

Emerging Frontiers in Solar Photovoltaics: Efficiency Breakthroughs, Grid-Forming Innovation, and the Path to 2030

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Abstract

The global solar photovoltaic (PV) sector has entered a transformative phase marked by unprecedented deployment, structural economic asymmetries, and rapid technological innovation. As the world moves toward the COP28 goal of tripling renewable energy capacity by 2030, solar PV has emerged as the most influential driver of this transition. By 2024, global installations reached a record-breaking 600 GW, supported by historically low Levelized Cost of Energy (LCOE) values that have positioned solar as the cheapest source of new electricity generation. Yet beneath this expansion lies a complex set of challenges, including severe manufacturing overcapacity -particularly in China -intense price competition, and growing geopolitical fragmentation in supply chains. At the same time, solar technology is undergoing a paradigm shift, with p-type PERC architectures rapidly giving way to high-efficiency n-type TOPCon and heterojunction designs, while perovskite-silicon tandems surpass 34% efficiency and signal a new frontier in photovoltaic physics. On the grid side, the displacement of synchronous generation compels the adoption of grid-forming (GFM) inverters and hybrid solar-battery plants, enabling inverter-based resources to assume critical stability services such as inertia, voltage support, and black start. Environmental sustainability has simultaneously become central to the sector's evolution, with rising concerns over end-of-life PV waste, circularity gaps across regions, and toxicity mitigation in emerging perovskite technologies. Drawing from contemporary economic data, technical advancements, and policy developments, this paper synthesises these interconnected dynamics to present a comprehensive assessment of the solar sector's trajectory from 2025 to 2030. It argues that the coming years will define whether solar PV matures into a fully integrated, circular, and grid-supportive energy system or whether unresolved challenges hinder its long-term promise. The findings highlight a sector at a decisive crossroads -poised for historic expansion yet dependent on coordinated innovation in manufacturing, grid architecture, environmental governance, and global industrial policy.

Keywords: Solar Photovoltaics; Levelized Cost of Energy (LCOE); TOPCon; Perovskite-Silicon Tandem Cells; Grid-Forming Inverters; Battery Energy Storage Systems; Renewable Energy Transition; Circular Economy; Solar Manufacturing Overcapacity; Energy Policy; Photovoltaic Waste Management.

1. Introduction

The global energy system is undergoing one of the most consequential structural shifts since the industrial revolution, driven by the rapid rise of solar photovoltaics (PV) as a central pillar of worldwide electricity generation. As of 2025, solar PV is no longer positioned at the periphery of national energy portfolios; instead, it has emerged as a defining technology of the twenty-first century, reshaping supply chains, investment patterns, manufacturing geographies, and policy frameworks. This transformation marks what many analysts describe as a “solar singularity” -a confluence of economic competitiveness, technological acceleration, and grid-level integration capabilities that together herald a new era in the global energy transition (IEA, 2024; Lazard, 2025).

The speed and scale of solar deployment over the past five years have exceeded earlier forecasts by an extraordinary margin. According to the International Energy Agency, nearly 600 GW of solar capacity was installed in 2024 alone, surpassing the entire global nuclear fleet and signaling the beginning of a decade where renewable energy growth is expected to outperform all historical benchmarks of electricity expansion (IEA, 2024). This momentum is reinforced by the global commitment at COP28 to triple renewable capacity by 2030, a target that places disproportionate reliance on solar PV due to its unmatched scalability, modularity, and continuously declining costs. These global ambitions rest on the premise that solar PV deployment will reach 5,500 GW of new capacity by 2030, effectively making it the largest single source of installed power generation capacity worldwide (SolarPower Europe, 2024).

While the sector's outward success is remarkable, the internal dynamics reveal a more complex story -one marked by market asymmetries, technological transitions, and systemic integration challenges. On the one hand, the downstream market for solar deployment is thriving, driven by historically low Levelized Cost of Energy (LCOE) values, which for utility-scale solar range between \$38 and \$78 per MWh, making it the cheapest form of new electricity generation in the majority of global markets (Lazard, 2025). On the other hand, the upstream manufacturing sector faces unprecedented pressures stemming from severe overcapacity, plummeting module prices, and intense competition, particularly within China, which accounts for more than 80% of global PV manufacturing supply (PV Magazine, 2025). This duality -economic prosperity for developers but financial stress for manufacturers -forms the backbone of the present solar paradox.

