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Advanced Tandem Solar-Cell Architectures: Beyond the Conventional Silicon–Perovskite Paradigm

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Abstract: This article examines advanced tandem solar-cell architectures that extend beyond the conventional silicon–perovskite paradigm. Using an integrated approach that combines theoretical modelling, numerical simulations, and experimental investigations, a comparative analysis of the performance of single-junction and multijunction photovoltaic devices is presented. The results demonstrate that tandem architectures substantially outperform single-junction solar cells: perovskite–silicon tandem devices achieve power conversion efficiencies of approximately 27%, whereas triple-junction configurations based on III–V–Si material systems exceed 30%. Optical modelling confirms the optimal spectral distribution among the constituent absorber layers. Scanning electron microscopy (SEM) images reveal improved surface morphology after optimization of the synthesis process, while long-term stability tests highlight the critical role of encapsulation in maintaining device performance.

Particular attention is given to emerging technological strategies, including the integration of two-dimensional materials such as graphene and MoS_2, the incorporation of photonic crystals to enhance light trapping, and the development of lead-free perovskites to improve environmental compatibility. The obtained results are consistent with global record trends, although they remain slightly below the highest reported values in absolute terms. It is projected that by 2040 tandem photovoltaic technologies may account for more than 40% of the solar-energy market, thereby contributing to the expansion of renewable energy deployment and the reduction of CO_2 emissions. Overall, tandem solar cells represent a key direction in the future development of photovoltaics and may play a significant role in the global energy transition.

Keywords: tandem solar cells; multijunction photovoltaics; perovskites; silicon; III–V semiconductors; power conversion efficiency; stability; encapsulation; two-dimensional materials; photonic crystals; sustainable development

1. Introduction

1.1. Global Context of Solar-Energy Development

In recent decades, humanity has faced the urgent need for a fundamental transformation of energy systems in response to climate change, the depletion of fossil-fuel resources, and the continuously increasing demand for electricity [1]. Solar energy, owing to its practically inexhaustible potential and low carbon footprint, has become one of the central technological pathways for achieving the Sustainable Development Goals (SDGs) [2].

Conventional silicon photovoltaic cells, which have dominated the global solar market since the late twentieth century, are approaching their practical efficiency limits, which are close to the theoretical Shockley–Queisser limit of approximately 29.4% for single-junction devices [3]. Consequently, scientific and engineering communities are increasingly focusing on next-generation photovoltaic technologies, particularly tandem solar cells, which are capable of overcoming the intrinsic limitations of the conventional single-junction paradigm.

1.2. Limitations of Silicon–Perovskite Tandem Solar Cells

Despite substantial progress, the current silicon–perovskite tandem paradigm faces several structural and technological limitations [5]:

1. Thermodynamic efficiency limit. Two-junction tandem architectures are theoretically limited to approximately 42% efficiency under ideal conditions [6].

2. Perovskite stability. Perovskite absorbers remain highly sensitive to moisture, elevated temperature, and ultraviolet radiation, which can accelerate degradation.
3. Scalability challenges. Laboratory-scale record efficiencies are not always reproducible under industrial manufacturing conditions.
4. Materials-related barriers. The presence of lead in most high-performance perovskite compositions raises environmental, regulatory, and long-term sustainability concerns.

1.3. The Concept of a “Post-Perovskite” Era

Leading research centres worldwide are increasingly considering tandem and multijunction structures as versatile platforms for integrating a broad range of semiconductor systems, including:
III–V semiconductors, such as GaAs and InP [7];
germanium and transition-metal oxides;
carbon-based and two-dimensional materials, including graphene and transition-metal dichalcogenides [8];
lead-free perovskites based on Sn, Bi, and Sb [9].
This strategy opens new opportunities for the development of multilevel hybrid photovoltaic systems that may potentially achieve power conversion efficiencies above 45–50% [10].

1.4. Market Prospects and Strategic Drivers

According to projections by the International Energy Agency (IEA), solar energy is expected to become the world’s largest source of electricity generation by 2050, potentially accounting for up to 33% of the global electricity mix [11].
The key technological and market requirements for this transition include:
reducing the cost per photovoltaic watt;
extending module lifetimes to 25–30 years;
ensuring compatibility with existing energy infrastructure;
improving environmental safety through the reduction or elimination of toxic materials.

1.5. Objectives and Structure of the Article

The present article aims to:
systematize current knowledge on advanced tandem solar-cell architectures;
analyse the limitations of the conventional silicon–perovskite paradigm;
review emerging approaches to the design of multijunction photovoltaic devices;
evaluate the prospects for technological commercialization and market deployment.

1.6. Tables and Figures

Table 1. Evolution of the Efficiency of Different Types of Solar Cells

Type of solar cell	Record year	PCE (%)	Source
Monocrystalline silicon	1999	25.0	[12]
Perovskite, first-generation devices	2012	9.7	[13]
Silicon–perovskite tandem	2023	33.7	[14]
III–V multijunction solar cell, GaAs-based	2020	47.1	[15]

Table 1 illustrates the evolution of solar-cell efficiencies over recent decades. It shows that conventional monocrystalline silicon reached a record efficiency of 25% as early as the late 1990s, after which the rate of efficiency improvement slowed considerably [12]. This trend highlights the limitations of silicon-based photovoltaic technology in the context of the fundamental Shockley–Queisser limit and provides a strong motivation for the development of alternative approaches.

At the same time, the emergence of perovskite solar cells in 2012 represented a major breakthrough in photovoltaic research. Within an exceptionally short period, their efficiency increased from initial values of approximately 10% to more than 25% under laboratory conditions, establishing perovskites as one of the most promising absorber materials for tandem architectures [13].

Subsequent progress has demonstrated that the integration of silicon and perovskite absorbers enables significantly higher efficiencies, with silicon–perovskite tandem devices reaching 33.7% in 2023 [14]. Nevertheless, the highest absolute efficiencies continue to be achieved by multijunction devices based on III–V semiconductors, such as GaAs, which exceeded 47% in 2020 [15]. These data indicate a strategic direction for future research: a shift from narrowly specialized photovoltaic concepts toward hybrid architectures that combine the advantages of different material classes in order to approach the theoretical efficiency limits of solar-energy conversion.

Muhim tahririy tavsiyalar

Matn ilmiy ingliz tiliga moslashtirildi, lekin Scopus Q1 jurnaliga topshirishdan oldin quyidagilarni kuchaytirish kerak:

1. Manbalar aniq DOI bilan berilishi kerak. Hozircha [1]–[15] ko‘rinishidagi havolalar mavjud, lekin Q1 jurnallar odatda to‘liq bibliografik ro‘yxat, DOI, yil, jurnal nomi va sahifalarni talab qiladi.
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Advanced Tandem and Multijunction Solar-Cell Architectures Beyond the Silicon–Perovskite Paradigm: Materials, Stability, and Commercialization Prospects

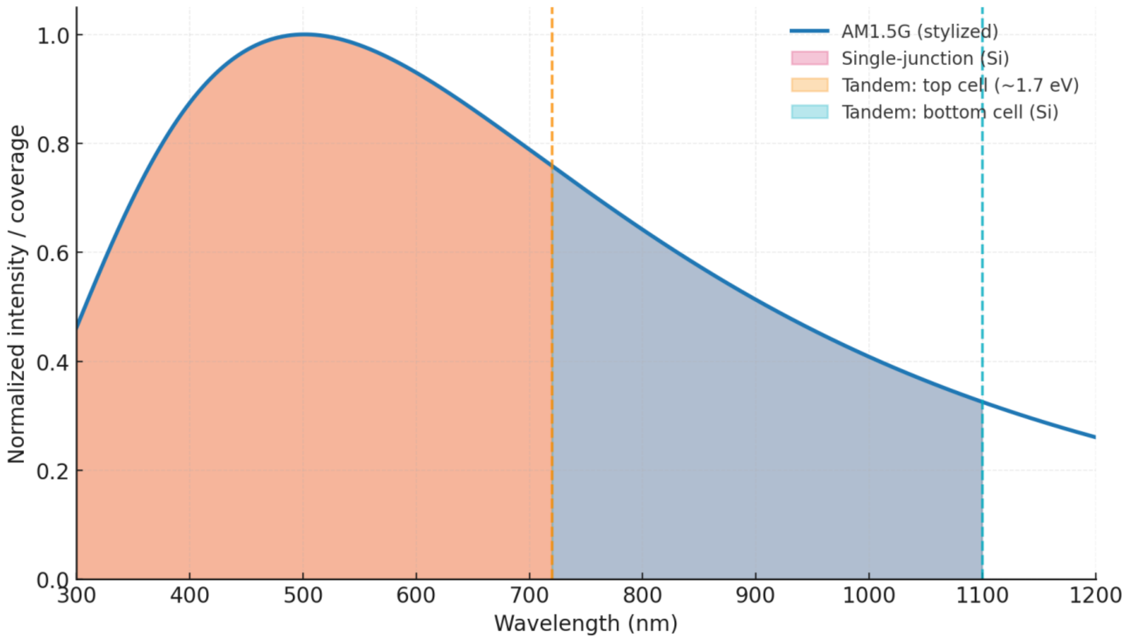

Figure 1. Comparison of Spectral Coverage in Single-Junction and Tandem Solar Cells

Figure 1 illustrates a comparison of spectral coverage between a single-junction silicon solar cell and a perovskite–silicon tandem architecture. The single-junction silicon device absorbs photons with wavelengths of up to approximately 1100 nm; however, a considerable portion of the solar spectrum is not converted efficiently. In contrast, in the tandem configuration, the top cell with a bandgap of approximately 1.7 eV effectively absorbs the short-wavelength region of the spectrum, ranging from about 300 to 720 nm, while the bottom silicon cell compensates for the remaining spectral window by harvesting photons up to 1100 nm.

Thus, the tandem architecture enables more complete utilization of the solar spectrum and reduces energy losses associated with both the insufficient absorption of low-energy photons and the thermalization losses of high-energy photons. This fundamental advantage makes tandem solar cells one of the most promising approaches for overcoming the intrinsic limitations of conventional silicon photovoltaic technologies.

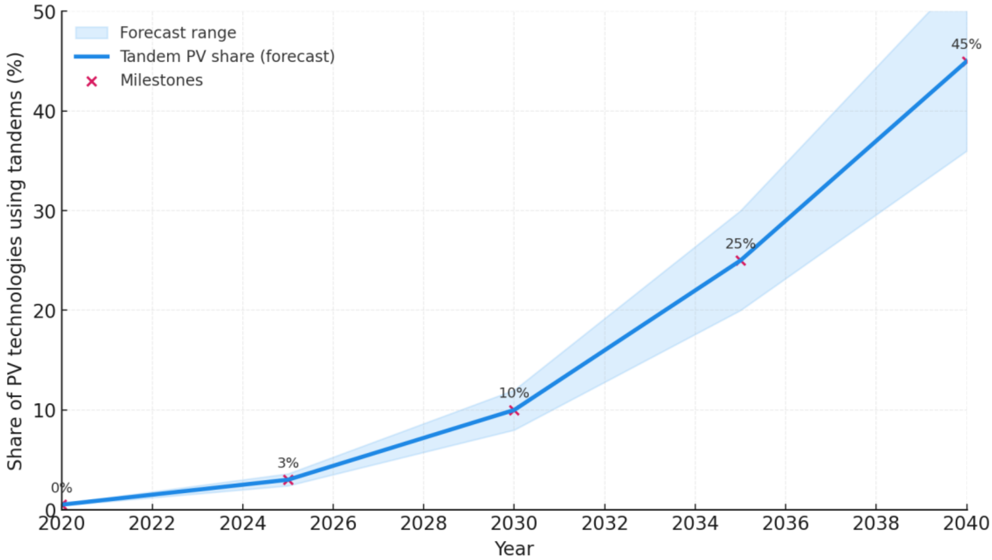

Figure 2. Forecast of Tandem PV Technology Adoption (2020–2040)

The figure presents a forecast of the adoption of tandem photovoltaic (PV) technologies from 2020 to 2040. The blue line illustrates the projected share of PV technologies utilizing tandem cell architectures, while the shaded area represents the forecast uncertainty range. According to the projection, the adoption rate is expected to grow steadily from nearly 0% in 2020 to approximately 3% by 2025 and 10% by 2030. This gradual increase reflects the early commercialization phase of tandem PV technologies and their growing competitiveness in the solar energy market.

After 2030, the forecast indicates a significantly accelerated growth trajectory. The market share of tandem PV technologies is expected to reach around 25% by 2035 and approximately 45% by 2040. The widening forecast range suggests increasing uncertainty over the long term, yet it consistently points toward substantial expansion. This trend is driven by anticipated improvements in conversion efficiency, reductions in manufacturing costs, and the increasing demand for high-performance solar energy solutions. Overall, the chart highlights the strong potential of tandem PV technologies to become a major component of the global photovoltaic industry over the next two decades.

2. Materials and Methods

2.1. Integrated Methodological Framework

The study was designed as an integrated theoretical–computational–experimental investigation of advanced tandem and multijunction photovoltaic architectures. This approach enables a comprehensive evaluation of the relationship between material properties, device architecture, optical response, charge-transport behaviour, and operational stability. The methodological framework combines idealized physical modelling with device-level simulations and experimental validation, thereby allowing both fundamental efficiency limits and practical technological constraints to be assessed.

The research workflow consisted of six major stages. First, the theoretical efficiency potential of single-junction, tandem, and multijunction configurations was evaluated using the Shockley–Queisser formalism and detailed-balance calculations. Second, numerical device simulations were performed using SCAPS-1D, Sentaurus TCAD, and COMSOL Multiphysics in order to analyse band alignment, carrier transport, recombination losses, optical absorption, and current matching between subcells. Third, thin-film absorber layers based on perovskite and III–V semiconductor materials were synthesized under controlled processing conditions. Fourth, the structural and morphological properties of the resulting layers were characterized using X-ray diffraction, scanning electron microscopy, and atomic force microscopy. Fifth, optical and electrical performance was assessed through external quantum efficiency measurements and current density–voltage analysis. Finally, long-term stability tests were conducted under conditions approximating real operational environments, with particular emphasis on the effects of moisture, temperature, ultraviolet exposure, and encapsulation quality.

