

Solar Photovoltaic Technology, What's Next?

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Article Info

Article info:

Received: 03-12-2025

Revised: 11-01-2026

Accepted: 19-01-2026

Keywords:

Circular economy;
Digitalization; Energy
transition; Perovskite
tandem; Solar photovoltaic

How To Cite:

N. Apriandi, Y. M.
Safarudin, "Solar
Photovoltaic Technology,
What's Next?", Apex
Energy, vol. 1, no. 1, p 16-
23, 2026.

Abstract

Solar photovoltaic (PV) technology has rapidly evolved into one of the most transformative pillars of the global energy transition. Continuous efficiency improvements, coupled with dramatic reductions in the levelized cost of electricity (LCOE), have positioned PV as the most competitive renewable energy source worldwide. Yet, as crystalline silicon technology approaches its efficiency saturation and accounts for over 90% of the market, the question of "what's next?" becomes increasingly critical. This short communication highlights the emerging frontiers that will shape the next phase of PV development. At the device level, perovskite/silicon tandems, thin films, and other novel absorbers are pushing performance beyond the limitations of single-junction devices, although stability, toxicity, and scalability remain significant barriers. From a sustainability perspective, the projected accumulation of more than 60 million tonnes of PV waste by 2050 underscores the urgent need for circular economy strategies, including eco-design, recycling innovations, and second-life applications. At the system level, integrating PV with storage, hydrogen, and smart grids is essential to overcome intermittency, while digitalization through artificial intelligence (AI), machine learning (ML), and digital twins is redefining PV operation and maintenance. The synthesis of these trajectories indicates that the future of PV extends beyond efficiency improvements to encompass holistic integration, environmental responsibility, and socio-economic inclusivity. PV is no longer merely a technology of cost competitiveness but a strategic enabler of resilient, circular, and net-zero energy systems.



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Introduction

The rapid advancement of solar photovoltaic (PV) technology has been instrumental in reshaping the global energy landscape [1][2][3]. With the levelized cost of electricity (LCOE) for PV declining by more than 80% in the past decade, solar energy is now recognized as one

of the most cost-competitive energy sources worldwide [4]. Crystalline silicon continues to dominate the market, representing over 90% of global PV deployment, with cell efficiencies steadily approaching the theoretical Shockley–Queisser limit [5]. Despite these remarkable milestones, the critical question of “what’s next?” is increasingly relevant as the world strives to align PV technology with the broader imperatives of sustainability, decarbonization, and long-term energy security.

While silicon-based technologies have driven exponential deployment, their efficiency potential is nearing saturation, highlighting the need for disruptive innovations in materials and device architectures. Perovskite/silicon tandem cells have emerged as the most promising candidates, with record efficiencies surpassing >29% in laboratory settings [6][7]. Other thin-film and emerging technologies, such as organic photovoltaics, quantum-dot absorbers, and kesterite-based compounds, offer prospects for flexible, lightweight, and niche applications, though their long-term stability and scalability remain unresolved challenges [8].

Sustainability concerns further complicate the PV landscape. The cumulative end-of-life PV waste is projected to exceed 60 million tonnes by 2050 [9]. Current recycling approaches are limited, energy-intensive, and economically unattractive, resulting in low recovery rates of critical materials such as silver and indium. Circular economy strategies, including eco-design for recyclability, modular dismantling, and closed-loop material recovery, are thus urgently required to ensure that PV technology contributes to the energy transition without creating new environmental burdens [10].

System-level integration represents another decisive frontier. The inherent intermittency of solar generation challenges grid stability and necessitates coupling PV with large-scale storage systems and flexible demand-side management. Hybridization with battery storage and green hydrogen, together with advanced power electronics, provides pathways to dispatchable, resilient renewable power [11][12][13]. Concurrently, the digitalization of PV systems through artificial intelligence (AI), machine learning (ML), and digital twins is revolutionizing operation and maintenance practices, enabling predictive fault detection, real-time optimization, and enhanced lifecycle management [14][15][16].

Beyond technological progress, PV's role in achieving global sustainability targets extends to socio-economic dimensions. PV deployment is increasingly linked to equitable energy access, job creation, and industrial competitiveness, particularly in emerging markets, where solar energy can directly support the Sustainable Development Goals (SDGs) (UNDP, 2022). Therefore, the evolution of PV technology must transcend the narrow focus on cost and efficiency to encompass resilience, circularity, and socio-economic inclusivity.

Against this backdrop, this short communication highlights the emerging trajectories of solar PV development and integration, emphasizing the frontier challenges and transformative opportunities that define the next phase of global PV advancement.

What’s Next?

Emerging Material and Device Innovations

Pursuing higher efficiency and lower cost continues to drive PV research beyond conventional crystalline silicon. Tandem solar cells, particularly perovskite/silicon combinations, have already demonstrated record efficiencies exceeding >29%, signaling their potential to surpass single-junction limitations. Their advantages include tunable band gaps,

lightweight structures, and solution-processability, making them strong candidates for next-generation PV modules. However, unresolved challenges remain. Issues of thermal and moisture stability, lead toxicity, and limited scalability in industrial manufacturing hinder the development of perovskite devices. Unless these challenges are systematically addressed, perovskites may remain confined to laboratory breakthroughs rather than be deployed at scale.

