INTERNATIONAL JOURNAL OF RENEWABLE, GREEN, AND SUSTAINABLE ENERGY (IJRGSE)

eISSN: 3087-4300

Volume. 03, Issue. 04, pp. 01-11, April 2026"

Advanced Tandem and Thin-Film Photovoltaic Architectures: An Integrative Research Study on Efficiency Limits, Numerical Optimization, Stability, and Cost Competitiveness in Perovskite, GeSe, CIGS, and Silicon Solar Cells

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Article received: 05/02/2026, Article Accepted: 23/03/2026, Article Published: 07/04/2026

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ABSTRACT

This article develops a publication-ready integrative research study based strictly on the supplied references and examines the evolving technological, theoretical, numerical, and techno-economic landscape of next-generation solar cells, with particular emphasis on perovskite photovoltaics, tandem solar architectures, GeSe thin-film devices, CIGS-associated heterostructures, and the continuing benchmark role of crystalline silicon. The reviewed literature indicates that the contemporary photovoltaic field is no longer defined only by incremental material improvements within isolated single-junction platforms. Instead, it is increasingly shaped by the interaction between theoretical efficiency limits, absorber-layer engineering, interface control, defect management, tandem integration, stability enhancement, and cost-performance trade-offs (Al-Harbi & Kais, 2015; Andreani et al., 2019; Hadi et al., 2016; Zhang et al., 2023). Perovskite solar cells occupy a central place within this transition because they combine exceptional optoelectronic tunability with compatibility for tandem configurations and numerical design optimization, yet they remain constrained by long-term operational stability and commercialization uncertainty (Guo & Min, 2017; Zhao, 2022; Baumann et al., 2024; Zhu et al., 2023). In parallel, GeSe and CIGS-related thin-film systems continue to provide valuable pathways for absorber diversification, defect-tolerant performance, and tandem integration possibilities (Xue et al., 2017; Liu et al., 2017; Liu et al., 2020; Al-Hattab et al., 2021).

Using a qualitative integrative methodology, this study synthesizes foundational theory, simulation-based device research, materials-oriented investigations, and cost-oriented analyses. Four major findings emerge. First, the literature consistently shows that efficiency improvement is increasingly being pursued through tandem and multi-junction strategies rather than through single-junction refinement alone (Hadi et al., 2016; Liu, Junbo, & Xudong, 2023; Singh et al., 2023). Second, SCAPS-based numerical simulation has become a critical tool for absorber, transport-layer, defect, and interface optimization across multiple material systems (Atourki et al., 2016; Sharma et al., 2023; Ompong & Clements, 2024). Third, stability has emerged as the decisive bottleneck separating laboratory excellence from real-world deployment in perovskite-containing devices (Baumann et al., 2024; Zhu et al., 2023). Fourth, cost competitiveness remains unresolved: perovskites may outperform crystalline silicon in some future scenarios, but only if manufacturability, durability, and module-level reliability converge with their strong device-level performance potential (Woodhouse et al., 2019; Liu et al., 2025). The article concludes that the future of solar cell research will depend on integrating theoretical limits, practical material engineering, reliable device architectures, and lifecycle-aware economic analysis into a unified photovoltaic design paradigm.

Keywords: Perovskite solar cells, tandem photovoltaics, GeSe thin films, SCAPS-1D, photovoltaic stability, solar cell efficiency, cost competitiveness.

INTRODUCTION

Photovoltaic science has entered a phase in which the principal challenge is no longer simply whether sunlight can be converted into electricity efficiently, but how increasingly sophisticated solar cell architectures can be made simultaneously efficient, stable, manufacturable, and economically viable over time. The references supplied for this article show that the field has evolved from a largely single-technology conversation dominated by crystalline silicon into a far more diverse and strategically layered research landscape. In this landscape, perovskite absorbers, GeSe thin films, CIGS-based heterostructures, and tandem or multi-junction systems are being investigated not as isolated alternatives, but as components of a broader search for photovoltaic architectures capable of overcoming the physical and commercial limitations of earlier generations (Andreani et al., 2019; Al-Harbi & Kais, 2015; Liu et al., 2020; Zhang et al., 2023).

At the foundation of this transformation lies the issue of efficiency. The long history of photovoltaic development has always been shaped by the tension between thermodynamic possibility and material reality. Andreani et al. (2019) frame silicon solar cells as moving toward their efficiency limits, which signals a mature technology approaching asymptotic gains rather than radical leaps. Al-Harbi and Kais (2015) examine the theoretical limits of photovoltaic efficiency and discuss possible improvements through broader conceptual approaches, including analogies learned from photosynthesis and quantum coherence. Hadi et al. (2016) extend this discussion to the theoretical efficiency limit for a two-terminal multi-junction step-cell using detailed balance methods, indicating that next-generation gains are increasingly expected from structural complexity rather than from single-junction optimization alone. The significance of these works is that they position photovoltaic research as a field driven as much by theoretical architecture as by incremental material refinement.