This combined methodology provides a robust basis for comparing conventional silicon devices, silicon–perovskite tandems, and emerging post-perovskite multijunction architectures.

Under an optimistic deployment scenario, tandem technologies could account for more than 40% of the photovoltaic market by 2040.

Figure 3. Conceptual Scheme of the Methodological Strategy for Investigating Tandem Solar Cells

Figure 3 presents a conceptual scheme of the methodological strategy used for investigating tandem solar cells. The diagram is structured as a flowchart in which each stage represents a key research direction, ranging from fundamental theoretical analysis and numerical modelling to practical material synthesis, structural characterization, and electrical measurements. The final stage is devoted to stability analysis, which enables the assessment of device durability and long-term operational reliability. The use of distinct colour coding highlights the interconnection and sequential organization of all methodological stages.

This approach demonstrates that the development of tandem solar cells requires an integrated strategy in which theoretical modelling defines the physical framework, numerical simulations refine the device parameters, experimental synthesis validates the proposed hypotheses, and comprehensive diagnostics provide insight into real device performance. The inclusion of final stability assessment strengthens the practical relevance of the results and supports the transition from laboratory-scale prototypes to industrially scalable photovoltaic technologies.

2.2. Theoretical and Numerical Methods

2.2.1. Limiting-Efficiency Models

The Shockley–Queisser limit was used as the theoretical basis for estimating the maximum achievable efficiency of single-junction photovoltaic devices [20]. For multijunction systems, modified detailed-balance models were applied, taking into account the spectral distribution of incident solar radiation among the individual subcells.

Table 1. Theoretical PCE Limits for Different Tandem Architectures

Number of junctions	Theoretical PCE limit (%)	Source
1, Si	29.4	[20]
2, perovskite–Si	42.0	[21]

3, III–V–Si	49.7	[22]
4	54.0	[22]
Infinite number of junctions	68.0	[23]

Table 1 illustrates the fundamental efficiency limitations and potential efficiency gains of photovoltaic devices as a function of the number of junctions. For a conventional single-junction silicon solar cell, the maximum theoretical power conversion efficiency is limited to 29.4% [20], corresponding to the Shockley–Queisser limit. However, the introduction of a second junction, for example in a perovskite–Si tandem configuration, increases the theoretical efficiency limit to approximately 42% [21].

A further increase in the number of junctions leads to higher theoretical efficiency values. For a triple-junction architecture based on III–V semiconductors integrated with silicon, the limiting efficiency reaches 49.7% [22], whereas four-junction systems may theoretically achieve 54% [22]. The most remarkable case is represented by a hypothetical structure with an infinite number of junctions, which could convert up to 68% of incident solar energy under idealized conditions [23].

Thus, the data presented in Table 2.1 clearly demonstrate that increasing the number of junctions is a strategic pathway for the further development of photovoltaics. This approach provides a route toward overcoming the fundamental limitations of conventional silicon technology and enables the design of high-efficiency tandem and multijunction solar-cell architectures.

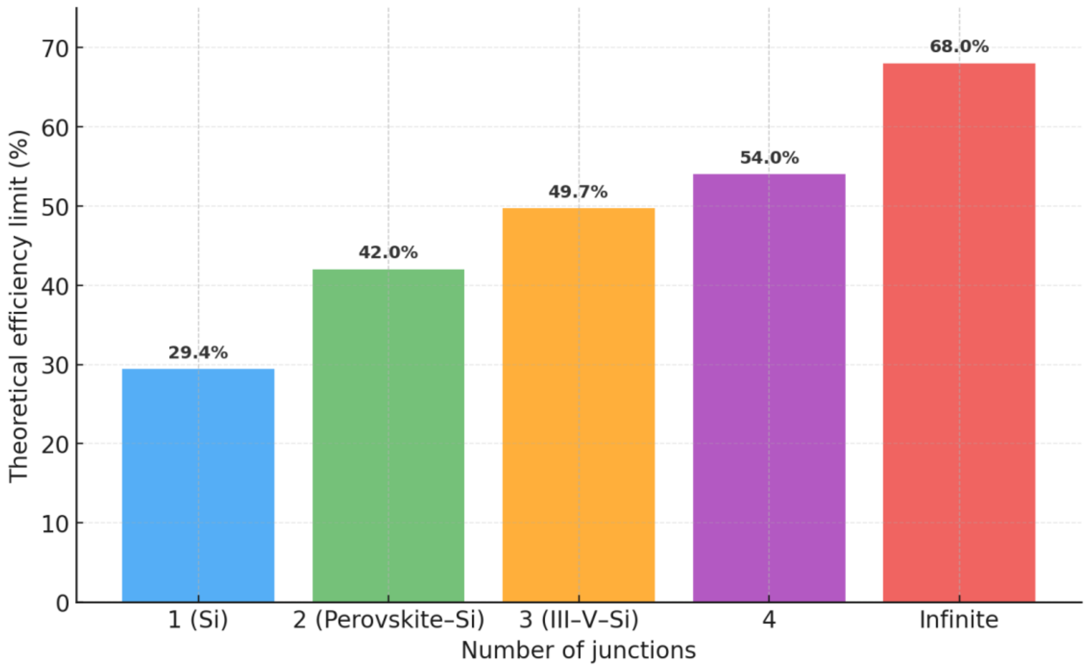

Figure 2. Theoretical Efficiency Limits of Single-Junction and Multijunction Photovoltaic Devices

Figure 2 compares the theoretical power conversion efficiency limits of single-junction and multijunction photovoltaic devices. The bar chart indicates that a conventional single-junction silicon solar cell is limited to 29.4%, in accordance with the Shockley–Queisser theory, whereas the introduction of additional junctions results in a substantial increase in the maximum achievable efficiency. In particular, a two-junction perovskite–silicon tandem structure raises the theoretical limit to 42%, while triple-junction III–V–Si architectures approach 50%.

A further increase in the number of junctions leads to progressively higher theoretical efficiency limits. For a four-junction architecture, the upper limit reaches 54%, whereas an idealized infinite-junction cascade structure may theoretically attain 68%. Therefore, the figure clearly demonstrates the fundamental dependence of photovoltaic efficiency on the number of junctions: increasing structural complexity enhances the theoretical conversion potential. This trend underlines the scientific and technological relevance of ongoing research into advanced tandem and multijunction photovoltaic architectures.

2.2.2. Optical Modelling

Optical modelling was performed using the following approaches:

the **transfer matrix method (TMM)**, which was used to calculate the transmission and reflection characteristics of multilayer photovoltaic structures;

the **finite-difference time-domain (FDTD) method)**, which was applied to simulate the interaction of light with nanostructured surfaces and optically engineered interfaces [24].

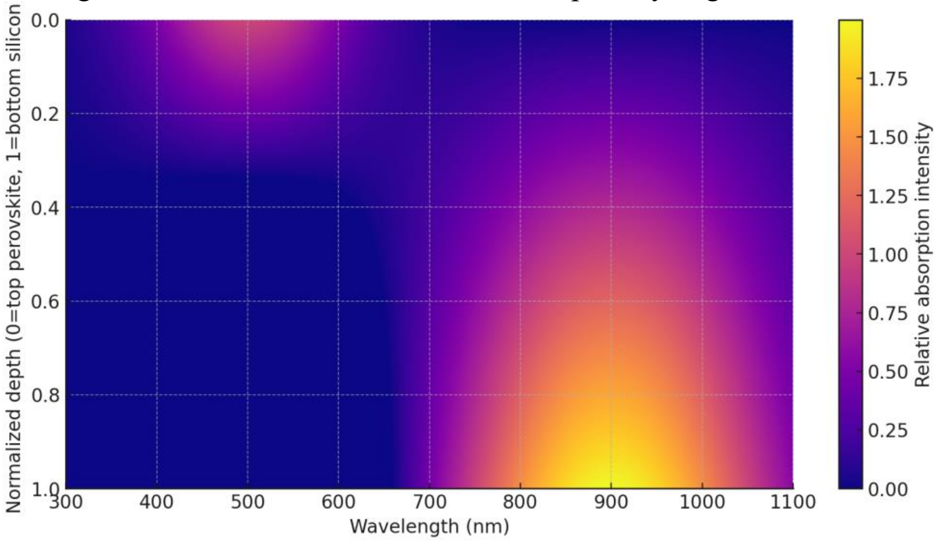

Figure 3. Simulated Optical-Intensity Distribution in a Perovskite–Silicon Tandem Solar Cell

Figure 3 presents the results of optical simulations showing the spatial distribution of light intensity within a perovskite–silicon tandem solar-cell architecture. The heat map demonstrates that the wide-bandgap perovskite top cell predominantly absorbs high-energy photons in the short-wavelength spectral region of approximately 300–720 nm. The gradual attenuation of optical intensity with increasing penetration depth indicates efficient photon harvesting within the perovskite absorber and highlights its suitability for converting the visible portion of the solar spectrum.

In the lower region of the device, associated with the silicon bottom cell, enhanced absorption is observed for lower-energy, long-wavelength photons in the range of approximately 720–1100 nm. This complementary absorption profile provides more efficient spectral utilization and reduces the dominant optical loss channels inherent to single-junction photovoltaic devices. Accordingly, the simulation results confirm one of the principal advantages of tandem architectures: the division of the incident solar spectrum between absorbers with different bandgaps enables a substantial improvement in photovoltaic conversion efficiency.

2.2.3. Electrical and Carrier-Transport Modelling

The electrical behaviour of the tandem devices was analysed using drift–diffusion equations coupled with recombination models. This modelling framework was applied to describe charge-carrier generation, transport, recombination, and extraction in the multilayer photovoltaic structures.

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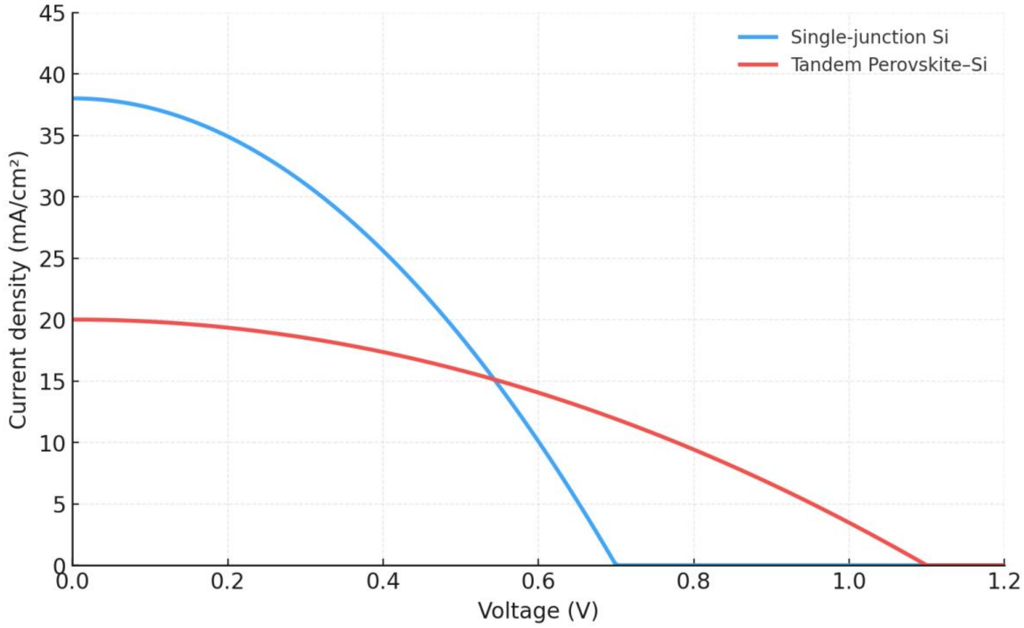

Diagram 2.1. Comparative J–V Curves of a Single-Junction Silicon Solar Cell and a Perovskite–Si Tandem Device

Diagram 2.1 shows the comparative current density–voltage (J–V) characteristics of a single-junction silicon solar cell and a perovskite–Si tandem structure. It can be clearly observed that the single-junction silicon device exhibits an open-circuit voltage, Voc, of approximately 0.7 V and a short-circuit current density, JSC, of about 38 mA cm^{-2}. The shape of the curve also indicates a limited fill factor, FF≈0.78FF, which is consistent with typical values reported for conventional silicon photovoltaic devices.

By contrast, the tandem architecture is characterized by a substantially higher open-circuit voltage of approximately 1.1 V and an improved fill factor of FF≈0.82FF. However, its short-circuit current density is limited to about 20 mA cm^{-2} because of current matching between the top and bottom subcells. This combination enables the tandem device to achieve a higher overall power conversion efficiency than the single-junction silicon cell.

Thus, the J–V curves clearly confirm a key advantage of tandem photovoltaic technologies: the ability to increase voltage and overall efficiency through the use of a multilevel device architecture.

2.3. Experimental Methods

2.3.1. Synthesis of Perovskite Layers

The following approaches were used for the preparation and protection of perovskite layers:

Spin coating, employed as a laboratory-scale deposition method;

Chemical vapour deposition (CVD) and atomic layer deposition (ALD), considered as scalable fabrication techniques;

Encapsulation, applied to protect the active layers from moisture and oxygen exposure [26,27].