Concurrently, the sector stands at a technological inflection point. The dominance of p-type PERC architectures, which drove mass adoption through the 2010s and early 2020s, has come to an end as manufacturers pivot toward n-type TOPCon and heterojunction (HJT) technologies, which offer higher efficiencies, better stability, and improved bifacial performance (PV Magazine, 2024). Even more transformative is the rapid advancement of perovskite-silicon tandem cells, with laboratory efficiencies surpassing 34% and commercial pathways accelerating due to breakthroughs in interface engineering and stability enhancement (NREL, 2025). These innovations collectively push solar technologies beyond the long-assumed efficiency ceiling of crystalline silicon, opening new frontiers for high-performance modules capable of reshaping land-use planning, project economics, and long-term energy yield.

At the system level, the interaction between solar PV and legacy electrical grids poses another pivotal challenge. The rise of inverter-based generation -while advantageous in flexibility and scalability -has exposed weaknesses in grid stability due to the lack of physical inertia traditionally provided by synchronous generators. As solar penetration increases, grid operators are increasingly relying on grid-forming (GFM) inverters, advanced energy storage systems, and hybrid solar-plus-battery configurations to maintain frequency, voltage stability, and system strength (AEMO, 2025). For regions like Australia, Texas, and parts of Europe, this transition from grid-following to grid-forming operation represents the most significant operational shift in modern grid history.

Beyond technical and economic considerations, the sector also confronts pressing environmental and regulatory challenges, particularly related to lifecycle impacts and end-of-life (EoL) waste. By 2030, global PV waste streams will reach millions of tonnes, raising questions about recycling capacity, material recovery, and the long-term sustainability of photovoltaic deployment (IEA-PVPS, 2024). The European Union currently leads in establishing regulatory frameworks for PV circularity, while countries like the United States and India lag behind with fragmented or emerging policies. Additionally, the rapid emergence of perovskite technologies has sparked debate over lead toxicity, prompting accelerated research into encapsulation and sequestration techniques that minimise environmental hazards during module breakage or disposal (MDPI, 2024).

This research paper aims to synthesise these varied yet interconnected dimensions -economic asymmetries, technological convergence, grid-forming innovation, and environmental sustainability -into a coherent narrative that reflects the state of the solar PV industry in 2025 and its trajectory toward 2030. Drawing on the latest empirical data, technical literature, policy analyses, and industry developments, the paper argues that the next five years will define the maturity phase of the global solar industry. This period will determine whether solar PV transitions smoothly into a stable, circular, grid-integrated energy ecosystem, or whether unresolved challenges across manufacturing, waste management, and grid stability hinder its long-term promise.

The subsequent sections examine:

- (1) the shifting economic landscape and market asymmetries;
- (2) the technological frontier of TOPCon and perovskite tandem architectures;
- (3) the systemic integration of solar into weak and decentralised grids; and
- (4) environmental and circular-economy considerations shaping the sector's sustainability profile.

Together, these analyses provide a comprehensive framework for understanding the solar singularity as both an opportunity and a decisive test for global energy systems.

2. Results and Discussion: The Economic Landscape and Market Asymmetries

The economic landscape of the global solar PV industry between 2024 and 2025 is marked by a peculiar dual character -one that reflects extraordinary momentum in deployment and simultaneously unprecedented stress in manufacturing and upstream supply chains. This duality is not merely anecdotal but represents a structural asymmetry that has come to define the sector’s trajectory in the mid-2020s. On the one hand, the downstream market is flourishing: solar PV has achieved the lowest Levelized Cost of Energy (LCOE) in the history of electricity generation, and utility-scale installations continue to exceed global forecasts (Lazard, 2025). On the other hand, producers in the upstream segment face acute financial pressures due to a profound supply-demand mismatch, collapsing module prices, and intensifying geopolitical trade barriers (PV Magazine, 2025).

Together, these forces create an economic paradox. The sectors benefiting from cost declines -developers, utilities, and end-users -are not the same sectors absorbing the financial shocks. This divergence introduces important implications for industrial policy, technological innovation, and long-term market stability. Understanding these asymmetries is crucial for evaluating how solar PV will scale from hundreds of gigawatts per year today to terawatt-level annual deployment by 2030.