This theoretical context is essential for understanding the rise of perovskite solar cells. The perovskite literature in the supplied references consistently emphasizes both opportunity and constraint. Guo and Min (2017) discuss progress in preparation processes and stability, thereby highlighting the dual character of perovskites: promising performance but persistent fragility. Zhao (2022), Xu (2021), and Wang (2019) each investigate optimized design or device performance through dissertation-level work focused on perovskite materials and related tandem configurations, suggesting that the field has matured enough to support deep structural and simulation-oriented research. Sharma et al. (2023), Ouslimane et al. (2021), Ompong and Clements (2024), Katubi et al. (2024), and Chabri et al. (2023) all rely on numerical investigation, especially SCAPS-based simulation, to optimize perovskite absorber layers, transport layers, thicknesses, defect densities, and overall device configurations. The cumulative message is that perovskites are not merely interesting because they are efficient; they are interesting because they are tunable. That tunability allows them to function as a platform for exploring structural optimization at a depth that older photovoltaic systems often did not permit so flexibly.

At the same time, the literature makes it clear that efficiency without stability is insufficient. Baumann et al. (2024) present one of the strongest indications of this by focusing on the stability and reliability of perovskite-containing solar cells and modules, including degradation mechanisms and mitigation strategies. Zhu et al. (2023) reinforce this concern by addressing long-term operating stability in perovskite photovoltaics. These studies reveal an increasingly recognized truth in the field: perovskites may be among the most exciting materials in modern photovoltaics, but their practical future depends on whether they can sustain performance under prolonged operational stress. This challenge transforms the meaning of progress. A device with extremely high modeled or laboratory efficiency may still fail to matter commercially if environmental exposure, interfacial degradation, ion migration, or thermal instability rapidly undermine its output.

This concern has driven increasing interest in tandem architectures. The tandem concept is attractive because it allows multiple absorbers with complementary bandgaps to capture broader segments of the solar spectrum. Zhang et al. (2023) highlight research progress toward perovskite/crystalline silicon tandem solar cell technology with efficiency greater than 30, suggesting that tandem systems are already central to the field’s highest aspirations. Liu, Junbo, and Xudong (2023) discuss four-terminal perovskite/CIGS tandem solar cells, while Singh et al. (2023) and Singh, V. K., et al. (2023) theoretically investigate tandem systems involving MAPbI3-on-CuInSe2 and Sb2S3-on-Si, respectively. Cui (2023) explores tandem perovskite solar cells under concentrated light conditions, while Wang (2019) examines tandem configuration with CIGS. The range of these studies shows that tandem photovoltaics are not a niche subtopic. They are becoming one of the most important strategic routes for escaping the efficiency ceilings of conventional single-junction devices.

Parallel to the perovskite and tandem literature is a substantial set of studies on GeSe thin-film solar cells. These references are particularly valuable because they broaden the discussion beyond perovskite optimism and silicon benchmarking. Xue et al. (2017) demonstrate GeSe thin-film solar cells fabricated by rapid thermal sublimation, indicating that GeSe is a serious photovoltaic absorber rather than a speculative candidate. Liu et al. (2017) investigate the physical and electronic properties of GeSe for photovoltaic applications, while Chen et al. (2018, 2019) and Liu et al. (2020, 2021) show the importance of film orientation, deposition approach, and valence band structure in enabling defect-tolerant and stable GeSe photovoltaics. Han and Wu et al. (2023) extend this through simulation and optimization of thin-film solar cells using GeSe as the absorption layer. The GeSe literature matters because it introduces an alternative research logic: the search for stability and defect tolerance through intrinsically promising thin-film materials rather than solely through perovskite-centered advancement.

CIGS-related research also plays a bridging role in the supplied references. Atourki et al. (2016) study thin-film CIGS bilayer solar cells numerically, while Al-Hattab et al. (2021) simulate a heterostructure CIGS/GaSe solar cell system. CIGS also appears in tandem contexts, especially when paired with perovskite absorbers (Liu, Junbo, & Xudong, 2023; Wang, 2019). This indicates that CIGS remains a strategically relevant material system, especially as a lower-junction partner in tandem configurations. Its role in the literature is not simply historical or transitional; it serves as a technologically mature counterpart against which newer absorber classes can be paired and assessed.

The supplied references also highlight the growing importance of simulation as a core method in photovoltaic research. SCAPS-1D appears repeatedly as a tool for understanding absorber thickness, defect density, transport-layer selection, interface effects, and tandem architecture feasibility (Atourki et al., 2016; Ouslimane et al., 2021; Sharma et al., 2023; Ompong & Clements, 2024; Singh et al., 2023; Katubi et al., 2024). This suggests that numerical simulation is no longer ancillary to experimental research. It is a central mechanism for narrowing design space, identifying performance sensitivities, and testing architectural combinations that may be difficult or costly to fabricate immediately. The significance of this methodological trend is profound. It allows the field to move from material trial-and-error toward digitally guided photovoltaic design.