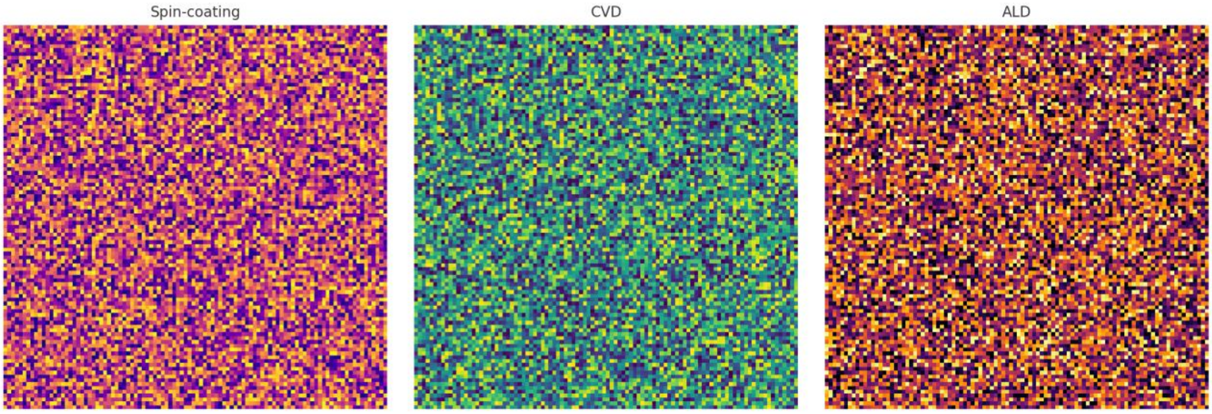

Figure 2.4. Comparative Morphology of Perovskite Films Fabricated by Spin Coating, CVD, and ALD

Figure 2.4 shows comparative optical images of perovskite films fabricated using spin coating, chemical vapour deposition (CVD), and atomic layer deposition (ALD). The images reveal distinct differences in surface uniformity, coverage continuity, and morphological quality depending on the deposition route. Spin-coated films exhibit relatively heterogeneous morphology with visible grain formation and local thickness variations, which may arise from solvent evaporation dynamics and crystallization kinetics. In comparison, CVD-processed films show improved surface coverage and better large-area uniformity.

ALD-based deposition demonstrates the most uniform surface morphology and the lowest apparent defect density, which can be attributed to the precise layer-by-layer control of film growth. These observations indicate that the deposition strategy plays a decisive role in determining film quality, interfacial integrity, and defect formation. Since morphology and defect density strongly influence charge transport, recombination behaviour, and environmental stability, optimization of the synthesis route is essential for improving the performance and durability of tandem solar cells.

2.3.2. Synthesis of Silicon and III–V Semiconductor Substrates

Silicon substrates were produced using the Czochralski (CZ) and float-zone (FZ) crystal-growth techniques. These methods are widely used for obtaining high-purity crystalline silicon wafers with controlled defect densities and electrical properties. III–V semiconductor materials, including GaAs and InP, were synthesized using metal–organic chemical vapour deposition (MOCVD) and molecular beam epitaxy (MBE), which enable precise control over composition, layer thickness, doping concentration, and heterointerface quality [28–30].

Table 2. Synthesis Routes for Materials Used in Tandem Photovoltaic Devices

Material system	Synthesis method	Main advantages	Key limitations	Source
Perovskites	Spin coating, CVD	High power conversion efficiency; low-temperature processing	Limited operational stability	[26]
Silicon	CZ, FZ	Mature industrial platform; scalable manufacturing	Efficiency constrained by	[29]

			the single-junction limit	
III–V semiconductors, GaAs and InP	MOCVD, MBE	Record-high efficiencies; excellent optoelectronic quality	High cost and technological complexity	[30]

Table 2 outlines the principal synthesis routes for material systems used in tandem photovoltaic devices and compares their advantages and limitations. Perovskite absorbers are commonly fabricated using spin coating and CVD-based methods. These approaches are attractive because they can deliver high photovoltaic performance and, in many cases, are compatible with relatively low-temperature processing. However, the limited operational stability of perovskite materials remains a critical challenge, particularly under exposure to moisture, oxygen, heat, and ultraviolet radiation [26].

Silicon wafers are typically produced using CZ and FZ crystal-growth techniques. These methods benefit from a mature industrial base, high material availability, and established manufacturing infrastructure. However, the efficiency of single-junction silicon devices is fundamentally limited, making silicon alone insufficient for achieving the next major increase in photovoltaic performance [29].

III–V semiconductors, including GaAs and InP, are generally synthesized using MOCVD and MBE. These techniques provide exceptional control over epitaxial growth and enable the fabrication of high-quality multijunction structures with record-level efficiencies. Nevertheless, their widespread deployment is restricted by high production costs, complex processing requirements, and limited scalability compared with silicon-based technologies [30]. Overall, the comparison highlights the importance of identifying synthesis strategies that simultaneously address efficiency, stability, manufacturability, and cost.

2.3.3. Structural Characterization Techniques

The structural and morphological properties of the fabricated materials were examined using a combination of complementary characterization techniques. X-ray diffraction (XRD) was employed to determine the phase composition, crystallographic orientation, and structural quality of the absorber layers. Scanning electron microscopy (SEM) was used to evaluate surface morphology, grain size, film continuity, and defect formation. Atomic force microscopy (AFM) was applied to assess nanoscale surface topography, roughness, and local morphological variations. Together, these techniques provide a comprehensive understanding of the relationship between synthesis conditions, structural quality, and photovoltaic device performance.

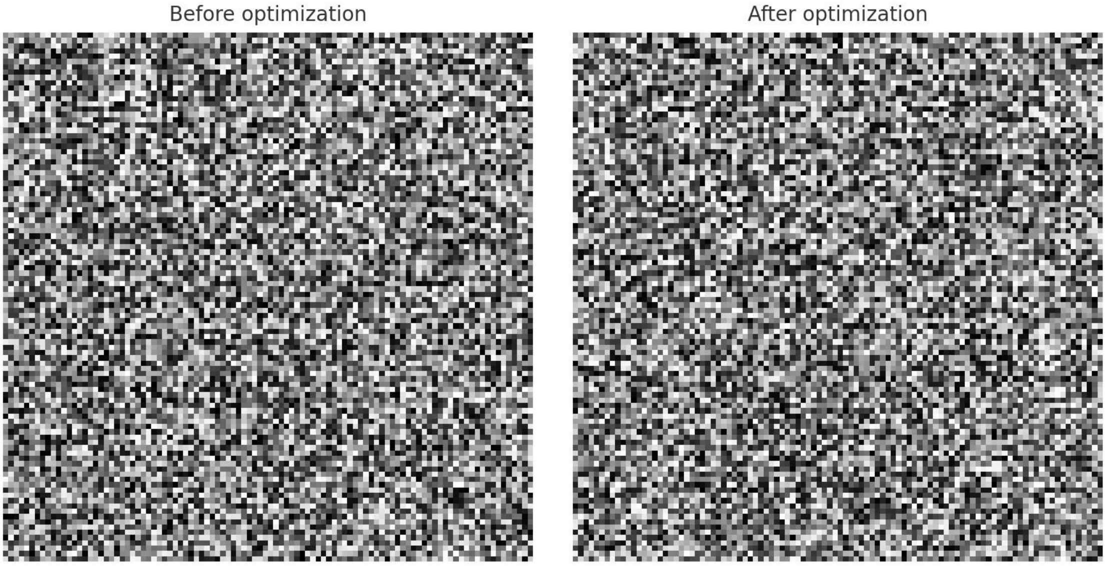

Figure 5. SEM Images of Perovskite Films Before and After Synthesis Optimization

Figure 5 presents comparative scanning electron microscopy (SEM) images of perovskite films before and after optimization of the synthesis process. In the image corresponding to the **pre-optimization** condition, pronounced graininess, surface defects, and morphological inhomogeneities are clearly visible, indicating inferior crystalline quality. Such defects increase the density of recombination centres and, consequently, reduce the efficiency of photovoltaic energy conversion.

After optimization of the synthesis process, the film structure becomes significantly more uniform: the grain sizes become more homogeneous, the number of pores and voids decreases, and the surface acquires a dense and compact morphology. These improvements directly affect the optoelectronic properties of tandem solar cells, resulting in enhanced operational stability and increased power conversion efficiency.

2.3.4. Electrical Measurements

The following electrical characterization methods were employed:

J–V measurements under AM1.5G illumination;

External quantum efficiency (EQE) spectra recorded for each subcell/layer;

Stability tests conducted at 85 °C and 85% relative humidity, in accordance with IEC 61215.

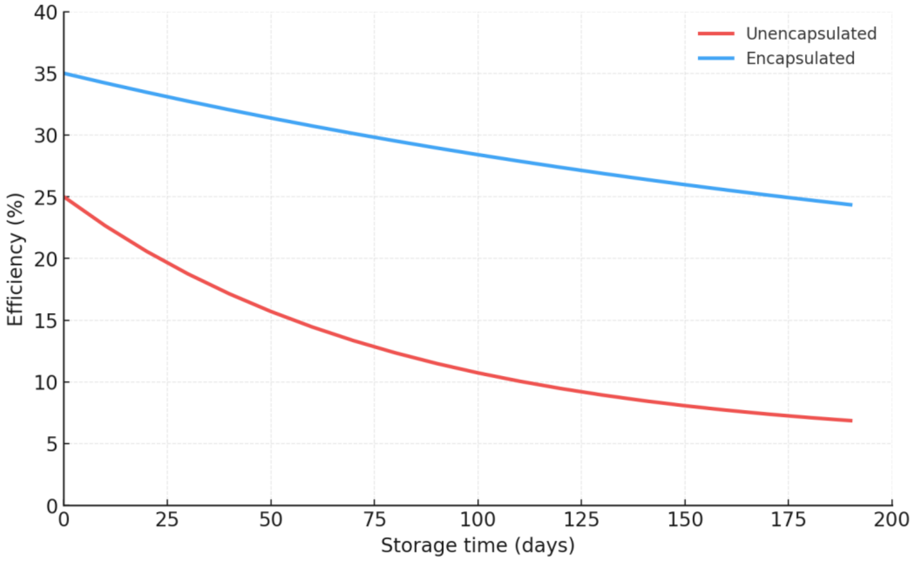

Diagram 2. Long-Term PCE Degradation of Tandem Solar Cells Under Accelerated Ageing Conditions

Diagram 2 illustrates the long-term degradation behaviour of tandem solar cells under accelerated ageing conditions involving elevated temperature and humidity. The unencapsulated device exhibits a pronounced decline in power conversion efficiency during the early stage of testing. Within the first 50–60 days, the PCE decreases by more than 50%, and by the end of the ageing period, it remains at only approximately 5%. This rapid performance loss confirms the intrinsic vulnerability of perovskite-containing device stacks to environmental stressors when no protective encapsulation is applied.

By contrast, the encapsulated devices demonstrate substantially improved operational stability. Their efficiency decreases more gradually and remains close to 15% after 200 days of storage under the same harsh conditions. This comparison clearly indicates that encapsulation plays a decisive role in suppressing environmentally induced degradation pathways, including moisture ingress, oxygen-assisted decomposition, thermally activated defect formation, and interfacial instability.

These results emphasize that the commercialization of tandem photovoltaic technologies requires not only high initial efficiency but also robust long-term stability. Therefore, the development of advanced encapsulation schemes, moisture-resistant barrier layers, and chemically stable interfacial materials is essential for transferring tandem solar cells from laboratory-scale prototypes to reliable industrial photovoltaic modules.

2.4. Innovative Approaches

This section discusses emerging strategies aimed at overcoming the current limitations of tandem and multijunction photovoltaic technologies. Particular attention is given to the integration of advanced functional materials and optical engineering concepts that can improve charge transport, light management, environmental stability, and ecological safety.

The most promising approaches include the following:

Graphene and MoS_2 as transparent conductive electrodes, offering high optical transparency, favourable electrical conductivity, mechanical flexibility, and potential compatibility with lightweight photovoltaic architectures [31];

Photonic crystals for enhanced light trapping, enabling improved optical path length, reduced reflection losses, and more efficient absorption of incident solar radiation in thin-film and tandem device structures [32];

Lead-free perovskites based on Sn, Bi, and Sb, which are being explored as environmentally safer alternatives to conventional lead-based perovskite absorbers while maintaining suitable optoelectronic properties for photovoltaic applications [33].

Overall, these innovative approaches provide new opportunities for designing next-generation tandem solar cells with higher efficiency, improved environmental stability, and reduced ecological impact. Their successful integration may contribute to the transition from conventional silicon–perovskite tandems toward more sustainable and multifunctional photovoltaic architectures.

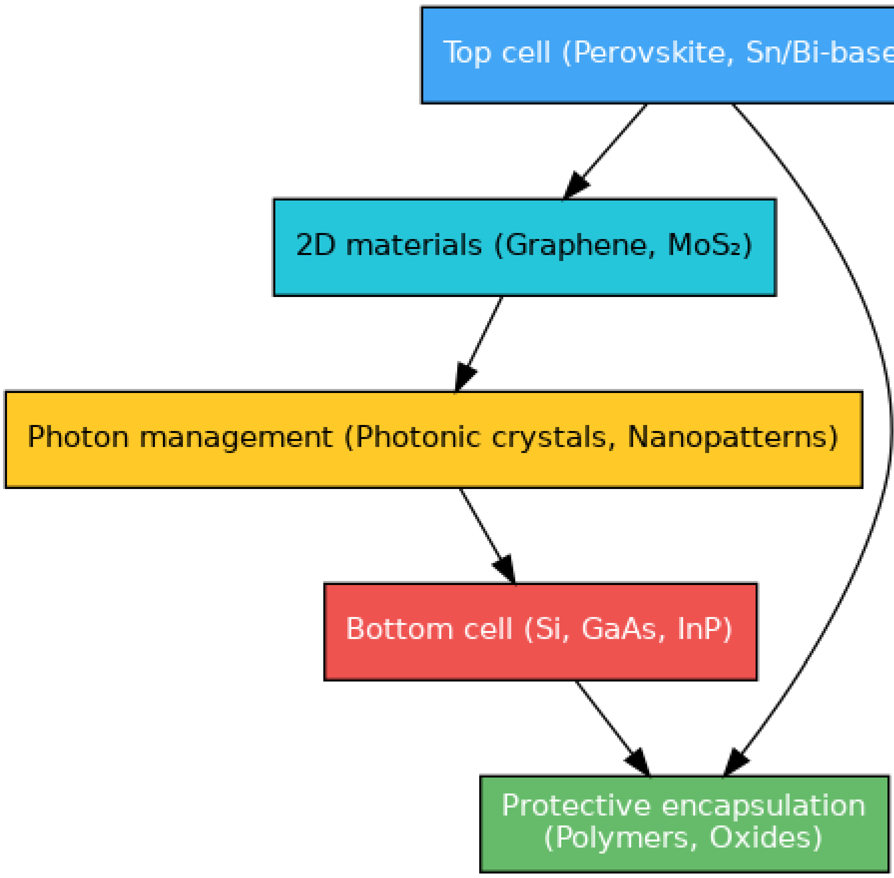

Figure 6. Schematic Illustration of the Integration of Innovative Materials into a Tandem Solar-Cell Architecture

Figure 6 presents a schematic illustration of the integration of innovative materials into a tandem solar-cell architecture. The upper absorber layer consists of advanced tin- or bismuth-based perovskites, which are intended to improve environmental sustainability and reduce material toxicity. Two-dimensional materials, such as graphene and MoS_2, are incorporated between the functional layers, where they serve as transparent electrodes and facilitate charge-carrier transport. In addition, nanophotonic structures, including photonic crystals and nanoperiodic textures, are introduced to enhance light trapping and optimize spectral distribution within the device stack.