Alternative device concepts such as organic photovoltaics, quantum-dot absorbers, and Kesterite thin films offer additional opportunities. Their flexibility, compatibility with building-integrated photovoltaics (BIPV), and potential for low-cost manufacturing broaden PV's market scope. Nevertheless, their relatively low efficiency and poor long-term durability compared to silicon-based modules underscore a trade-off between functionality and performance. The future of emerging PV devices, therefore, lies not only in improving efficiency but also in their ability to complement silicon in niche applications, diversify the PV market, and enable integration into unconventional surfaces and environments.

Sustainability and Circular Economy Perspectives

While PV technology is often celebrated for its environmental benefits, the sustainability of the sector is increasingly under scrutiny. By 2050, the cumulative volume of decommissioned PV modules is projected to exceed 60 million tonnes, posing unprecedented waste management challenges. Current recycling approaches are inefficient and economically unattractive, recovering only low-value materials at high processing costs. This raises concerns that PV could shift from being an environmentally favorable technology to a future source of resource and waste burdens.

To mitigate this, circular economy strategies must be integrated into the design and production stages of PV modules. Eco-friendly encapsulants, modular dismantling strategies, and second-life applications can significantly reduce the environmental footprint of PV deployment. However, the implementation of such strategies remains limited due to weak policy incentives, lack of standardization, and underdeveloped recycling markets. A critical challenge lies in reconciling the urgent need for low-cost PV deployment with the equally urgent requirement for long-term sustainability. Without proactive interventions, the PV industry risks reproducing the same linear economy pitfalls it was designed to replace.

System Integration and Digitalization

The large-scale penetration of PV introduces system-level challenges that extend beyond device efficiency. Intermittency and variability remain central barriers to PV's role as a reliable baseload source. While hybrid PV-battery systems are already commercially viable, they remain costly and limited in capacity for seasonal balancing. Coupling PV with green hydrogen production, thermal storage, and advanced grid-management strategies offers a pathway toward dispatchable renewable electricity, but the economics and technical maturity of such solutions remain uneven.

Parallel to this, digitalization is transforming PV operation and maintenance. Artificial intelligence (AI), machine learning (ML), and digital twins enable predictive maintenance, real-time optimization, and adaptive control at both module and farm scales. However, these advances also introduce new risks, including cybersecurity vulnerabilities, data privacy concerns, and the potential exclusion of developing economies that lack digital infrastructure. Thus, while digitalization enhances PV reliability and efficiency, it also widens the

technological gap between advanced and emerging economies. Critical attention must therefore be paid to developing interoperable, secure, and accessible digital solutions that support equitable PV deployment globally.

Synthesis: Current Achievements and Future Directions

Table 1. Solar PV Technology: State-of-the-Art, Frontier Challenges, and Future Directions.

Domain	State of the art (Current achievements)	Frontier Challenges	Future research directions
Materials & Devices	Crystalline silicon dominates (>90% market share), efficiencies approaching ~27%; perovskite/silicon tandems are achieving >29% in labs.	Stability of perovskite devices; scalability of tandem architectures; toxicity and supply-chain constraints.	Durable, non-toxic tandem materials; scalable fabrication; novel absorbers (organic, quantum-dot, kesterite) for niche applications (e.g., flexible/BIPV)
Manufacturing & Cost	LCOE reduction by >80% over the past decade; giga-scale PV manufacturing in China and beyond	Material intensity (silver, indium); supply chain resilience; geopolitical dependencies	Alternative abundant materials; localized manufacturing; circular supply chains
Sustainability & Circular Economy	Growing awareness of PV waste management; initial recycling pilot plants in the EU, Japan	High cost of recycling; inefficient material recovery; >60 million tonnes PV waste projected by 2050	Eco-design for recyclability; closed-loop recycling; second-life PV modules and materials recovery innovations
System Integration	PV is widely integrated into grids; hybrid PV-battery systems are commercially viable	Intermittency management; grid congestion; limited seasonal storage	PV-hydrogen coupling; large-scale hybrid PV-thermal storage; smart grid integration for dispatchable renewables
Digitalization & O&M	AI/ML for fault detection and predictive maintenance is emerging; digital twins are under development	Data interoperability, cybersecurity risks, and high initial costs for digital systems	Advanced digital twins for PV farms; real-time adaptive control; global AI-enabled PV operation platforms
Socio-Economic Dimensions	PV creates jobs and drives decarbonization; LCOE parity with fossil fuels in many regions	Unequal access in developing economies, land use conflicts, and policy uncertainty	Equitable PV access; community-based PV; integration with sustainable development goals (SDGs)

Table 1 synthesizes the evolution of solar photovoltaic technology by systematically linking state-of-the-art achievements, frontier challenges, and future research directions across multiple interdependent domains. Rather than serving as a descriptive summary, the table reveals a fundamental shift in PV's innovation trajectory, from a predominantly device-centric, efficiency-driven paradigm toward a multidimensional co-evolution encompassing material science, manufacturing economics, system integration, circular-economy principles, and socio-economic transformation. Importantly, the juxtaposition of these domains exposes critical tensions, such as the mismatch between rapid efficiency gains in advanced devices and the slower maturation of sustainability, recycling infrastructure, and equitable access. These insights indicate that future PV progress cannot be evaluated solely through efficiency improvements or cost reductions. Still, they must be assessed in terms of their systemic resilience and their long-term environmental and social implications.