Yet simulation also creates risks of overstatement. Morales-Acevedo (2023) revisits the fundamentals of solar cell physics and highlights common pitfalls when reporting calculated and measured photovoltaic parameters. This contribution is especially important because it reminds the field that simulated improvements, calculated photocurrent densities, and reported efficiencies must be interpreted carefully. In a research environment increasingly rich in theoretical tandem studies and simulation-based optimization, methodological discipline becomes essential. The future of photovoltaic progress depends not only on bold design claims but also on rigorous parameter interpretation and honest boundary-setting.

Economic viability is another critical dimension that appears explicitly in the supplied references. Woodhouse et al. (2019) provide a benchmark on crystalline silicon photovoltaic module manufacturing costs and sustainable pricing, emphasizing silicon’s deep industrial maturity. Liu et al. (2025) directly ask whether perovskite solar cells will outperform crystalline silicon in terms of cost effectiveness. This question is central because it reveals that the future of perovskites and tandem systems cannot be settled by efficiency alone. Silicon still benefits from well-established manufacturing ecosystems, known reliability, and cost reduction road maps. Thus, any new photovoltaic technology must compete not in an abstract scientific environment, but against an incumbent system with enormous industrial depth.

This point clarifies the broader problem that motivates the present article. The field is rich in high-efficiency claims, simulation-based optimizations, new absorber systems, and tandem architectures. However, the literature also reveals unresolved tensions among four major goals: theoretical efficiency, practical device optimization, long-term stability, and economic competitiveness. These goals are interdependent, but they are not automatically aligned. A high-efficiency tandem design may be difficult to manufacture. A stable material may be less efficient. A numerically optimized structure may underperform in practice. A low-cost device may suffer from lifetime limitations. The challenge is therefore not simply to maximize one parameter. It is to understand how the field is attempting to reconcile these parameters within emerging photovoltaic architectures.

There is also a literature gap that justifies this study. Many of the supplied references focus on specific subproblems: preparation processes, tandem simulations, absorber thickness, defect tolerance, SCAPS modeling, or cost-effectiveness. What is less developed in any single source is a broad integrative account of how these literatures together define the next stage of photovoltaic research. Such an account is important because modern solar cell development is increasingly interdisciplinary. Materials science, device physics, numerical simulation, manufacturing economics, and degradation science are no longer separable domains. The most consequential advances are likely to come from how they interact.

This article therefore has four main objectives. First, it synthesizes the theoretical and physical literature on efficiency limits and solar cell architecture. Second, it synthesizes the simulation-oriented literature on perovskite, GeSe, CIGS, and tandem device optimization. Third, it interprets the stability and degradation literature as a decisive commercialization filter. Fourth, it evaluates the techno-economic implications of these developments, especially in relation to crystalline silicon as the enduring industrial benchmark.

The article proceeds in a continuous academic format. The methodology explains the qualitative integrative approach used to analyze the supplied references. The results identify major trends in efficiency theory, simulation practice, absorber engineering, tandem design, stability management, and cost competitiveness. The discussion interprets these findings in depth, addresses limitations, and proposes future research directions. The conclusion argues that the future of solar cell development will depend on the integration of theoretical rigor, materials engineering, durable architecture design, and economically grounded deployment thinking.

Methodology

This study adopts a qualitative integrative research methodology based strictly on the references supplied in the prompt. The purpose of this methodology is to generate an original, publication-ready academic article from a heterogeneous but thematically connected body of photovoltaic literature without introducing external sources or unsupported claims. Because the supplied references include review articles, simulation studies, materials investigations, dissertations, stability analyses, and techno-economic reports, a narrow meta-analytic or single-metric comparative method would not be suitable. Instead, the present study uses thematic synthesis, comparative interpretation, and conceptual integration to identify how the references collectively define the present and future trajectory of advanced solar cell research.

The first stage of the methodology involved corpus classification. The supplied literature was mapped into five major thematic clusters. The first cluster consists of theoretical and efficiency-oriented studies, including work on the efficiency limits of photovoltaics, silicon approaching its efficiency ceilings, and the detailed-balance logic underlying multi-junction step-cell architectures (Al-Harbi & Kais, 2015; Andreani et al., 2019; Hadi et al., 2016). The second cluster consists of perovskite-oriented material and device studies, including work on preparation processes, device performance simulation, tandem architecture design, and SCAPS-based optimization of perovskite absorber parameters (Guo & Min, 2017; Zhao, 2022; Xu, 2021; Sharma et al., 2023; Ouslimane et al., 2021; Ompong & Clements, 2024; Katubi et al., 2024). The third cluster concerns tandem architectures more broadly, including perovskite/silicon, perovskite/CIGS, MAPbI3-on-CuInSe2, and Sb2S3-on-Si systems (Liu, Junbo, & Xudong, 2023; Cui, 2023; Wang, 2019; Singh et al., 2023; Singh, V. K., et al., 2023; Zhang et al., 2023). The fourth cluster covers GeSe and thin-film heterostructure research, including GeSe deposition, defect tolerance, orientation control, and related CIGS/GaSe or CIGS bilayer simulation studies (Xue et al., 2017; Liu et al., 2017; Chen et al., 2018, 2019; Liu et al., 2020, 2021; Atourki et al., 2016; Al-Hattab et al., 2021; Han & Wu et al., 2023). The fifth cluster concerns stability, reliability, and cost competitiveness, including work on degradation mechanisms, long-term stability, silicon module cost benchmarks, and perovskite cost-effectiveness (Baumann et al., 2024; Zhu et al., 2023; Woodhouse et al., 2019; Liu et al., 2025).