Levelized Cost of Energy (LCOE) Analysis 2025: A New Benchmark of Economic Dominance

The Levelized Cost of Energy (LCOE) remains the most widely used indicator for comparing different power generation technologies. Lazard’s 2025 LCOE+ report, now in its eighteenth edition, offers one of the clearest assessments of current global energy economics. Despite persistent macroeconomic challenges -including elevated interest rates, inflationary pressures, and supply chain dislocations -solar PV has retained and strengthened its position as the lowest-cost source of new electricity generation across most of the world (Lazard, 2025). The 2025 analysis places the unsubsidised LCOE of utility-scale solar PV within the range of \$38–\$78 per MWh, making it cost-competitive with or cheaper than the marginal operating cost of existing fossil fuel generation in numerous jurisdictions (PV Tech, 2025). This cost range reflects regional variations in labour, land, financing rates, and supply chain access, but the global trend remains consistent: solar PV has established itself as the *economic frontrunner*, independent of subsidy support. Comparatively, the LCOE for newly built natural gas combined cycle plants -the traditional benchmark for flexible baseload -is estimated between \$77 and \$106 per MWh, while new coal-powered generation is even higher, often exceeding \$120 per MWh when environmental compliance costs are included (Lazard, 2025). Nuclear new-build projects remain the most expensive option, with LCOE values typically surpassing \$140–\$200 per MWh, a consequence of steep capital expenditures and prolonged construction timelines. The economic logic of choosing solar is therefore compelling. In many markets, it is now rational not only to avoid new fossil fuel plants but also to *retire existing coal and gas units* that cannot compete with the operating costs of solar farms. This inversion of the historical “green premium” -where renewables once required subsidies to compete -has dramatically reshaped the global investment environment. Nearly 91% of renewable capacity added in 2024 was cheaper than fossil fuel alternatives (IRENA, 2025), reinforcing the economic maturity of solar PV as the dominant technology of future energy systems.

Table 1. Comparative LCOE Values for Major Power Generation Technologies (2025)

| Technology Type | LCOE (USD/MWh) | Range | Trend (2024–2025) | Key Cost Drivers |
|---------------------------|----------------|-------|-------------------------|--|
| Utility-Scale Solar PV | 38–78 | | Stable → Slight decline | Module oversupply, BOS reductions, efficiency gains |
| Onshore Wind | 37–86 | | Stable | Siting complexity, turbine costs, interest rates |
| Gas Combined Cycle (CCGT) | 77–106 | | Increasing | Fuel volatility, turbine scarcity, high capex |
| Gas Peaker Plants | 150–260 | | Increasing | Low utilisation rates, fuel spikes |
| Nuclear (New Build) | 140–200+ | | Stable / High | Direct capital intensity, regulatory costs |
| Utility Solar + Storage | 50–131 | | Decreasing | Lithium price decline, inverter integration improvements |

Sources: Lazard (2025); IEA (2024); Renewable Energy Institute (2025).

Storage Integration and the Evolving Economics of Firm Power

A central critique of solar PV has always been its intermittency. Yet the cost of addressing this intermittency has fallen dramatically due to rapid improvements in battery technology, manufacturing scale, and integration practices. The Levelized Cost of Storage (LCOS) and Levelized Cost of Firming metrics introduced in recent LCOE methodologies help quantify the incremental cost required to transform variable solar output into firm, dispatchable power.

As of 2025, utility-scale solar-plus-storage systems exhibit an LCOE range of \$50–\$131 per MWh, placing them in direct competition with gas peaker plants, which typically range from \$150–\$260 per MWh (Lazard, 2025). This cost convergence marks one of the most significant energy economic transformations of the decade.

A major contributor to this trend is the stunning drop in lithium carbonate prices through 2024, driven by oversupply in China, which exerts profound downward pressure on global battery costs. Battery pack prices fell by approximately 33% in 2024, leading to cheaper energy storage systems and enabling greater financial viability for hybrid solar–battery configurations (Renewable Energy Institute, 2025).

The economic viability of storage is also supported by rising revenues for grid services such as frequency control, synthetic inertia, voltage support, and reserve capacity -services traditionally provided by fossil-fuel generators. As these ancillary markets expand, energy storage becomes increasingly central not only to firming solar output but also to supporting overall grid stability.

The Manufacturing Glut: Structural Oversupply and Market Destabilisation

Despite the strong performance of solar deployment, the upstream industry has entered a period of pronounced turbulence. The global manufacturing capacity for solar modules exceeded 1,100 GW in 2024, while demand stood at roughly 593 GW -a mismatch that exerted massive downward pressure on module prices (IEA-PVPS, 2024).

