, manufacturers, and certification bodies, will be essential in bridging the gap between prototypes and commercial modules.
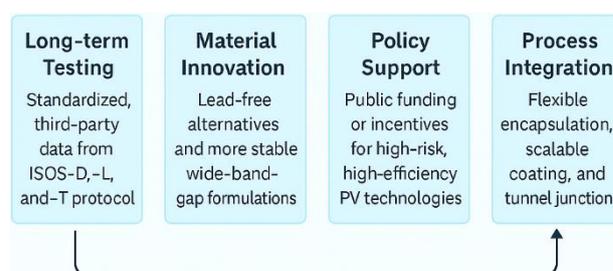

Fig. 9. Key research and industry pathways supporting the commercialisation of perovskite–silicon tandem solar cells.

9.5 Outlook to 2030

If technical and process bottlenecks continue to improve at the current pace, tandems with efficiencies above 30 % and multi-decade lifetimes could plausibly enter the market within the next five years. Early deployment is likely to target premium segments such as high-value rooftop systems, space-constrained utility sites, and building-integrated photovoltaics, where higher efficiency offsets added complexity. Recent analyses suggest that tandem modules could represent 10–15 % of new installations by 2030, provided continued progress is made in durability, manufacturing yield, and recycling infrastructure [34]. While not guaranteed, this outcome is increasingly within reach. Tandem photovoltaics have evolved from a high-risk laboratory concept into a credible commercial candidate. However, they still face significant hurdles: ensuring long-term stability, achieving

large-scale manufacturability, meeting certification requirements, and planning for end-of-life recycling. Overcoming these challenges will demand more than academic advances—it will require coordinated action across research, industry, and policy to bring perovskite–silicon tandem technology into mainstream energy markets.

Table 2. Summary of Key Studies on Perovskite–Silicon Tandem Solar Cells Across Themes.

Reference	Theme	Type	Main Contribution
Aydin et al. [34]	Commercialisation	Review	Industrial roadmap, stability bottlenecks, commercial forecasts
Hull et al. [28]	LCOE & Techno-economics	Modelling	Cost modelling for 2T/4T tandems at GW scale
Zafoschnig et al. [29]	LCOE comparison	Modelling	LCOE trade-offs between Si, perovskite, and tandem PV
Li et al. [30]	Process cost breakdown	Techno-economic	Early-stage CAPEX & material analysis for tandems
Wei et al. [26]	Stability & Phase segregation	Experimental	PbI_2-mediated instability suppression in wide-bandgap perovskites
Guo et al. [22]	Wide-bandgap stability	Experimental	Stability of Br-rich perovskite top cells
Zhang et al. [25]	Halide segregation suppression	Experimental	Doping strategies to improve thermal & ionic stability
Li et al. [27]	Stability testing protocols	Experimental	ISOS-D-1 applied to perovskite tandems
Raman et al. [23]	Encapsulation methods	Review	Review of industrial encapsulation materials & methods
Lago et al. [36]	Industrial QC & certification	Industry Review	Testing and certification metrics for tandem PV
Blakesley et al. [37]	Landscape & pilot deployment	Roadmap	Deployment overview, IEC progress, field durability challenges
Maalouf et al. [41]	Circular economy & lifecycle	LCA Review	Recycling pathways and environmental risks in tandem PV
Martinho [40]	Future challenges & R&D roadmap	Review	Technical scalability, stability, and market transition challenges
Hao et al. [39]	Yield predictions	Simulation	Bifacial tandem energy yield models under real-world conditions
Liang *et al.* [35]	Non-silicon tandem development	Experimental	Near-30% tandem with $CuInSe_2$, shows hybrid viability
Tong et al. [24]	Halide migration & phase issues	Review	Mechanistic insights on instability in mixed-halide perovskites
Schötz et al. [31]	Coating method comparison	Experimental	Spin vs slot-die crystallisation dynamics
Wang et al. [4]	Process control & scaling	Experimental	In situ analysis of large-area perovskite coating

10. CONCLUSION

Perovskite silicon tandem solar cells have reached a point where high efficiencies are no longer limited to the lab. Devices with certified performance above 29% are now being produced on pre-commercial lines, and the architecture has shown it can integrate with existing silicon processes. This review has outlined the major steps that made this possible — from materials development and interface design to scalable coating and encapsulation. However, the core challenges remain. Stability under realistic operating conditions still falls short of what's needed for long-term deployment. Manufacturing at scale, especially without sacrificing yield or reliability, also presents unresolved issues. And while the amount of lead in current perovskites is small, its presence will continue to raise concerns unless recovery and recycling strategies are developed in parallel. What makes tandem PV notable is that it doesn't

require a full system overhaul. It builds directly on the silicon infrastructure already in place. If the remaining technical and environmental issues can be addressed, tandems could offer a practical route to higher efficiency modules within this decade — not as a replacement for silicon, but potentially as an upgrade to it.

Declaration of Competing Interests

The author declares no competing financial or personal interests.

Author Contributions

James Riffat conceptualised the structure of the review, conducted the literature research, performed the analysis, and wrote the manuscript. All sections were reviewed and revised by the Seyed Reza Samaei to ensure consistency, accuracy, and coherence. The authors approved the final version of the manuscript.

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