The second stage involved thematic coding within and across these clusters. For the theoretical cluster, the primary coding themes were efficiency limits, thermodynamic constraints, spectral utilization, and architectural escalation beyond single-junction systems. For the perovskite cluster, the themes were tunability, absorber optimization, defect density, thickness control, transport-layer effects, and simulation-guided design. For the tandem cluster, the themes were multi-absorber complementarity, two-terminal versus four-terminal structures, concentrated-light performance, and spectrum-splitting logic. For the GeSe and thin-film cluster, the themes were defect tolerance, film quality, deposition pathways, band structure, interface behavior, and alternative absorber potential. For the stability and cost cluster, the themes were degradation, operational lifetime, manufacturability, module reliability, and economic competition with crystalline silicon. Several cross-cutting themes emerged across all clusters: the increasing importance of interfaces, the rise of simulation as a design tool, the tension between efficiency and stability, and the centrality of commercialization criteria.

The third methodological stage was intra-domain synthesis. This stage examined how each thematic cluster develops its own internal logic. Within the theoretical cluster, the synthesis focused on how the literature frames the limits of conventional photovoltaics and motivates the turn toward tandem and multi-junction architectures. Within the perovskite cluster, the synthesis examined how numerical simulation, absorber tuning, and structural optimization work together to raise predicted performance. Within the tandem cluster, the study compared how different absorber pairings and terminal configurations are used to overcome spectral and efficiency limitations. Within the GeSe cluster, the study focused on how thin-film device performance is linked to material properties, orientation, deposition quality, and defect tolerance. Within the stability and cost cluster, the synthesis clarified how durability and manufacturing economics increasingly shape the practical meaning of “high efficiency.”

The fourth stage was cross-domain comparative synthesis. This stage is central to the originality of the article. Instead of reviewing each material platform separately, the study asks how the supplied references collectively redefine the photovoltaic problem. The answer that emerges is that solar cell research is no longer organized around a single dominant optimization axis. Rather, it operates through simultaneous negotiation among efficiency, architecture, stability, and cost. Perovskites are strong in tunability and high projected efficiency but weak in long-term stability. Silicon is weaker in breakthrough headroom but stronger in industrial maturity. GeSe offers promise in defect tolerance and thin-film stability but remains less established. Tandem systems offer a path beyond single-junction limits but increase manufacturing and interfacial complexity. Comparative synthesis therefore focused on these relational trade-offs rather than on isolated material narratives.

The fifth methodological stage involved conceptual framework development. From the repeated patterns in the literature, the article develops a four-dimensional framework for next-generation photovoltaic development: theoretical ceiling, device architecture, operational durability, and economic viability. The theoretical ceiling dimension concerns whether a given solar cell class can meaningfully exceed the performance logic of mature single-junction systems. The device architecture dimension concerns absorber composition, layer structure, interfaces, and tandem design. The operational durability dimension concerns defect tolerance, environmental resilience, and degradation management. The economic viability dimension concerns manufacturing cost, scalability, and competition with incumbent photovoltaic technologies. This framework is not drawn from external theory; it is constructed inductively from the supplied references.

The sixth stage involved evidentiary discipline. Because the task requires the article to be based strictly on the supplied references, no external technical claims, efficiency numbers, or industry forecasts beyond those reasonably supported by the listed sources have been introduced. Some references contain abbreviated author lists or dissertation-level framing, and the study uses them according to their apparent conceptual contribution. Broader interpretive arguments are only made when multiple references support a common line of reasoning.

This methodology has several strengths. It allows diverse photovoltaic subfields to be brought into a unified research narrative. It respects the technical specificity of materials and simulation studies while also highlighting their shared strategic implications. It also suits a research environment in which the most important questions are not isolated experimental points but broader developmental tensions across the field. At the same time, the method has limitations. It cannot provide standardized quantitative comparison across device classes, because the studies differ in design, assumptions, and scale. It also does not experimentally validate a single architecture. Its contribution is interpretive and conceptual, not empirical in the narrow benchmark sense. For the purposes of the present article, however, that is precisely the appropriate form of contribution.

Through this methodology, the article identifies the central finding that modern photovoltaic research is converging toward a systems-oriented logic in which efficiency potential, structural design, stability, and cost must be solved together rather than sequentially.

Results

The integrative analysis of the supplied references yields several major findings. These findings show that advanced photovoltaic research is increasingly organized around architectural escalation, simulation-driven optimization, stability-centered realism, and cost-aware technology comparison.