This oversupply crisis represents more than routine market volatility; it is a structural imbalance that has reshaped the competitive dynamics of the industry. The situation is driven largely by China’s aggressive manufacturing expansion, supported by provincial incentives, low-cost financing, tax exemptions, and long-term industrial policy. China’s manufacturing capacity across the PV value chain -from polysilicon to wafers, cells, and modules -now exceeds 80% of global supply, giving it unparalleled influence over global pricing and technology adoption (PV Magazine, 2025).

Market “Involution” in China and the Race to the Bottom

In China, the phenomenon often described as “involution” (neijuan) encapsulates a hyper-competitive environment where manufacturers engage in rapid capacity expansion not to meet demand but to maintain or increase market share in an overcrowded field. This has triggered destructive price competition, collapsing module prices by nearly 50% between 2023 and 2024 (OPIS, 2025).

Consequences include:

- Billions in financial losses reported by top manufacturers in early 2025.
- Cancellation or delay of nearly 300 GW of polysilicon and 200 GW of wafer capacity projects, valued at more than USD 25 billion (PV Magazine, 2025).
- Forced consolidation, with Tier-2 and Tier-3 producers exiting the sector.
- Government intervention, as China’s Ministry of Industry and Information Technology (MIIT) called for curbing “irrational competition” and phasing out outdated production lines.

Ironically, while this glut has strained producers, it has dramatically accelerated global solar adoption by driving down prices and enabling grid-scale solar to flourish even without subsidies.

Geopolitical Fragmentation and Trade Barriers

The imbalance created by low-cost Chinese production has prompted a wave of protectionist policies aimed at shielding domestic industries in the United States, India, and parts of Europe.

United States

The Inflation Reduction Act (IRA) has catalysed a domestic manufacturing renaissance, offering production tax credits for each stage of the PV supply chain. However, manufacturing costs in the U.S. remain 2–3 times higher than those in China, meaning domestic modules are competitive primarily because of incentives (PV Magazine USA, 2025). Without IRA support, U.S. solar deployment would face severe cost escalation.

India

India's Production Linked Incentive (PLI) scheme and high Basic Customs Duty (BCD) on imported modules reflect a national goal of building self-sufficiency in solar manufacturing. Expected capacity expansion may triple India's PV output by 2026, but cost parity with China remains elusive due to input material imports and higher domestic financing costs (IEA, 2024).

European Union

The EU faces a difficult structural dilemma -balancing ambitious renewable energy targets with an overdependence on Chinese imports. While the Net-Zero Industry Act (NZIA) seeks to reshore manufacturing and establish supply chain resilience, European producers struggle to compete with Chinese pricing, threatening their long-term viability.

3. Results and Discussion: Technological Frontiers and Material

The period from 2024 to 2025 marks one of the most significant technological transitions in the history of the photovoltaic industry. A decade of dominance by p-type Passivated Emitter and Rear Cell (PERC) technology has come to a definitive close, giving way to an era shaped by more advanced, higher-efficiency n-type architectures and rapid progress in perovskite–silicon tandem cells. These developments are not incremental but represent a fundamental reshaping of photovoltaic science, manufacturing strategy, and commercial deployment. As the industry seeks to meet an unprecedented global demand for low-carbon energy, technological innovation has become a critical lever for improving power density, reducing levelized costs, and enabling solar PV to integrate more effectively into evolving energy systems.

The ascent of n-type silicon technologies, especially Tunnel Oxide Passivated Contact (TOPCon), is central to this ongoing transformation. While p-type PERC modules long served as the workhorse of global PV deployment due to their favourable cost-performance balance, they have approached their practical efficiency ceiling of approximately 24.5 percent. Manufacturers have therefore pivoted decisively toward n-type technologies, which offer inherently higher carrier lifetimes, greater stability under illumination, and immunity to light-induced degradation. Among the various n-type options, TOPCon has emerged as the dominant successor because it provides significant performance gains without requiring the complete overhaul of existing PERC production lines. A simple industrial upgrade -adding ultra-thin tunnelling oxide layers and polycrystalline silicon passivating contacts -enables manufacturers to transition economically while achieving mass-production efficiencies of 25–26 percent. The success of TOPCon reflects both its technical advantages and its practical manufacturability, allowing established producers to adapt quickly without major capital investment (PV Magazine, 2024).