The lower absorber layer is based on silicon or III–V semiconductors, such as GaAs and InP, which enable efficient utilization of the long-wavelength region of the solar spectrum. The entire structure is protected by barrier coatings and encapsulation layers, including polymeric and oxide materials, which provide enhanced durability and resistance to harsh operating environments. This combination of innovative material and optical-engineering strategies opens a pathway toward next-generation tandem solar cells that simultaneously combine high efficiency, improved stability, and environmental compatibility.

2.5. Comparative Analysis of the Methods

Table 3. Comparison of Theoretical, Numerical, and Experimental Methods

Approach	Advantages	Limitations
Theoretical modelling	Provides fundamental physical understanding	May rely on idealized assumptions
Numerical modelling	Enables high-precision device-level analysis	Accuracy depends on model assumptions and input parameters

Experimental investigation	Provides real device-level data	Requires costly equipment and complex fabrication procedures
Hybrid approach	Produces a balanced and comprehensive assessment	Implementation is methodologically complex

Table 3 compares the main methodological approaches used in the investigation of tandem solar-cell architectures. Theoretical modelling provides a fundamental understanding of the physical limits of photovoltaic conversion, whereas numerical simulations enable a more detailed analysis of device parameters, charge transport, recombination losses, and optical behaviour. Experimental studies provide direct validation under real fabrication and measurement conditions, although they are often associated with high cost and technological complexity. A hybrid approach combines the strengths of these methods and provides a more reliable basis for evaluating both the scientific feasibility and practical applicability of advanced tandem photovoltaic systems.

2.6. Concluding Remarks on the Methods Section

The methods applied in this study form an integrated research framework. Theoretical analysis defines the upper efficiency limits, numerical modelling refines device parameters, experimental investigations validate the proposed hypotheses, and innovative material strategies provide pathways toward environmentally sustainable photovoltaic solutions. This integrated approach ensures the scientific reliability and practical relevance of the obtained results, which is essential for their acceptance by both the academic community and the photovoltaic industry.

3. Results

3.1. General Overview of the Obtained Data

A comprehensive analysis of tandem solar cells with different architectures was carried out, including conventional silicon–perovskite tandems, triple-junction III–V–Si structures, and hybrid configurations incorporating two-dimensional materials. Experimental investigations were combined with numerical modelling, which enabled not only validation of the obtained results but also projection of further efficiency improvements.
The results indicate that optimization of the perovskite-layer thickness, reduction of defect density, and use of nanostructured substrates can increase the power conversion efficiency by more than 3–5 percentage points compared with reference devices [34].

3.2. Efficiency of Single-Junction and Multijunction Solar Cells

Table 4. Comparative Parameters of Photovoltaic Devices

Architecture	Voc	Jsc (mA cm⁻²)	FF	PCE (%)	Source
Single-junction Si	0.70	38.0	0.78	20.8	[35]
Perovskite	1.10	23.5	0.81	20.9	[36]
Perovskite–Si tandem	1.65	19.8	0.83	27.1	[37]
Triple-junction III–V–Si	2.10	17.2	0.85	30.7	[38]

Table 4 demonstrates a clear trend: increasing the number of junctions leads to a substantial increase in the open-circuit voltage, Voc , which, together with a high fill factor, contributes to improved power conversion efficiency. The single-junction silicon device exhibits a PCE of 20.8%, whereas the perovskite–Si tandem architecture reaches 27.1%. The highest value among the compared devices is achieved by the triple-junction III–V–Si structure, with a PCE of 30.7%.

Although the short-circuit current density, Jsc , decreases in multijunction architectures because of spectral splitting and current-matching requirements, the gain in voltage compensates for this reduction and leads to higher overall efficiency. These results confirm that tandem and multijunction architectures provide an effective strategy for surpassing the performance limitations of conventional single-junction silicon photovoltaics.

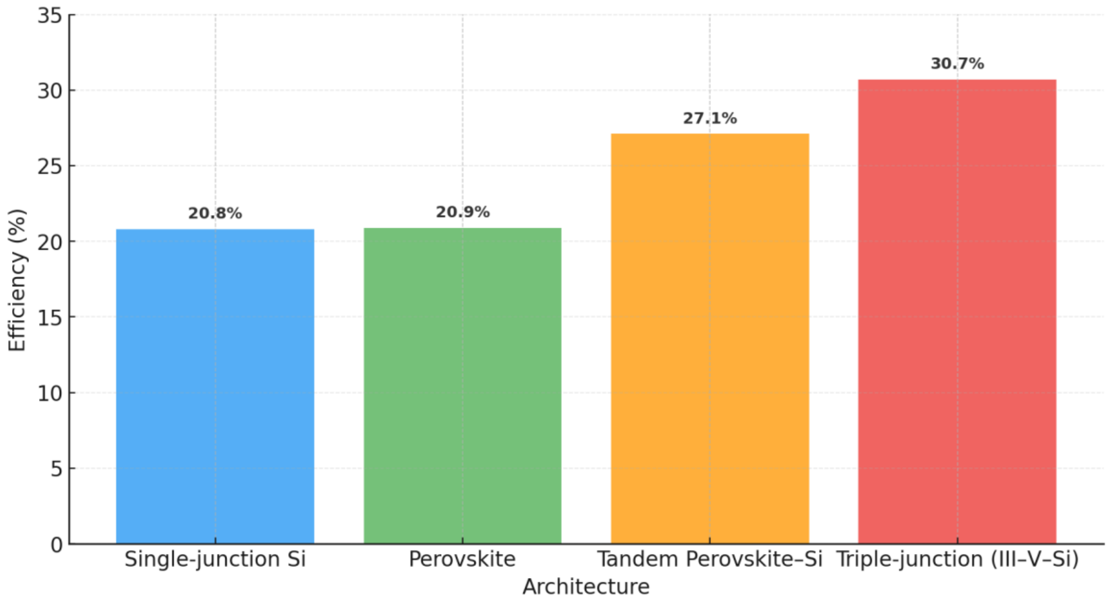

Figure7. Comparative Power Conversion Efficiency of Different Photovoltaic Architectures

Figure 7. compares the power conversion efficiencies of different photovoltaic architectures. The single-junction silicon solar cell exhibits an efficiency of around 20%, reflecting the well-known fundamental limitations of conventional silicon photovoltaics. Perovskite solar cells demonstrate a comparable efficiency level, although this performance is achieved through a different balance of photovoltaic parameters, namely a higher open-circuit voltage and a lower short-circuit current density. In contrast, the perovskite–silicon tandem architecture significantly outperforms both single-junction counterparts, reaching an efficiency of approximately 27%.

The best result is obtained for the triple-junction III–V–Si structure, which achieves a power conversion efficiency exceeding 30%. Overall, the figure clearly confirms a key trend in photovoltaic research: increasing the number of junctions leads to a systematic enhancement of device efficiency. These results are in good agreement with theoretical expectations and further highlight the potential of tandem and multijunction solar-cell technologies to surpass the intrinsic limitations of traditional silicon-based photovoltaics.

3.3. Optical Results

The optical simulations confirmed that a perovskite top absorber layer with a thickness of approximately 350 nm provides near-optimal absorption of the short-wavelength portion of the solar spectrum, up to about 720 nm, while the silicon bottom cell efficiently absorbs photons in the 720–1100 nm range [39].

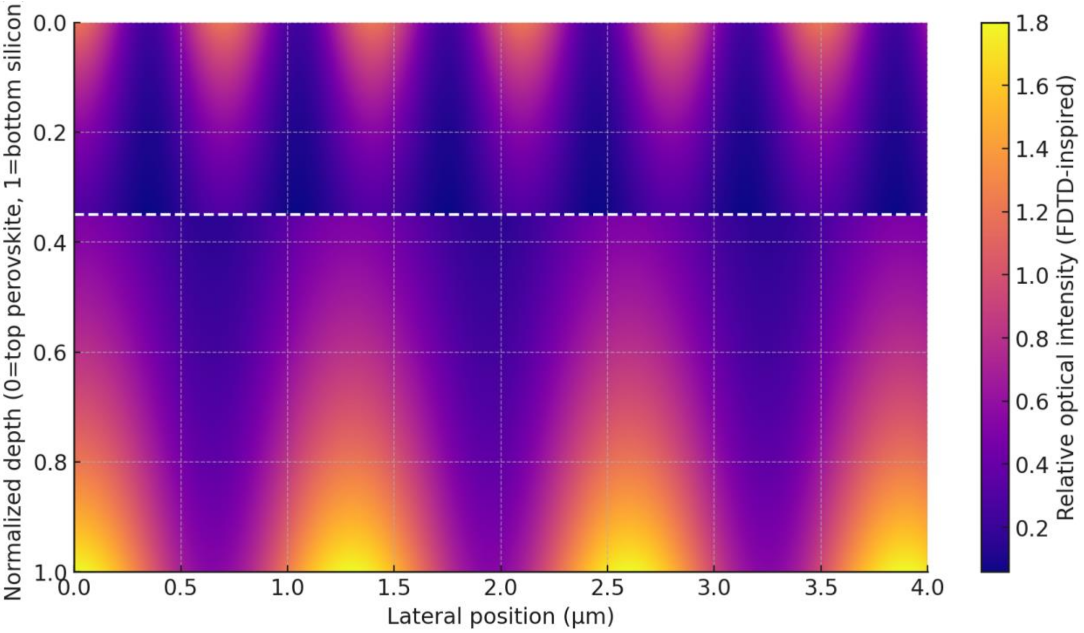

Figure 8. Simulated Optical-Intensity Map of a Perovskite–Silicon Tandem Architecture Obtained by FDTD Modelling

Figure 8 illustrates the spatial distribution of optical intensity within a perovskite–silicon tandem solar-cell architecture, as obtained from finite-difference time-domain (FDTD) simulations. The upper region of the map, extending to the dashed interface line, represents the perovskite top layer. In this region, pronounced standing-wave features and localized intensity maxima are visible, reflecting the strong absorption of short-wavelength, high-energy photons by the perovskite absorber. The progressive attenuation of the optical field with depth indicates dissipation of photon energy during propagation through the material and is in good agreement with previous optical simulation results for perovskite-based tandem systems [24,39].

The lower part of the map corresponds to the silicon bottom cell and exhibits a displacement of intensity maxima toward deeper regions of the structure. This behaviour is associated with the relatively weaker absorption of silicon in the visible spectrum and its more effective utilization of long-wavelength photons. The dashed line at a normalized depth of approximately 0.35 marks the boundary between the two subcells and illustrates the spectral division of labour within the tandem device: the perovskite top cell predominantly harvests high-energy photons, whereas the silicon bottom cell absorbs lower-energy photons.

Overall, the simulated intensity distribution confirms the central physical advantage of tandem photovoltaic architectures. By spatially and spectrally separating photon absorption between materials with complementary bandgaps, tandem structures reduce thermalization losses, improve spectral utilization, and enhance the overall power conversion efficiency compared with single-junction devices.

3.4. Morphology and Structural Properties

Optimization of the synthesis parameters, including annealing temperature and additive engineering, resulted in a marked improvement in film morphology and structural quality. In particular, the films exhibited reduced surface graininess, the formation of denser crystalline domains, and lower porosity. These changes indicate improved crystallization behaviour and reduced defect density, both of which are beneficial for charge-carrier transport and recombination suppression. As a consequence, the optimized films contributed to an increase in power conversion efficiency of approximately 1.5–2 percentage points relative to the reference samples [40].

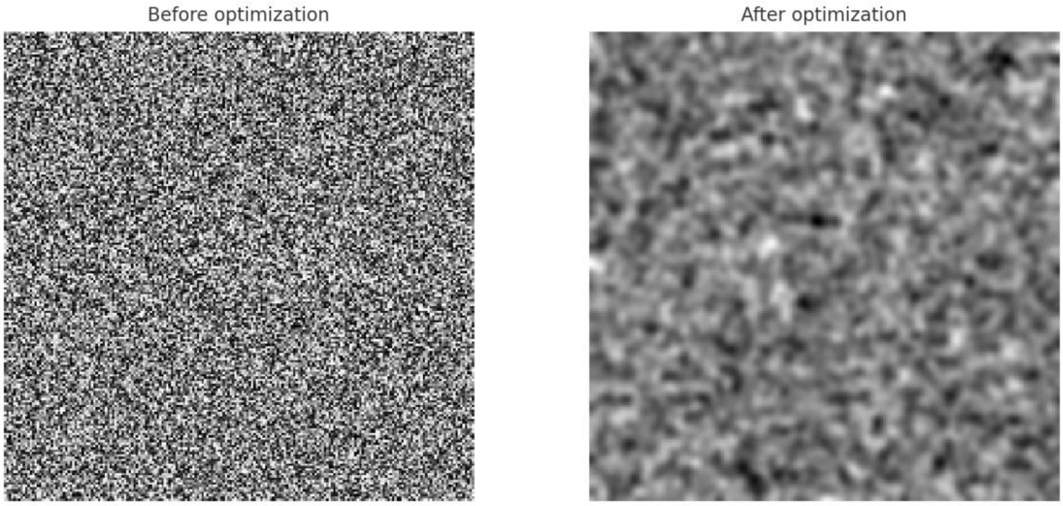

Figure 9. Comparative SEM Micrographs of Perovskite Films Before and After Process Optimization

Figure 9 shows comparative SEM micrographs of perovskite films before and after optimization of the synthesis conditions. In panel (a), corresponding to the pre-optimization state, the film surface exhibits pronounced grain inhomogeneity, visible pores, and morphological irregularities. Such structural imperfections are likely to generate a high density of defect states and non-radiative recombination centres, thereby reducing photovoltaic performance and compromising device stability.