The first major result is that the field increasingly recognizes the limitations of mature single-junction photovoltaic systems and is therefore shifting toward tandem and multi-junction architectures as the most plausible route for major efficiency gains. Andreani et al. (2019) discuss silicon solar cells moving toward their efficiency limits, which implies that silicon's extraordinary industrial success coexists with a narrowing margin for radical efficiency improvement. Al-Harbi and Kais (2015) reinforce this broader perspective by examining the theoretical limits of photovoltaic efficiency and exploring conceptual routes for improvement. Hadi et al. (2016) take the argument further by modeling the theoretical efficiency limit of a two-terminal multi-junction step-cell using detailed balance. These studies, taken together, show that next-generation photovoltaic development is increasingly motivated by the search for structural alternatives to the single-absorber paradigm.

The second major result is that perovskite solar cells are central to this structural transition because they combine strong optoelectronic promise with unusual adaptability for numerical and architectural optimization. Guo and Min (2017) identify preparation process and stability as central issues, which already suggests that perovskites are materials of high promise and high fragility. Zhao (2022) and Xu (2021) address optimized design and simulation research for perovskite solar cells, while Sharma et al. (2023) numerically analyze high-efficiency $CH_3NH_3PbI_3$ devices using SCAPS. Ouslimane et al. (2021) examine the effects of absorber thickness, defect density, and temperature in $MAPbI_3$ systems, and Ompong and Clements (2024) optimize formamidinium-based perovskite solar cells. Katubi et al. (2024) claim efficiencies above 35% in a simulated three-absorber perovskite system using SCAPS 1-D. The shared implication is that perovskites have become a design platform as much as a material class. They are valued not just because they work well, but because they can be structurally engineered in many directions.

The third major result is that SCAPS-1D has become one of the most important methodological tools in photovoltaic research, especially for absorber tuning and tandem feasibility analysis. Atourki et al. (2016) use SCAPS for CIGS bilayer solar cells, showing that the tool is not restricted to perovskites. Sharma et al. (2023), Ompong and Clements (2024), Chabri et al. (2023), Singh et al. (2023), and Singh, V. K., et al. (2023) all rely on SCAPS-based analysis for different absorber systems and tandem configurations. This indicates that numerical simulation has matured into a cross-platform design methodology. The importance of SCAPS in the reference set suggests that advanced photovoltaic research is increasingly predictive and exploratory, able to examine defect density, transport layers, absorber thickness, and band alignment prior to or alongside experimental realization.

The fourth major result is that tandem architectures are no longer peripheral hypotheses but a central strategic direction in solar cell research. Zhang et al. (2023) show progress toward perovskite/crystalline silicon tandem solar cell technology with efficiency greater than 30, indicating that tandem devices are already regarded as realistic performance pathways. Liu, Junbo, and Xudong (2023) focus on four-terminal perovskite/CIGS tandem cells, بينما Singh et al. (2023) examine MAPbI3-on-CuInSe2 monolithic and mechanically stacked tandem architectures. Singh, V. K., et al. (2023) extend tandem logic to Sb2S3-on-Si. Cui (2023) investigates tandem perovskite solar cells under concentrated light conditions, and Wang (2019) studies tandem configuration with CIGS. These studies collectively indicate that tandem research has diversified across absorber combinations, integration methods, and design assumptions. The field is not converging on one tandem formula alone, but on tandem logic as a general route to higher performance.

The fifth major result is that different tandem configurations imply different strategic trade-offs. Two-terminal monolithic tandem systems offer integrated performance and potentially reduced packaging complexity but raise stringent demands on current matching, interface engineering, and fabrication compatibility (Hadi et al., 2016; Singh et al., 2023). Four-terminal mechanically stacked systems offer greater design flexibility and fewer current-matching constraints, yet they can introduce other practical challenges related to optical management, mechanical integration, and manufacturing complexity (Liu, Junbo, & Xudong, 2023; Singh et al., 2023). The literature does not treat one configuration as universally superior. Instead, it implies that tandem design choices should be evaluated in relation to target application, fabrication capability, and performance-stability balance.

The sixth major result is that GeSe has emerged as a notable thin-film absorber class because of its favorable electronic properties, defect tolerance, and potential stability advantages. Xue et al. (2017) demonstrate GeSe thin-film solar cells fabricated by rapid thermal sublimation, providing foundational evidence that GeSe is experimentally viable. Liu et al. (2017) investigate its physical and electronic properties for photovoltaic applications. Chen et al. (2018, 2019) show that deposition method and film orientation matter significantly for device performance, while Liu et al. (2020) summarize GeSe thin-film solar cells more broadly. Liu et al. (2021) make a particularly significant contribution by showing that an antibonding valence band maximum enables defect-tolerant and stable GeSe photovoltaics. This is a major result because it introduces a materials logic distinct from perovskites. Whereas perovskites offer remarkable tunability but substantial stability challenges, GeSe suggests the possibility of inherent defect tolerance and durability through electronic structure.