To complement this analytical synthesis, Figure 1 presents a conceptual roadmap illustrating the non-linear progression of PV technologies from conventional silicon-based systems toward next-generation solar energy ecosystems. The roadmap emphasizes a clear transition from a narrow focus on performance and cost competitiveness to broader objectives of sustainability, integration, and resilience. Crucially, it demonstrates that the future success of PV will not hinge on a single technological breakthrough, but on the convergence and coordinated advancement of multiple innovation streams, including novel materials, circular design and recycling strategies, system-level integration with storage and hydrogen, and AI-driven digitalization. Together, Table 1 and Figure 1 underscore that the next phase of PV development is defined by systemic convergence rather than isolated optimization, positioning solar photovoltaics as a foundational pillar of resilient, circular, and net-zero global energy systems.

Conclusion

Solar photovoltaic technology has achieved remarkable progress over the past two decades, with crystalline silicon maintaining dominance and cost reductions driving unprecedented global deployment. However, the next phase of PV development demands more than incremental efficiency improvements. Critical challenges remain in advancing material stability, scaling up tandem and thin-film devices, and embedding circular-economy principles to address the looming end-of-life PV waste issue. At the same time, PV integration with storage, hydrogen, and smart grids, supported by AI-driven digitalization, will be essential for transforming intermittent solar power into a reliable cornerstone of future energy systems.

The trajectory of PV must therefore be redefined from a device-centric paradigm to a holistic system perspective that prioritizes sustainability, resilience, and socio-economic inclusivity. Rather than focusing solely on pushing technological frontiers, the future of PV lies in its ability to function as the backbone of net-zero energy systems, bridging technological innovation with equitable deployment, circularity, and global energy justice. This shift in perspective will ultimately determine whether PV remains a disruptive technology or evolves into a mature, sustainable, and transformative force in the global energy transition.

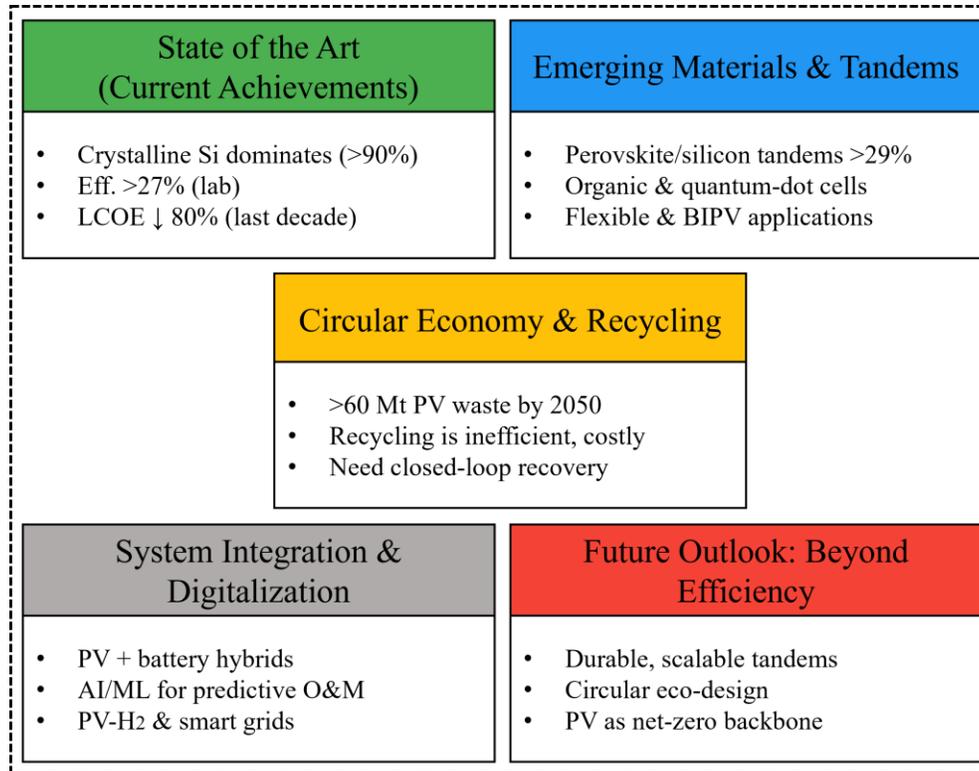


Figure 1. Roadmap of Next-Generation Solar PV Technology.

Acknowledgment

The authors acknowledge the institutional support from Politeknik Negeri Semarang and the valuable technical assistance from the Center for Applied Energy and Thermofluid Studies (CAETS) - CV. Kemossasak Teknologi. We also thank our colleagues and the anonymous reviewers for their constructive feedback. Any remaining errors are solely the responsibility of the authors.

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