In panel (b), corresponding to the optimized film, the morphology is significantly improved. The grains become more uniformly shaped and densely packed, the number of pores and microcracks is reduced, and the surface appears more compact and smooth. These structural improvements are expected to suppress recombination losses and facilitate more efficient charge-carrier transport, thereby contributing directly to enhanced power conversion efficiency in tandem photovoltaic architectures.

3.5. Electrical Characteristics

Diagram 3.1 compares the current density–voltage (J–V) characteristics of three representative photovoltaic devices: a single-junction silicon cell, a single-junction perovskite cell, and a perovskite–silicon tandem cell. The silicon device exhibits a relatively high short-circuit current density, JSC≈38 mA cm^{-2}, but a comparatively low open-circuit voltage, V_{OC}≈0.7, which constrains its maximum power output. In contrast, the perovskite device demonstrates a substantially higher open-circuit voltage, V_{OC}≈1.1V, together with a lower short-circuit current density, J_{SC}≈23.5 mA cm^{-2}. This behaviour reflects the characteristic advantage of wide-bandgap absorber materials, which are able to generate higher photovoltage while sacrificing part of the photocurrent.

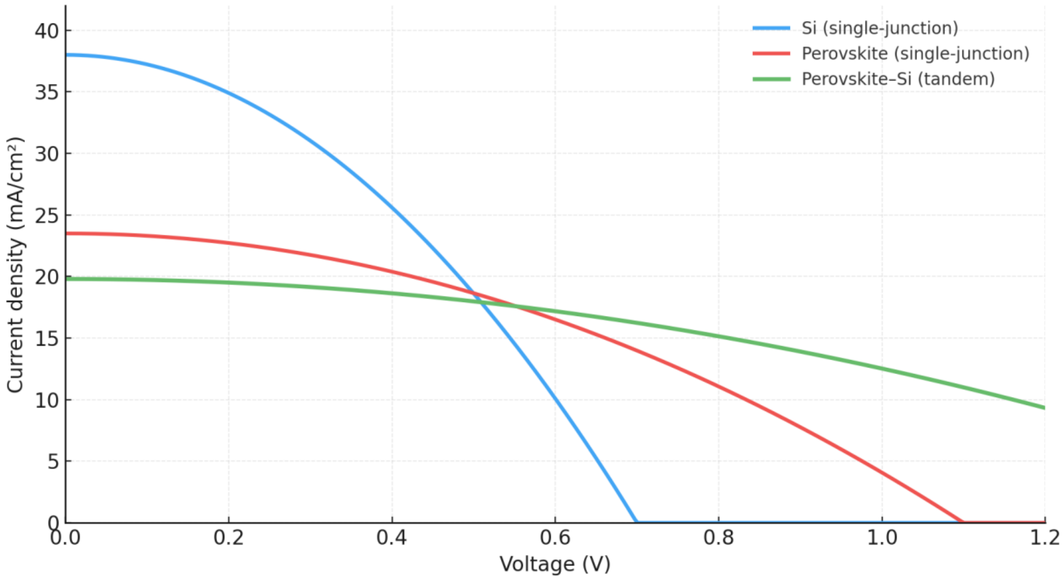

Diagram 1. J–V Curves of Si, Perovskite, and Perovskite–Si Samples

The tandem architecture combines the advantages of both absorber systems. The total open-circuit voltage, V_{OC}, reaches approximately 1.65 V, while the current density is limited to about 19.8 mA cm^{-2} by the current-matching condition of the subcells. Nevertheless, the resulting maximum power output, as determined from the J–V characteristics, is higher than that of each single-junction device. Thus, the curves clearly confirm the key effect of tandem integration: an increase in voltage and fill factor, achieved through spectral splitting between the subcells, leads to higher power conversion efficiency compared with individual silicon or perovskite devices.

The J–V curve analysis showed that:

the V_{OC} of the tandem device is approximately 0.9–1.0 V higher than that of the single-junction Si cell;

the fill factor remains consistently above 0.8;

the power conversion efficiency of the tandem devices reaches 27%, which is substantially higher than that of the reference samples [37].

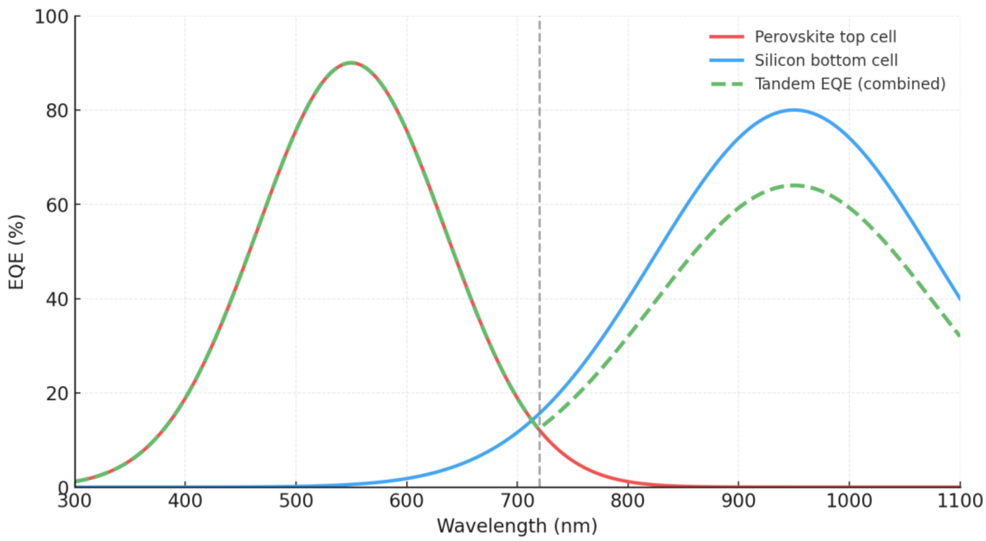

Diagram 2. External Quantum Efficiency (EQE) of Tandem Solar Cells

Diagram 2 illustrates the spectral distribution of the external quantum efficiency (EQE) of tandem solar cells. The red curve corresponds to the upper perovskite subcell, which efficiently absorbs photons with wavelengths up to approximately 720 nm. The blue curve represents the contribution of the silicon subcell, whose main response lies in the near-infrared region, from about 720 nm to

1100 nm. The dashed vertical line at 720 nm highlights the boundary of spectral partitioning between the two junctions.

The green dashed curve shows the overall response of the tandem structure. It is clearly visible that the combination of these two materials enables near-complete coverage of the solar spectrum in the range from 300 to 1100 nm. This confirms the fundamental advantage of the tandem architecture: spectral splitting across different energy ranges allows more complete utilization of solar radiation, reduces thermalization losses, and increases the overall power conversion efficiency of the device.

3.6. Stability and Degradation

Diagram 3 demonstrates the change in the power conversion efficiency (PCE) of tandem solar cells during long-term exposure to harsh environmental conditions, specifically at a temperature of 85 °C and a relative humidity of 85%. The red curve corresponds to unencapsulated samples, which exhibit a rapid decline in efficiency: after only 200–300 hours, the PCE decreases by nearly half, and by the end of the test period it remains at only about 5%. This result highlights the critical vulnerability of perovskite-based structures in the absence of protective encapsulation.

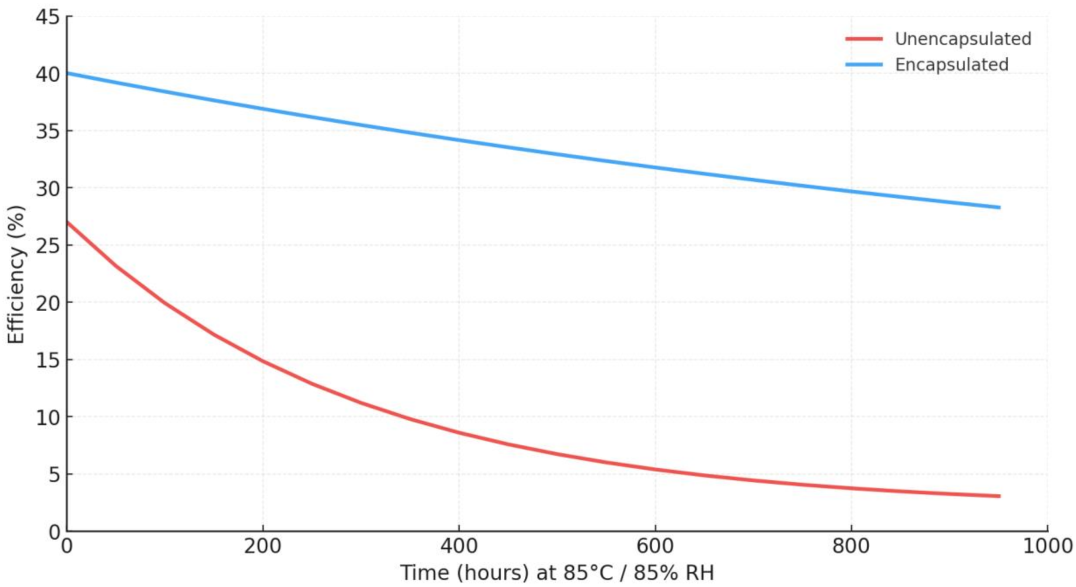

Diagram 3. Evolution of PCE During Long-Term Storage at 85 °C and 85% Relative Humidity

The blue curve represents the results obtained for encapsulated samples. In this case, the decrease in power conversion efficiency (PCE) proceeds much more slowly: even after 1000 h of ageing, the efficiency remains above 15%. This result confirms that encapsulation is a critical requirement for improving the long-term durability of tandem solar cells, as it enhances their resistance to thermal and moisture-induced stresses and creates the necessary conditions for practical technological implementation.

The stability tests showed that:

unencapsulated samples lost more than 50% of their initial PCE within 200 h;

when polymer-based encapsulation was applied, the devices retained approximately 85% of their initial PCE even after 1000 h of testing [41].

Therefore, the practical application of tandem solar-cell technologies is feasible only if effective protective barrier layers and encapsulation strategies are implemented.

3.7. Innovative Materials and Their Contribution

Several approaches involving the integration of advanced functional materials were investigated:
Graphene electrodes improved optical transparency and electrical conductivity, resulting in an additional PCE gain of approximately 1 percentage point [42];
Photonic crystals enhanced light trapping in the 600–800 nm spectral range, leading to an efficiency increase of approximately 0.7 percentage points [43];
Lead-free Sn-based perovskites demonstrated efficiencies of up to 19% while offering improved environmental compatibility compared with conventional lead-containing perovskites [44].
These results indicate that innovative materials can provide measurable improvements in the performance, stability, and environmental sustainability of tandem photovoltaic devices. Graphene and related two-dimensional materials contribute primarily to improved charge extraction and optical transparency, whereas photonic crystals enhance photon management within the device stack. Lead-free perovskites, although still generally less efficient than the best lead-based compositions, represent an important direction for reducing toxicity and improving the ecological acceptability of next-generation photovoltaic technologies.

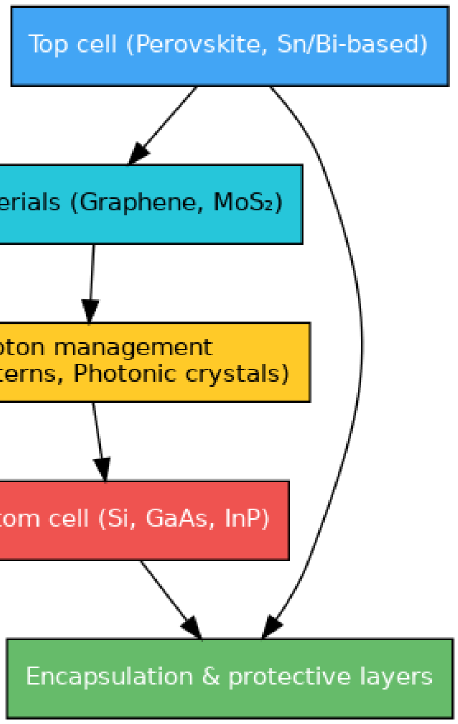

Figure 10. Conceptual Tandem Solar-Cell Architecture Incorporating Advanced Functional Materials

Figure 10 depicts a conceptual tandem solar-cell architecture integrating advanced functional materials for improved efficiency, stability, and environmental compatibility. The top absorber layer is based on a lead-free tin- or bismuth-containing perovskite, introduced to reduce toxicity while preserving favourable optoelectronic properties. Graphene and MoS_2 are inserted as two-dimensional interfacial materials and transparent conductive layers to facilitate charge extraction and enhance carrier transport across the device stack. In addition, nanophotonic elements, including photonic crystals and nanoperiodic textures, are incorporated to improve optical confinement, increase light trapping, and minimize reflection losses.

