REVIEW ARTICLE

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Recent Developments in Solar Energy (2023–2025)

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Abstract

Solar photovoltaics (PV) have entered an age of rapid innovation and widespread deployment. Between 2023 and 2025, crystalline silicon transitioned from p-type PERC to n-type architectures (TOPCon, heterojunction, and back-contact), and perovskite–silicon tandems achieved record-breaking efficiencies and early commercial rollouts. Within the system space, bifacial modules, agrivoltaics, and floating PV unlocked technical and geographical horizon. Concurrent innovations in power electronics, in particular grid-forming inverters and DC-coupled storage, are beginning to address grid integration challenges with very high penetrations of PV. Recent developments in materials, cell and module technologies, balance-of-system (BOS) technology, and grid integration are discussed in this paper; the remaining challenges in durability, supply chains, and market design are acknowledged; and the paper concludes with pragmatic advice for policymakers, industry, and researchers.

Keywords: photovoltaics, perovskite–silicon tandem, TOPCon, heterojunction, bifacial, agrivoltaics, floating PV, grid-forming inverters, storage, curtailment

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Introduction

Solar power has emerged as one of the fastest-growing and most revolutionary sectors in the global energy mix. As nations look to meet climate targets, decarbonize electricity, and reduce fossil fuel dependence, solar photovoltaics (PV) have been more important than ever. Over the past twenty years, the cost of solar power has decreased by leaps and bounds—more than 80% since 2010—making PV the least-cost renewable energy in all corners of the globe (IRENA, 2024). This cost plummet has come in tandem with a tremendous wave of innovation in materials, production, and system design, moving solar energy to the center stage of the global energy transition.

The last three years (2023–2025) have seen especially substantial progress beyond incremental efficiency gains. On the module and cell level, novel architectures such as TOPCon, heterojunction (HJT), and perovskite–silicon tandem configurations are shattering record-breaking performance benchmarks and paving the way to commercial acceptance. At the system level, bifacial, agrivoltaic, and floating PV installations are demonstrating how solar can be deployed more variably in a variety of environments, including agricultural land and aquatic systems. Grid integration studies have also moved rapidly forward, with grid-forming inverters and PV-plus-storage technologies allowing increased penetration levels without compromising on reliability.

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In addition to technological innovation, sustainability and supply chain resilience are central themes. Silver thrifting, wafer thinning, and recycling strategies are increasingly seen as central to ensuring that high deployment rates of PV do not erode long-term availability of resources. These activities are added to the broader trend towards circular economy models in clean energy.

Despite all this, problems remain in mass-producing, having long-term reliability under diverse climatic conditions, and supplying large amounts of solar energy to the power grid. Enjoyment of the latest achievements, therefore, requires not only an emphasis on technical efficacy but also a sensitivity to system-level, economic, and environmental factors. This report captures recent innovation in solar technology and deployment during the period 2023 to 2025, reviews emerging trends and challenges, and makes policy recommendations for sustaining momentum toward a cleaner, more resilient world energy system.

Literature Review

There has been a substantial transition in the solar PV industry to higher-efficiency n-type architectures, i.e., TOPCon, heterojunction (HJT), and back-contact cells, from the established p-type PERC cells. The commercial modules now achieve efficiencies over 22% regularly, with lab records surpassing 26% (PV Tech, 2025). Hybrid back-contact architectures are increasingly applied in premium and space-constrained applications. Meanwhile, perovskite–silicon tandem solar cells have demonstrated certified efficiencies exceeding 30% (Nature Photonics, 2025). Pilot installations in the United States and Europe, led by companies such as Oxford PV, indicate the strong potential of tandem technology for near-term commercialization (Oxford PV, 2024). Studies also highlight the importance of improving durability by reducing light-induced degradation, silver consumption, and encapsulant failures under extreme operating conditions (NREL, 2024).

System-Level Innovations

At the system level, several innovations are expanding the applications of PV. Bifacial modules have demonstrated 5–15% energy yield gains site-dependent on parameters such as albedo and module tilt (EPJ Photovoltaics, 2024). Agrivoltaic systems combine crop cultivation with energy generation, reporting double benefits in food yield and land-use efficiency, particularly in semi-arid and arid regions (Nature Communications Earth & Environment, 2025). Floating PV (FPV) installations also are gaining momentum, with cumulative capacity to surpass 20 GW by 2030. Asia and Europe are driving deployments, assisted by nascent standards for enhancing resilience in aquatic environments (S&P Global, 2024).

Grid Integration

As PV penetration increases, grid integration has been an top research and deployment focus. Grid-forming inverters are increasingly recognized for their ability to provide virtual inertia, black-starting capability, voltage regulation, and fault-ride-through capability that are essential to stabilizing renewable-dominant grids (NREL, 2024). To complement this, PV-plus-storage systems—especially DC-coupled architectures—are being adopted to recover clipped energy, reduce curtailment, and improve project economics in solar-high-penetration markets.

Durability and Supply Chains

Life cycle sustainability of PV is another growing priority. Silver thrifting, wafer thinning, and encapsulant durability under diverse climates are a few of the key areas of concern. Recycling pathways are also being developed for both silicon and perovskite modules, with circular economy approaches seeming to address long-term material sustainability and end-of-life management.

Trends

Recent developments highlight three dominant trends in solar energy. First, ongoing efficiency improvements of cells and modules, specifically through perovskite–silicon tandems, herald the beginning of the next efficiency era. Second, diversification at the system level—through bifacial, agrivoltaic, and floating PV—demonstrates the ways in which solar can be developed beyond conventional rooftop and utility-scale applications. Third, incorporation of storage and grid-forming capability represents a paradigm shift from solar as an intermittent resource to solar as a dispatchable, grid-supportive technology.

Challenges

Despite rapid progress, several challenges are placed on the path of deployment at large scale. Material sustainability remains a problem, particularly reliance on silver and rare metals. Durability-related issues like light and moisture degradation persist for emerging cell architectures such as perovskites. Grid integration challenges include ensuring stability at very high levels of penetration while reducing economic curtailment. Scaling new technology from pilot deployment to gigawatt-scale deployment also requires surmounting bottlenecks in manufacturing and establishing robust supply chains.

Recommendations

- To sustain solar energy momentum, policymakers, researchers, and industry leaders should:
- Accelerate commercialization of tandem technologies via pilot-to-market transition and stringent reliability testing.
- Promote system-level diversification by incentivizing agrivoltaics and floating PV where land and water are available.
- Strengthen grid integration frameworks through investments in grid-forming inverters, hybrid storage systems, and flexible market design.
- Encourage circular economy concepts by investing in recycling plants and encouraging material recovery of silicon and perovskite panels.
- Enhance supply chain resilience by reducing dependence on the critical minerals and expanding domestic production capacity.

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