The seventh major result is that interface engineering remains a decisive issue across photovoltaic platforms. Kemp et al. (2013) highlight interface recombination in depleted heterojunction photovoltaics, reminding us that absorber excellence alone does not guarantee device excellence. Atourki et al. (2016), Al-Hattab et al. (2021), and Chabri et al. (2023) all indirectly reinforce the importance of interfaces by studying heterostructures, bilayers, and transport-layer choices. In perovskite systems, transport materials and interface defects strongly influence output; in thin-film systems, heterojunction alignment can determine carrier extraction and recombination losses. The result here is that modern solar cell design is increasingly interface-limited rather than absorber-limited alone.

The eighth major result is that operational stability has become the decisive bottleneck in perovskite-containing technologies. Baumann et al. (2024) emphasize degradation mechanisms and mitigation strategies in perovskite-containing solar cells and modules, while Zhu et al. (2023) examine long-term operating stability in perovskite photovoltaics. These studies strongly indicate that high performance is no longer the only criterion by which perovskite progress is judged. Stability under heat, light, moisture, bias, and operational duration has become equally central. This finding transforms the meaning of “advanced” photovoltaic technology. A device may be advanced in efficiency but primitive in durability. True advancement requires convergence between the two.

The ninth major result is that simulation-based performance claims require methodological caution. Morales-Acevedo (2023) is especially important in this respect because the paper revisits common pitfalls in reporting calculated and measured photovoltaic parameters. This result matters because many of the supplied references involve numerical optimization and simulated tandem performance. The literature therefore contains a self-corrective element: while simulation is powerful, the field must avoid overstating numerically favorable conditions as if they were automatically realized in devices. This cautions against simplistic interpretation of very high predicted efficiencies without corresponding attention to material realism, contact losses, manufacturability, and degradation.

The tenth major result is that economic comparison with crystalline silicon remains unavoidable. Woodhouse et al. (2019) provide a benchmark for crystalline silicon photovoltaic module manufacturing costs and sustainable pricing, showing how strong the incumbent platform remains. Liu et al. (2025) directly question whether perovskite solar cells will outperform crystalline silicon in cost effectiveness. This is a crucial result because it indicates that future solar cell success is measured against a highly optimized industrial standard, not against hypothetical performance targets alone. Even if perovskite or tandem cells exceed silicon in efficiency, they must still prove themselves in cost, stability, manufacturing scalability, and module reliability.

The eleventh major result is that durability and cost are increasingly entangled. A device with lower manufacturing cost may become effectively expensive if it degrades quickly. Conversely, a more costly architecture may still be economically favorable if it sustains higher output for longer periods. The supplied references do not provide a single unified lifecycle economic model, but the juxtaposition of Woodhouse et al. (2019), Liu et al. (2025), Baumann et al. (2024), and Zhu et al. (2023) strongly implies that cost effectiveness cannot be separated from reliability. This is especially important for perovskite technologies, where nominally cheap materials may still face expensive encapsulation, stability mitigation, or replacement burdens.

The twelfth major result is that the photovoltaic field is converging toward a design paradigm in which no single variable can dominate. Efficiency, absorber choice, interface alignment, degradation behavior, and cost all appear repeatedly in the literature. The cumulative message is that the future of photovoltaic research lies not in isolated maximization of one parameter, but in integrated architecture design. This integrated logic is one of the clearest outcomes of the present study.

Discussion

The findings of this study reveal that modern solar cell research is increasingly defined by a systems problem rather than a single-material problem. The field is not simply trying to discover the best absorber or the highest reported efficiency. It is trying to reconcile several goals that are individually desirable but collectively difficult to satisfy: theoretical efficiency expansion, robust device architecture, long-term operational stability, and real economic competitiveness. This integrative challenge is what gives contemporary photovoltaic research both its dynamism and its difficulty.

A first major implication concerns the status of crystalline silicon. The literature suggests that silicon remains both the benchmark and the challenge. Andreani et al. (2019) make clear that silicon solar cells are moving toward their efficiency limits, which can be interpreted in two ways. On one hand, this means silicon may offer limited room for dramatic performance escalation within conventional single-junction logic. On the other hand, it means silicon has achieved an extraordinary level of maturity and optimization. Woodhouse et al. (2019) reinforce this by providing cost benchmarks and pricing road maps that show how deeply industrialized silicon has become. This dual status gives silicon unusual strategic power. It is simultaneously a technological ceiling and a commercial floor. New technologies must surpass its limitations while surviving its competitiveness.

This is why tandem research is so important. Tandem systems offer a way of treating silicon not as an obstacle but as a foundation. Perovskite/silicon tandems exemplify this logic. Rather than displacing silicon entirely, they attempt to stack a high-bandgap absorber above a silicon base cell in order to extend spectral utilization and exceed the efficiency ceiling of silicon alone (Zhang et al., 2023). This is conceptually elegant because it leverages silicon’s industrial maturity while adding architectural sophistication. Yet the tandem strategy also raises deeper questions. Does pairing a fragile but high-performing material with a durable and mature one create a commercially coherent device, or does it merely import instability into a strong platform? The literature suggests that this remains unresolved.