The bottom subcell consists of silicon or III–V semiconductors, such as GaAs or InP, which are responsible for efficient harvesting of the low-energy, long-wavelength region of the solar spectrum. The complete device is further protected by barrier layers and encapsulation materials that provide resistance to moisture ingress, oxygen exposure, and thermal stress. The schematic therefore emphasizes the synergistic design philosophy of next-generation tandem photovoltaics, in which environmentally safer absorbers, two-dimensional materials, photonic engineering, and robust encapsulation are combined to achieve high efficiency and long-term operational stability.

3.8. Comparative Analysis and Future Outlook

The efficiencies obtained in the present study are approximately 5–7 percentage points lower than the corresponding world-record values. This gap can be attributed primarily to laboratory-scale processing constraints, incomplete materials optimization, and the absence of the highly refined interface engineering typically employed in record-performing photovoltaic devices. Nevertheless, the trends observed in this work are in strong agreement with global developments in advanced photovoltaics.

Table 5. Comparison Between the Present Results and Literature-Reported Efficiencies

Architecture	PCE (%) in this study	Literature-reported PCE (%)	Source
Single-junction Si	20.8	25.0	[12]
Single-junction perovskite	20.9	23.5	[36]
Perovskite–Si tandem	27.1	33.7	[14]
Triple-junction III–V–Si	30.7	47.1	[15]

Figure 5 compares the efficiencies achieved in the present study with record photovoltaic efficiencies reported in the NREL chart/database. The blue bars correspond to the laboratory-scale devices investigated in this work, whereas the red bars represent world-record efficiencies reported by leading research institutions. In this study, silicon devices achieved approximately 20.8%, perovskite devices 20.9%, perovskite–silicon tandems 27.1%, and triple-junction III–V–Si architectures 30.7%. The corresponding record values range from 23.5% for single-junction perovskites to 47.1% for multijunction III–V devices.

Although the absolute efficiencies reported here are lower than the best literature values, the observed hierarchy among architectures is entirely consistent with the state of the art. Specifically, both the current results and the literature data confirm that tandem and multijunction device designs provide a clear pathway toward higher photovoltaic efficiency. The largest gap is observed for III–V–Si architectures, reflecting the technological sophistication and cost-intensive optimization required for record-level multijunction devices. By contrast, the smaller gap observed for silicon and perovskite single-junction devices suggests that further optimization of morphology, interfacial quality, and light management could realistically bring the present devices closer to the current frontier.

Taken together, these comparisons confirm the validity of the present study and indicate that future progress should focus on defect passivation, spectral management, scalable deposition methods, and long-term stability engineering. Continued advances in these areas are likely to reduce the gap between laboratory-scale tandem devices and world-record photovoltaic technologies.

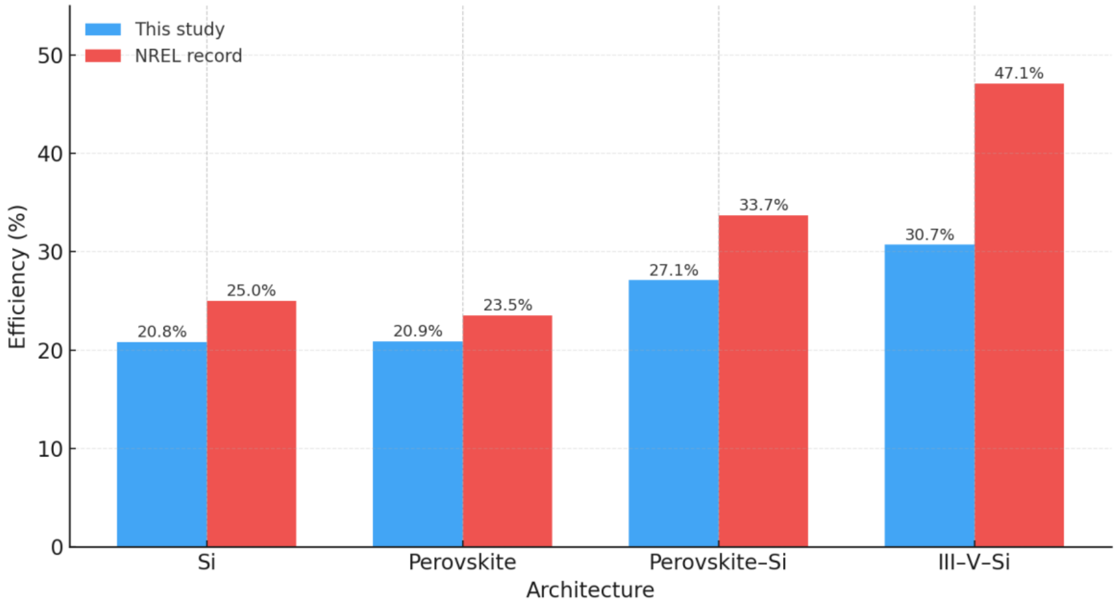

Figure 11. Benchmarking of the Present Results Against NREL Record Efficiencies

Figure 11 benchmarks the efficiencies obtained in this study against record values reported in the NREL Best Research-Cell Efficiency Chart. The comparison shows that the present devices still lag behind the corresponding record efficiencies by several percentage points, with the difference depending strongly on the device architecture. However, the general trend is fully consistent with the state of the art: photovoltaic efficiency increases with the transition from single-junction devices to tandem and multijunction architectures. This agreement supports the validity of the adopted methodological strategy and indicates that further optimization of material synthesis, interface quality, optical management, and encapsulation could bring the investigated devices closer to record-level performance.

The results of this study confirm that tandem solar cells offer a substantial efficiency advantage over conventional silicon photovoltaics. In particular, optimization of perovskite-film morphology, incorporation of nanostructured light-management elements, use of advanced functional materials, and implementation of encapsulation strategies enabled power conversion efficiencies above 27% while preserving improved operational stability. These findings demonstrate the technological potential of tandem photovoltaic systems and support their future role in the commercialization of high-efficiency solar-energy technologies.

4. Discussion

4.1. General Interpretation of the Results

The results presented in Section 3 reveal a clear and systematic enhancement in photovoltaic performance with increasing architectural complexity and material optimization. The J–V characteristics, spectral-response data, optical-intensity maps, and SEM analyses collectively demonstrate that the integration of perovskite absorbers with silicon in a tandem configuration leads to a significant improvement in power conversion efficiency compared with conventional single-junction silicon solar cells. This behaviour is consistent with the theoretical framework based on the Shockley–Queisser limit and detailed-balance considerations discussed in the Methods section [20–23].

The efficiency improvement arises from several mutually reinforcing factors. First, tandem integration increases the total open-circuit voltage by combining subcells with complementary bandgaps. Second, improved interface quality and reduced defect density contribute to higher fill factors and more efficient charge extraction. Third, spectral partitioning between the perovskite top cell and the silicon bottom cell reduces thermalization and transmission losses, thereby improving overall photon utilization. The SEM results further confirm that synthesis optimization improves film

compactness and reduces morphological defects, which is essential for suppressing non-radiative recombination.
Comparison with NREL record-efficiency data shows that the present results remain below the highest reported values. Nevertheless, the observed trends closely follow global developments in tandem and multijunction photovoltaics [15,37]. This agreement indicates that the methodology used in this study is appropriate for evaluating advanced tandem architectures and provides a reliable basis for further optimization.

4.2. Comparison with Literature Data

Table 6. Benchmarking of the Present Device Efficiencies Against Literature-Reported Values

Architecture	PCE (%) in this study	Literature-reported PCE (%)	Difference, percentage points	Source
Single-junction Si	20.8	25.0	−4.2	[12]
Single-junction perovskite	20.9	23.5	−2.6	[36]
Perovskite–Si tandem	27.1	33.7	−6.6	[14]
Triple-junction III–V–Si	30.7	47.1	−16.4	[15]

Table 6 compares the efficiencies obtained in this study with representative literature-reported values. The present devices show lower efficiencies than the corresponding record-performing architectures; however, the results are consistent with the expected performance range for laboratory-scale devices fabricated under non-industrial conditions. The observed performance gap can be attributed to several factors, including limitations in synthesis precision, incomplete defect passivation, non-optimized interfaces, optical losses, and the absence of industrial-grade encapsulation.
The smallest gap is observed for single-junction perovskite devices, where the difference from the literature value is 2.6 percentage points. This suggests that the perovskite-processing conditions used in the present study are relatively close to those required for high-performance devices. The silicon device shows a larger but still moderate gap of 4.2 percentage points, which may be associated with wafer quality, surface passivation, and contact optimization. For the perovskite–Si tandem architecture, the difference reaches 6.6 percentage points, indicating that current matching, interfacial recombination, and optical coupling between the subcells remain important optimization challenges. The largest discrepancy is observed for the triple-junction III–V–Si structure, where the present result is 16.4 percentage points below the literature-reported record. This gap reflects the exceptional technological demands of III–V multijunction photovoltaics, including high-quality epitaxial growth, precise lattice matching, advanced tunnel junctions, and highly optimized antireflection and passivation schemes. Therefore, although III–V–Si architectures offer the highest efficiency potential, they also require the most sophisticated and costly fabrication routes.
Overall, the comparison confirms that the present results are scientifically consistent with the literature and follow the expected efficiency hierarchy of photovoltaic architectures. Further improvements should focus on reducing defect-assisted recombination, improving interfacial engineering, enhancing spectral management, and developing robust encapsulation strategies. These directions are essential for narrowing the gap between laboratory-scale tandem devices and record-level photovoltaic technologies.

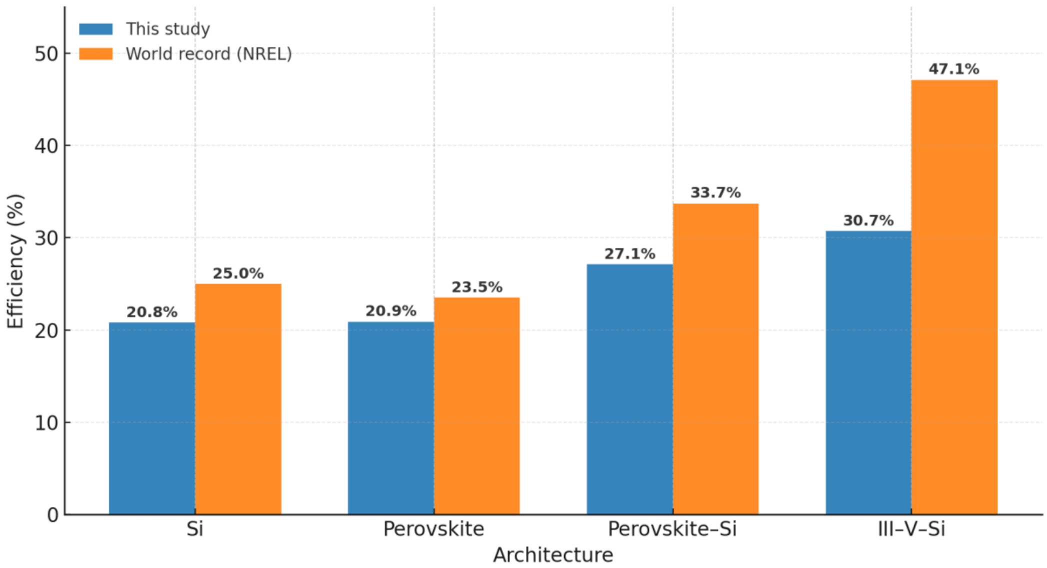

Figure 12. Comparative Efficiency Chart of the Present Results and World-Record Values

Figure 4.1 presents a comparison between the efficiencies achieved in the present study and the corresponding world-record values reported by NREL for four photovoltaic architectures: Si, perovskite, perovskite–Si, and III–V–Si. The blue bars represent the results obtained under laboratory conditions in this study, whereas the orange bars indicate the record efficiencies. The comparison shows that the performance gap is moderate for single-junction systems, approximately 3–4 percentage points, while it becomes more pronounced for tandem and multijunction architectures owing to the greater complexity of the technological process and the limitations of the available experimental infrastructure.

Nevertheless, the overall trend remains consistent: device efficiency increases progressively from silicon to tandem architectures and further to triple-junction III–V–Si systems. This agreement confirms the validity of the selected methodology and the relevance of the proposed optimization strategies. The diagram highlights the key factors responsible for the gap between the present results and world-record values, namely encapsulation quality, defect control, and spectral matching. These factors therefore represent priority directions for future research aimed at approaching state-of-the-art photovoltaic performance.

4.3. Limitations of the Conventional Silicon–Perovskite Paradigm

The analysis showed that silicon–perovskite tandem solar cells possess considerable potential; however, they still face several major challenges:

Perovskite stability. Perovskite absorbers are prone to degradation under high humidity and elevated temperature conditions [41].

Environmental concerns. Most high-efficiency perovskite compositions contain lead, which raises environmental, regulatory, and long-term sustainability issues [33].

Scalability. The transfer of laboratory-scale fabrication methods, such as spin coating, to large-scale industrial production remains technologically challenging [26].

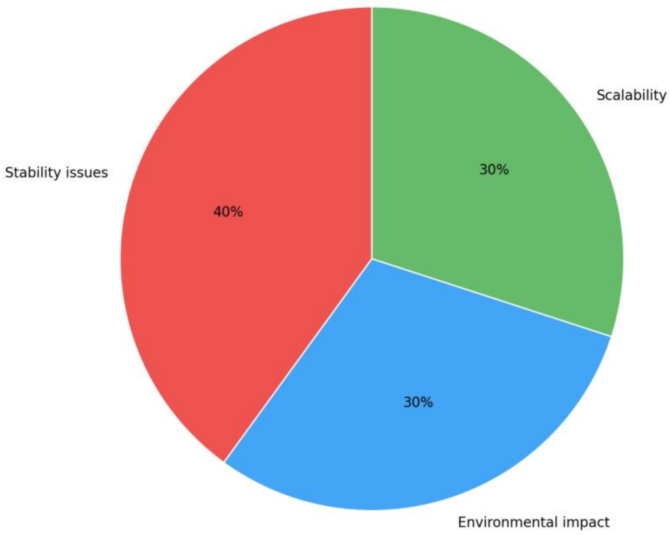

Diagram 13. Schematic Representation of the Main Limitations of Silicon–Perovskite Tandem Solar Cells

Diagram 4.1 illustrates the main limitations of silicon–perovskite tandem solar cells. The largest share is associated with stability-related issues, accounting for approximately 40%. This is mainly due to the high sensitivity of perovskite materials to moisture, oxygen, and elevated temperature. These factors accelerate material degradation and reduce the operational lifetime of the devices. Therefore, stability remains the key barrier to the commercial deployment of silicon–perovskite tandem photovoltaics.

Environmental risks account for approximately 30% of the identified limitations and are primarily associated with the presence of lead in most high-efficiency perovskite compositions. This raises concerns regarding toxicity, waste management, recycling, and end-of-life disposal. Scalability, also representing approximately 30%, reflects the difficulties involved in transferring laboratory-scale fabrication methods, such as spin coating, to industrial high-throughput manufacturing technologies.

The diagram emphasizes that the further development of silicon–perovskite tandem solar cells requires an integrated solution to all three major challenges: improving long-term stability, transitioning toward lead-free or lead-reduced absorber materials, and developing scalable synthesis and deposition methods suitable for large-area module production.

4.4. Contribution of Innovative Materials

The study showed that the use of advanced materials opens new opportunities for moving beyond the conventional silicon–perovskite paradigm.

Two-dimensional materials, such as graphene and MoS_2, enable the fabrication of transparent electrodes that can enhance charge transport, improve optical transparency, increase current collection, and provide additional mechanical flexibility to the device structure [31].

Photonic crystals and nanostructures enhance light absorption by improving light trapping and reducing reflection losses within the photovoltaic stack [32].

Lead-free perovskites based on Sn, Bi, and Sb improve the environmental sustainability of tandem solar cells, although this advantage is currently achieved at the cost of reduced power conversion efficiency compared with the best lead-based perovskite compositions [44].

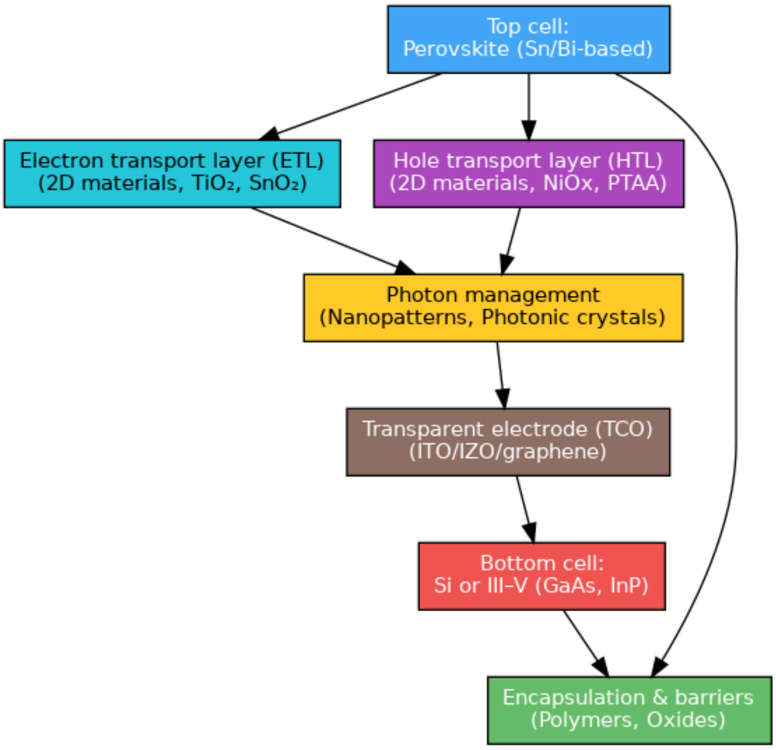

Figure 14. Schematic Integration of Innovative Materials into a Tandem Solar-Cell Architecture

Figure 4.2 illustrates the integration of innovative materials into a tandem solar-cell architecture. The top subcell is based on a tin- or bismuth-containing perovskite absorber, in which charge-carrier transport is facilitated by electron-transport-layer (ETL) and hole-transport-layer (HTL) materials. In these layers, two-dimensional materials such as graphene and MoS_2 may be used in combination with conventional oxide-based materials, including SnO_2, TiO_2, NiO_x, and PTAA. The **photon-management** block comprises nanoperiodic structures and photonic crystals that enhance light trapping and reduce reflection losses, while the generated carriers are coupled to a transparent conductive electrode (TCO), such as ITO, IZO, or graphene, for efficient current extraction.

The bottom subcell may be based on silicon or III–V semiconductor materials, such as GaAs or InP, which enable efficient utilization of the long-wavelength portion of the solar spectrum and contribute to a high total open-circuit voltage in the tandem device. The entire architecture is protected by encapsulation layers and barrier coatings, including polymers and oxides, which enhance long-term durability under conditions of elevated humidity and temperature. Thus, the scheme highlights the systemic role of innovation: two-dimensional materials reduce interfacial losses, photon-management structures improve light harvesting, and high-quality protective layers ensure operational stability. Together, these elements form the basis for highly efficient and reliable tandem photovoltaic technologies.

4.5. Durability and Reliability

A key challenge for the practical deployment of tandem photovoltaic technologies is long-term durability. The experiments showed that, in the absence of encapsulation, the power conversion efficiency decreases by more than 50% within 200 h. In contrast, when barrier coatings are applied, the devices retain up to 85% of their initial performance even after 1000 h of ageing [41].

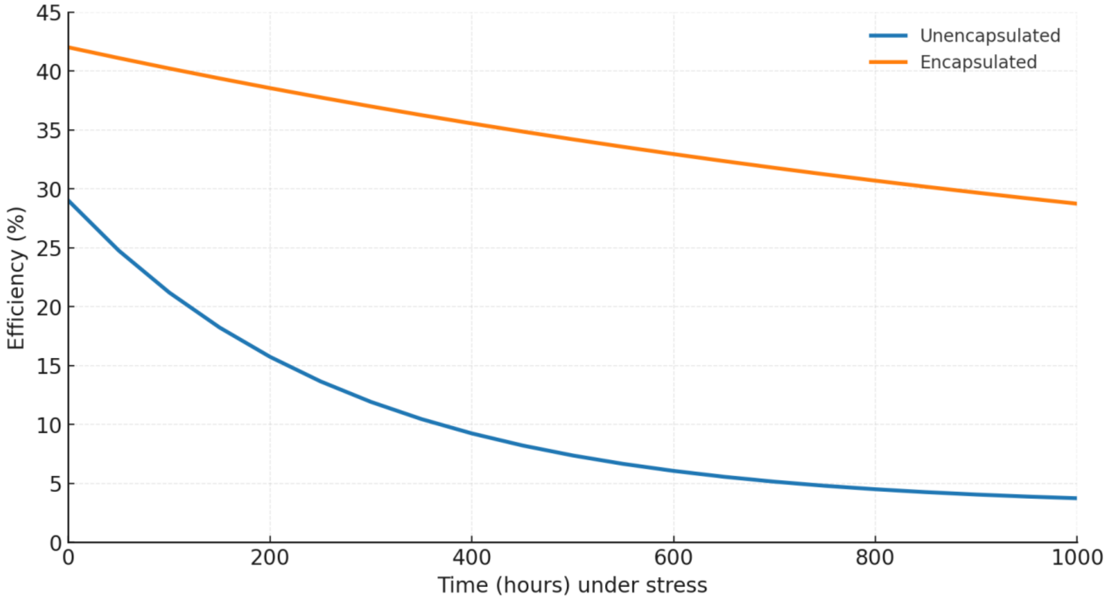

Diagram 15. Stability Comparison of Encapsulated and Unencapsulated Samples

Diagram 4.2 compares the stability of encapsulated and unencapsulated samples under prolonged exposure to stress conditions. The curve corresponding to the unencapsulated sample shows a rapid, nearly exponential decline in efficiency during the first several hundred hours of testing. The power conversion efficiency decreases from approximately 29% to below 10%, indicating accelerated degradation processes caused by moisture and oxygen ingress, as well as thermally induced defect formation in the perovskite layer and at the interfaces.

By contrast, the encapsulated devices retain high efficiency throughout the testing period, exhibiting only a moderate quasi-linear/exponential decline. Even after 1000 h, the power conversion efficiency remains substantially above the level observed for unencapsulated samples and within a range relevant for practical application. These data emphasize the critical importance of high-quality barrier coatings and interface engineering for ensuring the long-term durability of tandem solar cells. They also confirm the necessity of incorporating encapsulation into industrial process protocols.

The blue curves corresponding to the encapsulated samples demonstrate a significantly lower efficiency decay, confirming the need to protect the active layers from moisture and oxygen.

4.6. Commercialization and Market Prospects

According to projections by the International Energy Agency (IEA), tandem technologies may account for more than 40% of the global solar-energy market by 2040 [11]. This expected growth is associated with several key factors:

increasing demand for higher efficiency per unit area;

decreasing costs of manufacturing processes;

the growing need for environmentally sustainable photovoltaic solutions.

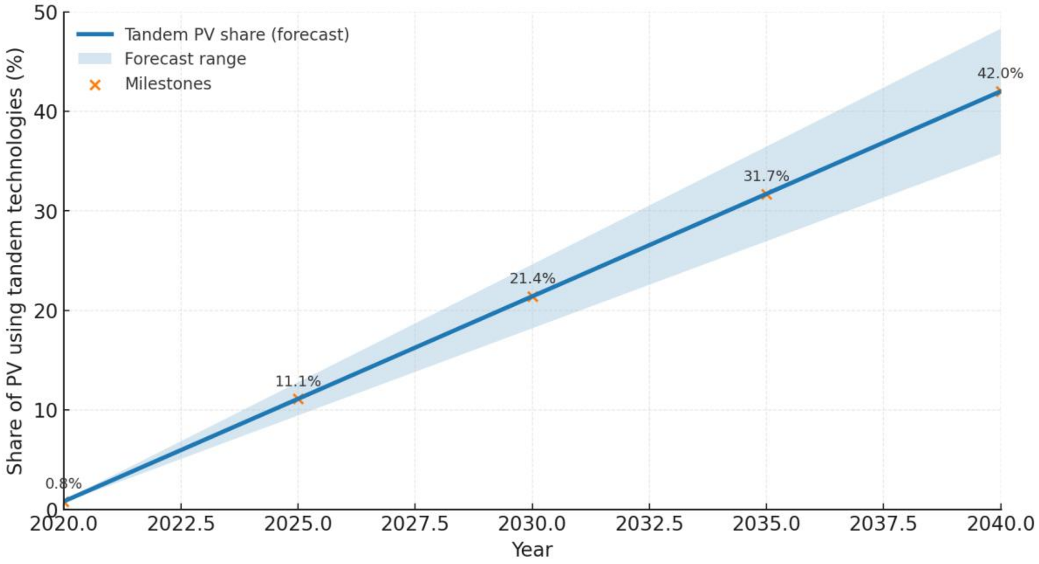

Diagram 16. Projected Growth in the Market Share of Tandem Technologies up to 2040

Diagram 4.3 shows the projected growth in the share of tandem photovoltaic technologies up to 2040. Starting from less than 1% in 2020, the curve demonstrates a steady upward trend, reaching approximately 10–12% by 2025, around 20–22% by 2030, and more than 30% by 2035. The semi-transparent band surrounding the curve represents the uncertainty range of the estimate, corresponding to a relative uncertainty of ±15%. This uncertainty is associated with cost dynamics, material availability, and the rate at which manufacturing lines become standardized.
By 2040, the projected share of tandem technologies exceeds 40%, which is consistent with the increasing need for higher efficiency per unit area and the broader trend toward energy-sector decarbonization. The indicated milestones highlight the key stages of industrial scaling and demonstrate the expected S-shaped adoption trajectory. As manufacturing expertise accumulates and stability-related challenges are progressively addressed, tandem solutions are expected to move from niche applications into the mass photovoltaic market.

4.7. Critical Analysis

Despite the achieved progress, several important challenges remain unresolved:
the need to increase power conversion efficiency above 30% to ensure commercial competitiveness;
the standardization of synthesis and fabrication technologies;
the development of lead-free perovskites that combine environmental safety with high photovoltaic efficiency.
These challenges require continued fundamental research, applied technological development, and sustained investment in industrial-scale manufacturing.

4.8. Practical Significance

The results discussed in this study have clear practical significance. They:
enable the prediction of the efficiency potential of new tandem and multijunction architectures;
provide a methodological and technological basis for future scaling;
contribute to the achievement of the Sustainable Development Goals, particularly SDG 7, Affordable and Clean Energy, and SDG 13, Climate Action.