A second major implication concerns the role of simulation in guiding the field. The dominance of SCAPS-based studies in the supplied references indicates that photovoltaic research has entered a highly simulation-literate phase. This is not a weakness; it is a sign of maturation. Simulation allows researchers to explore design space systematically, compare transport layers, assess defect sensitivity, and model tandem behavior before costly fabrication (Atourki et al., 2016; Ouslimane et al., 2021; Sharma et al., 2023; Ompong & Clements, 2024). However, Morales-Acevedo (2023) provides an important corrective by warning about common pitfalls in reporting calculated and measured photovoltaic parameters. This suggests a critical tension. Simulation accelerates exploration, but it can also create a culture of optimistic numerics if its assumptions are not sufficiently constrained by experimental realism. Future research must therefore preserve a disciplined relationship between numerical elegance and material truth.

A third implication concerns perovskites as a research platform. The literature shows that perovskites are extraordinarily versatile. They can be tuned, layered, optimized, and integrated into tandem systems with apparent ease at the conceptual level. This is why so many of the supplied studies revolve around perovskite absorber parameters, perovskite-based tandem designs, and perovskite-centered performance simulations (Zhao, 2022; Xu, 2021; Sharma et al., 2023; Ompong & Clements, 2024; Katubi et al., 2024). Yet the same literature makes clear that perovskites are also a platform of instability. Baumann et al. (2024) and Zhu et al. (2023) emphasize degradation and long-term operational challenges in such a way that one cannot honestly discuss perovskite photovoltaics as a solved performance story. The most important conclusion here is that perovskites are not a completed technology. They are a highly promising, highly unstable design space.

This duality has theoretical significance. In innovation studies, a technology may be considered “strong” because of high performance or “weak” because of low reliability. Perovskites challenge this binary. They are simultaneously strong and weak. Their strength lies in tunability, bandgap engineering, and tandem compatibility. Their weakness lies in durability and reliability. The field’s next phase will depend on whether these two trajectories can be reconciled. If not, perovskites may remain scientifically impressive but commercially peripheral. If yes, they may reshape the photovoltaic industry.

A fourth major implication concerns the importance of alternative absorber materials such as GeSe. The GeSe literature in the supplied references is particularly valuable because it offers a different pathway for photovoltaic advancement. Instead of optimizing a spectacular but unstable material, GeSe research seeks to build on favorable electronic structure, thin-film processability, and defect tolerance (Liu et al., 2017; Chen et al., 2018; Liu et al., 2021). This suggests that the future of photovoltaic research should not be reduced to a perovskite-versus-silicon narrative. Alternative thin-film materials may provide routes to strong and stable performance, especially if their interfaces and film quality can be sufficiently refined. The fact that GeSe appears in both experimental and simulation-oriented studies shows that it is being treated as a serious platform rather than a speculative curiosity.

This raises an important strategic question: should the field prioritize ultra-high projected efficiency through complex tandem systems, or should it also invest more heavily in absorber systems that may not yet dominate headlines but offer better intrinsic stability or defect tolerance? The literature does not provide a single answer, but it strongly suggests that diversification is rational. A photovoltaic future dominated by one material class would be technically risky. Tandem systems, GeSe thin films, and heterostructure innovations all reduce the danger of overdependence on one solution logic.

A fifth implication concerns interfaces as the hidden determinants of device quality. Many solar cell discussions begin with bandgaps, absorber types, or overall efficiency. The supplied references repeatedly suggest that the deeper bottlenecks often lie at interfaces: absorber/transport boundaries, heterojunction alignments, deposition-induced morphology, and recombination-sensitive surfaces (Kemp et al., 2013; Chen et al., 2019; Chabri et al., 2023). This is especially important in tandem systems, where multiple absorbers and interconnection layers must coexist. A theoretically ideal tandem pairing may still fail if interfaces create severe recombination or poor carrier selectivity. This means the next phase of device research may require even greater attention to interfacial materials science than to absorber innovation alone.

A sixth implication is that stability research is becoming a commercialization filter. Earlier in the development of emerging photovoltaics, efficiency breakthroughs often dominated discourse. The references supplied here suggest a more mature research culture. Baumann et al. (2024) and Zhu et al. (2023) show that the field now understands degradation mechanisms and long-term operation as central scientific questions. This is an important sign of maturity because it marks a transition from novelty-driven science to deployment-oriented science. A technology becomes commercially relevant not when it first performs well, but when the field becomes serious about why it stops performing well.

This change in emphasis also affects how cost should be interpreted. The question raised by Liu et al. (2025) about whether perovskites can outperform crystalline silicon in cost effectiveness is much more complex than a simple bill-of-materials comparison. The cost of a photovoltaic technology includes its manufacturing pathway, defect tolerance, module integration, encapsulation burden, degradation rate, and replacement implications. Woodhouse et al. (2019) show the strength of silicon not just in cost reduction but in road-mapped industrial confidence. Perovskites may be cheap at the material level, but if they require expensive stability mitigation or suffer rapid degradation, their effective system cost rises. Thus, techno-economic competitiveness should be understood as durability-adjusted performance rather than nominal production cost alone.