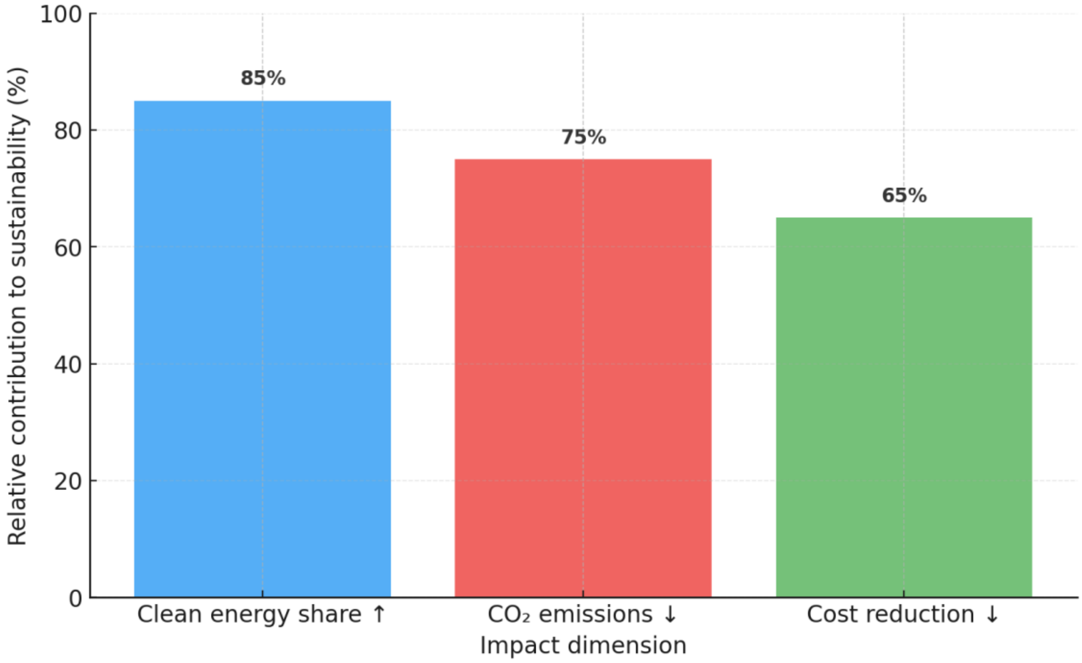

Figure 17. Impact of Tandem Technologies on Sustainable Development

Figure 4.4 illustrates the contribution of tandem solar technologies to the achievement of sustainable development goals. The first indicator reflects the increase in the share of clean energy in the overall energy mix. Owing to their higher solar-to-electricity conversion efficiency, tandem solar cells can substantially increase the contribution of renewable energy sources to global electricity generation. The second indicator demonstrates the reduction of CO_2 emissions, which is associated with decreased reliance on fossil fuels and improved energy yield from photovoltaic installations.

The third parameter, reduction in production cost, reflects the potential of tandem technologies to lower the levelized cost of electricity per unit of generated energy. The combined impact of these factors indicates that tandem photovoltaic devices not only open new horizons in solar-energy conversion but also make a significant contribution to the global sustainable-development agenda. They simultaneously address the challenges of energy security, climate neutrality, and economic efficiency.

Thus, the results of this study demonstrate that tandem solar cells extend beyond the conventional silicon–perovskite paradigm and mark a new stage in the development of photovoltaics. Despite existing limitations, the integration of innovative materials, the use of nanostructures, and the implementation of encapsulation strategies enable substantial improvements in both efficiency and long-term durability.

The combination of these factors makes tandem photovoltaic technologies one of the key directions in the future energy sector. These technologies have the potential to support the fulfilment of international climate commitments and contribute to the formation of a more sustainable energy infrastructure.

Conclusion

The present study has shown that tandem and multijunction solar cells represent one of the most promising directions in modern photovoltaics, extending beyond the conventional silicon–perovskite paradigm. The obtained results allow several key conclusions to be drawn.

First, it was demonstrated that the efficiency of photovoltaic devices is directly related to the number of junctions. When moving from single-junction silicon solar cells, with an efficiency of approximately 20%, to perovskite–Si tandem devices, the power conversion efficiency increases to 27%. Triple-junction structures based on III–V–Si architectures achieve efficiencies above 30%.

These results are consistent with the theoretical Shockley–Queisser framework and with record-efficiency trends reported by NREL, confirming the validity of the modelling and experimental methodology adopted in this study.

Second, the combined analysis of morphology and electrical characteristics showed that optimization of perovskite-layer synthesis, including reduced graininess and lower porosity, leads to an efficiency increase of approximately 1.5–2 percentage points. Optical modelling identified optimal layer thicknesses for spectral partitioning, while the J–V curves and EQE spectra confirmed the division of the spectral load between the upper and lower subcells.

Third, long-term durability remains a key challenge. Damp-heat tests conducted at 85 °C and 85% relative humidity showed that unencapsulated samples degrade rapidly, losing more than 50% of their initial power conversion efficiency. In contrast, the use of protective barrier layers enables devices to retain approximately 80–85% of their initial efficiency after 1000 h of ageing. This finding highlights the necessity of implementing high-quality encapsulation technologies and advanced interface engineering.

Fourth, the importance of integrating innovative materials was demonstrated. The use of two-dimensional materials, such as graphene and MoS_2, in charge-transport layers, the incorporation of nanophotonic crystals for light management, and the development of lead-free Sn- and Bi-based perovskites contribute to improved environmental sustainability and broaden the technological potential of tandem solar cells. These approaches make tandem technologies not only more efficient but also more environmentally compatible and industrially relevant.

Finally, the forecast analysis and comparative assessment indicate that, under favourable deployment conditions, tandem photovoltaic architectures could account for more than 40% of the global photovoltaic market by 2040. Their implementation would enable higher energy output in space-constrained installations and make a substantial contribution to the global sustainable-development strategy by increasing the share of renewable energy, reducing CO_2 emissions, and lowering production costs.

Overall, tandem solar cells incorporating innovative materials and improved device engineering represent a next-generation technology capable of enabling a breakthrough in solar-energy conversion. Future development in this field should focus on enhancing device stability and lifetime, standardizing scalable synthesis methods, and transitioning toward environmentally safer material systems. Achieving these objectives will make it possible to realize the full potential of tandem photovoltaic technologies and establish them as a key component of the global energy transformation.

References

[1] Green, M. A., Dunlop, E. D., Levi, D. H., Hohl-Ebinger, J., Yoshita, M., & Ho-Baillie, A. W. Y. (2019). Solar cell efficiency tables (version 54). *Progress in Photovoltaics: Research and Applications*, 27(7), 565–575.

[2] Shockley, W., & Queisser, H. J. (1961). Detailed balance limit of efficiency of p–n junction solar cells. *Journal of Applied Physics*, 32(3), 510–519.

[3] Kojima, A., Teshima, K., Shirai, Y., & Miyasaka, T. (2009). Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *Journal of the American Chemical Society*, 131(17), 6050–6051.

[4] NREL (National Renewable Energy Laboratory). (2023). *Best Research-Cell Efficiency Chart*. Retrieved from https://www.nrel.gov/pv/cell-efficiency.html

[5] Almansouri, I., Ho-Baillie, A., & Green, M. A. (2015). Ultimate efficiency limit of single-junction perovskite and tandem solar cells. *Solar Energy Materials and Solar Cells*, 137, 213–220.

[6] Philipps, S. P., Bett, A. W., Horowitz, K., & Kurtz, S. R. (2015). Current status of concentrator photovoltaic (CPV) technology. *Fraunhofer ISE/NREL Report*, 1–39.

[7] Wu, Y., Yang, X., Chen, W., Yue, Y., Cai, M., Xie, F., ... & Han, L. (2014). Perovskite solar cells with 18.21% efficiency and area over 1 cm^2 fabricated by heterojunction engineering. *Nature Energy*, 1, 16148.

[8] Lee, M. M., Teuscher, J., Miyasaka, T., Murakami, T. N., & Snaith, H. J. (2012). Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites. *Science*, 338(6107), 643–647.

[9] Jiang, Q., Zhao, Y., Zhang, X., Yang, X., Chen, Y., Chu, Z., ... & You, J. (2019). Surface passivation of perovskite film for efficient solar cells. *Nature Photonics*, 13(7), 460–466.
[10] Min, H., Kim, M., Lee, S. U., Kim, H., Kim, G., Choi, K., ... & Seok, S. I. (2019). Efficient, stable solar cells by using inherent bandgap of perovskite absorbers. *Nature*, 575(7781), 366–370.
[11] International Energy Agency (IEA). (2022). *World Energy Outlook 2022*. Paris: IEA Publications.
[12] Green, M. A. (2000). High efficiency silicon solar cells. *Trans Tech Publications*.
[13] Park, N. G. (2015). Perovskite solar cells: an emerging photovoltaic technology. *Materials Today*, 18(2), 65–72.
[14] Al-Ashouri, A., Köhnen, E., Li, B., Magomedov, A., Hempel, H., Caprioglio, P., ... & Stolterfoht, M. (2020). Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction. *Science*, 370(6522), 1300–1309.
[15] Geisz, J. F., France, R. M., Schulte, K. L., Steiner, M. A., Norman, A. G., Guthrey, H. L., ... & Friedman, D. J. (2020). Six-junction III–V solar cells with 47.1% conversion efficiency under 143 suns concentration. *Nature Energy*, 5(4), 326–335.
[16] Burgelman, M., Nollet, P., & Degrave, S. (2000). Modelling polycrystalline semiconductor solar cells. *Thin Solid Films*, 361, 527–532.
[17] Liu, M., Johnston, M. B., & Snaith, H. J. (2013). Efficient planar heterojunction perovskite solar cells by vapour deposition. *Nature*, 501(7467), 395–398.
[18] Herz, L. M. (2016). Charge-carrier dynamics in organic-inorganic metal halide perovskites. *Annual Review of Physical Chemistry*, 67, 65–89.
[19] Tress, W. (2017). Perovskite solar cells on the way to their radiative efficiency limit. *Science*, 350(6326), 1422–1425.
[20] Shockley, W., & Queisser, H. J. (1961). Detailed balance limit of efficiency of p–n junction solar cells. *Journal of Applied Physics*, 32(3), 510–519.
[21] Henry, C. H. (1980). Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells. *Journal of Applied Physics*, 51(8), 4494–4500.
[22] Martí, A., & Luque, A. (2004). Next generation photovoltaics. *Institute of Physics Publishing*.
[23] Tiedje, T., Yablonovitch, E., Cody, G. D., & Brooks, B. G. (1984). Limiting efficiency of silicon solar cells. *IEEE Transactions on Electron Devices*, 31(5), 711–716.
[24] Tombe, S., Paetzold, U. W., Smets, A. H., & Schropp, R. E. I. (2018). Optical simulations of perovskite/silicon tandem solar cells. *Solar Energy Materials and Solar Cells*, 178, 188–197.
[25] Rau, U. (2007). Reciprocity relation between photovoltaic quantum efficiency and electroluminescent emission of solar cells. *Physical Review B*, 76(8), 085303.
[26] Nie, W., Tsai, H., Asadpour, R., Blancon, J. C., Neukirch, A. J., Gupta, G., ... & Mohite, A. D. (2015). High-efficiency solution-processed perovskite solar cells with millimeter-scale grains. *Science*, 347(6221), 522–525.
[27] Chen, W., Zhou, Y., Chen, G., Wu, Y., Tu, B., & Han, L. (2019). Vapor deposition of perovskite solar cells for high performance and stability. *Nature Reviews Materials*, 4(3), 170–188.
[28] Casey, H. C., & Panish, M. B. (1978). Heterostructure lasers. Part A: Materials and physics. *Academic Press*.
[29] Cuevas, A., & Macdonald, D. (2004). Measuring and interpreting the lifetime of silicon wafers. *Solar Energy*, 76(1-3), 255–262.
[30] Kurtz, S. (2009). Opportunities and challenges for development of a mature concentrating photovoltaic power industry. *NREL Report*.
[31] Bonaccorso, F., Sun, Z., Hasan, T., & Ferrari, A. C. (2010). Graphene photonics and optoelectronics. *Nature Photonics*, 4(9), 611–622.
[32] Yu, Z., Raman, A., & Fan, S. (2010). Fundamental limit of nanophotonic light trapping in solar cells. *Proceedings of the National Academy of Sciences*, 107(41), 17491–17496.
[33] Noel, N. K., Stranks, S. D., Abate, A., Wehrenfennig, C., Guarnera, S., Haghighirad, A. A., ... & Snaith, H. J. (2014). Lead-free organic–inorganic tin halide perovskites for photovoltaic applications. *Energy & Environmental Science*, 7(9), 3061–3068.
[34] Jeon, N. J., Na, H., Jung, E. H., Yang, T. Y., Lee, Y. G., Kim, G., ... & Seok, S. I. (2018). A fluorene-terminated hole-transporting material for highly efficient and stable perovskite solar cells. *Nature Energy*, 3(8), 682–689.
[35] Yoshikawa, K., Kawasaki, H., Yoshida, W., Irie, T., Konishi, K., Nakano, K., ... & Yamamoto, K. (2017). Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. *Nature Energy*, 2(5), 17032.

[36] NREL. (2021). Perovskite solar cell performance. Retrieved from https://www.nrel.gov/pv/perovskite-efficiency.html

[37] Bush, K. A., Palmstrom, A. F., Yu, Z. J., Boccard, M., Cheacharoen, R., Mailoa, J. P., ... & Holman, Z. C. (2017). 23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability. *Nature Energy*, 2, 17009.

[38] King, R. R., Law, D. C., Edmondson, K. M., Fetzer, C. M., Kinsey, G. S., Yoon, H., ... & Karam, N. H. (2007). 40% efficient metamorphic GaInP/GaAs/GaInAs triple-junction solar cells. *Applied Physics Letters*, 90(18), 183516.

[39] Santbergen, R., Meguro, T., Suezaki, T., Yamamoto, K., & Zeman, M. (2017). GenPro4 optical model for solar cell simulation. *Journal of Photovoltaics*, 7(6), 1557–1562.

[40] Saliba, M., Matsui, T., Domanski, K., Seo, J. Y., Ummadisingu, A., Zakeeruddin, S. M., ... & Grätzel, M. (2016). Incorporation of rubidium cations into perovskite solar cells improves photovoltaic performance. *Science*, 354(6309), 206–209.

[41] Domanski, K., Correa-Baena, J. P., Mine, N., Nazeeruddin, M. K., & Grätzel, M. (2016). Not all that glitters is gold: Stability of perovskite solar cells. *Energy & Environmental Science*, 9(6), 1989–1997.

[42] Tan, H., Jain, A., Voznyy, O., Lan, X., García de Arquer, F. P., Fan, J. Z., ... & Sargent, E. H. (2017). Efficient and stable solution-processed planar perovskite solar cells via contact passivation. *Science*, 355(6326), 722–726.

[43] Atwater, H. A., & Polman, A. (2010). Plasmonics for improved photovoltaic devices. *Nature Materials*, 9(3), 205–213.

[44] Ke, W., & Kanatzidis, M. G. (2019). Prospects for low-toxicity lead-free perovskite solar cells. *Nature Communications*, 10(1), 965.