A seventh implication concerns the relation between theory and engineering. Al-Harbi and Kais (2015) and Hadi et al. (2016) highlight theoretical limits and detailed-balance methods, while many later references focus on SCAPS-based engineering or dissertation-level structural optimization. This suggests that the photovoltaic field is now richly layered between idealized theory and practical design. Neither can be abandoned. Theory provides the map of what is possible; simulation explores what may be plausible; experimentation tests what is real; stability science determines what endures; economics decides what survives commercially. The present literature set is valuable precisely because it contains traces of all these layers.

An eighth implication concerns methodological honesty in the age of high-efficiency claims. Katubi et al. (2024) report efficiencies above 35% in a multi-absorber perovskite architecture using SCAPS, and several tandem simulation papers suggest very strong theoretical outputs. These are exciting results, but Morales-Acevedo (2023) reminds the field that reported efficiencies and parameter interpretations can be misleading when measured and calculated values are conflated or reported without careful contextualization. The implication is that photovoltaic progress must be evaluated through multiple filters: theoretical validity, numerical plausibility, experimental verifiability, and long-term relevance. A field driven only by ever-higher reported efficiencies risks detaching from the realities of manufacturing and operation.

A ninth implication concerns the future research agenda. The supplied literature suggests that the most important future studies will likely be those that integrate, rather than isolate, key design variables. For example, tandem studies should increasingly include realistic stability scenarios. Perovskite optimization studies should connect simulated performance with degradation-aware architecture design. GeSe and CIGS studies should continue probing interfaces and manufacturability alongside basic absorber properties. Cost studies should move closer to lifecycle and reliability-based analysis. The field appears ready for research that is more integrated and less compartmentalized.

This study also has limitations. First, it is based strictly on the supplied references and therefore does not include other important photovoltaic literatures that might further enrich the analysis, such as broader lifecycle assessment, encapsulation engineering, or industrial manufacturing case studies beyond the listed sources. Second, the references vary in type and depth, including journal articles, conference-like summary pieces, dissertations, and reports. Third, because the article is qualitative and integrative, it cannot provide a standardized empirical ranking of photovoltaic architectures or materials. Fourth, several references include abbreviated author lists, which limits detailed reconstruction of each study’s exact experimental scope. These limitations define the study’s role accurately: it is a conceptual and interpretive synthesis, not a unified benchmark experiment.

Despite these limitations, the article offers a strong integrative conclusion. The future of solar cell development will likely not be decided by one material alone, one efficiency record alone, or one simulation result alone. It will be decided by how well the field integrates physical theory, device architecture, interface control, operational stability, and economic realism into coherent photovoltaic systems.

Conclusion

This article has developed a complete, publication-ready research study based strictly on the supplied references and has shown that the contemporary photovoltaic field is being reshaped by the convergence of four major imperatives: extending efficiency beyond single-junction limits, optimizing device architectures through simulation and materials engineering, ensuring operational durability, and achieving cost competitiveness against crystalline silicon. The literature demonstrates that tandem and multi-junction strategies are increasingly central because mature single-junction platforms, especially silicon, approach practical efficiency ceilings even while retaining industrial strength (Andreani et al., 2019; Hadi et al., 2016; Zhang et al., 2023). Perovskite systems are especially significant because they combine strong tunability with tandem compatibility, yet their future remains constrained by unresolved stability and reliability concerns (Guo & Min, 2017; Baumann et al., 2024; Zhu et al., 2023).

A major conclusion of the study is that numerical simulation, particularly through SCAPS-1D, has become a core design methodology in advanced solar cell research. It enables optimization of thickness, defect density, transport layers, and tandem architectures across perovskite, CIGS, and related thin-film systems (Atourki et al., 2016; Sharma et al., 2023; Ompong & Clements, 2024; Singh et al., 2023). However, simulation must be interpreted with methodological caution and linked to experimental realism and durability considerations (Morales-Acevedo, 2023). Another major conclusion is that GeSe and related thin-film absorbers deserve continued strategic attention because they offer an important counterpoint to the dominant perovskite narrative through their emphasis on defect tolerance, film engineering, and structural stability (Xue et al., 2017; Liu et al., 2020; Liu et al., 2021).

The study also concludes that cost competitiveness cannot be separated from stability. Crystalline silicon remains commercially formidable not only because of its performance but because of its manufacturing maturity, established cost structures, and reliable operational history (Woodhouse et al., 2019). Emerging technologies such as perovskites may become economically transformative only if their impressive efficiency potential converges with long-term reliability and scalable manufacturing (Liu et al., 2025).

Overall, the references strongly support the view that the next stage of photovoltaic advancement will depend on integrated design thinking. The most successful solar cell architectures of the future will not simply be those that report the highest nominal efficiency, but those that combine strong spectral utilization, robust interfaces, material resilience, realistic manufacturability, and lifecycle-aware economic value. The field is therefore moving toward a more mature paradigm in which scientific ambition and engineering discipline must advance together.

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