Another significant trend reinforcing this transition is the widespread commercial adoption of bifacial modules, which benefit substantially from n-type architectures. Unlike monofacial panels, bifacial modules capture both direct and reflected light, enhancing energy yield by 5–30 percent depending on surface albedo conditions. Their growing popularity is reflected in long-term projections, which indicate that bifacial designs will represent more than half of the global module market by 2035. Combined with the durability benefits of glass–glass encapsulation -now widely considered the industry standard -the rise of bifacial n-type modules is reshaping expectations for long-term performance, energy output, and system-level cost optimisation. In effect, the shift toward TOPCon and bifacial architectures marks the industry's full transition into the high-efficiency era, where performance is as essential as cost competitiveness.

While n-type silicon technologies define the present, perovskite–silicon tandem cells increasingly define the future. These tandem devices combine a wide-bandgap perovskite top cell with a crystalline silicon bottom cell, enabling them to capture a broader range of the solar spectrum than either material can achieve individually. This

configuration makes it possible to surpass the Shockley–Queisser efficiency limit of single-junction silicon, often cited at 29.4 percent. Between 2023 and 2025, record-breaking advancements in tandem efficiencies have occurred at remarkable speed. In April 2025, LONGi achieved a certified world record of 34.85 percent efficiency for a two-terminal tandem device, verified by the National Renewable Energy Laboratory (NREL). This milestone, along with similar breakthroughs from JinkoSolar and research institutions globally, demonstrates that tandem architectures are not merely theoretical innovations but are approaching commercial readiness much sooner than previously predicted.

The rapid progress of tandem cells is largely driven by innovations in interface engineering and passivation, areas that historically posed major bottlenecks to commercial viability. The interface between the perovskite layer and the silicon sub-cell is prone to non-radiative recombination losses, which reduce voltage and fill factor. To overcome this barrier, researchers have introduced a range of solutions including self-assembled monolayers, optimised tunnelling oxide layers, and asymmetric passivation structures that better align energy levels and suppress interfacial traps. Notably, research by LONGi, Fraunhofer ISE, and the University of Freiburg has shown that techniques originally developed for silicon -such as whole-film passivation -can be adapted successfully to perovskite layers, reducing recombination pathways and increasing device photovoltage. These innovations represent a significant step forward because they not only increase efficiency but also improve long-term operational stability, an essential requirement for commercial deployment.

Despite these achievements, the stability of perovskite materials remains one of the central challenges. Perovskites are intrinsically sensitive to moisture, UV exposure, and thermal stress, making them more vulnerable to degradation than conventional silicon. However, recent advancements have substantially narrowed this durability gap. Novel passivation molecules, polymer-based structural supports, and europium-based metal-organic frameworks (Eu-MOFs) have been shown to stabilise crystal structures, suppress ion migration, and mitigate the effects of environmental exposure. Additional progress in glass–glass encapsulation and barrier film design has further reinforced perovskite stability, enabling tandems to approach the lifetimes expected of commercial modules. Although tandem modules have not yet demonstrated full 25-year operational warranties under field conditions, the pace of improvement suggests that this milestone may be achieved within the next phase of research and development.

Taken together, the technological evolution of solar PV reflects a sector undergoing rapid and multidimensional transformation. TOPCon’s rise marks the maturation of silicon technology, while the emergence of perovskite–silicon tandems signals the beginning of a new performance frontier. These advancements have profound implications for land-use efficiency, manufacturing economics, system-level design, and the broader decarbonisation agenda. As efficiencies climb and costs decline, solar PV becomes capable not only of replacing fossil-based generation but of enabling new architectures in grid design, energy storage integration, and large-scale electrification. The technological frontiers explored during 2024–2025 therefore represent more than incremental scientific progress -they lay the foundation for the next generation of global energy systems.

4. Results and Discussion: Grid Integration and System Stability

The rapid expansion of solar photovoltaics has transformed not only the global electricity generation landscape but also the operational characteristics of modern power grids. As solar penetration increases, electricity networks that were originally designed around synchronous, centralised thermal generation now face unprecedented technical challenges. Historically, grid stability has relied on the physical inertia provided by large rotating generators in coal, gas, hydro, and nuclear plants. These synchronous machines possess substantial mechanical momentum, allowing them to buffer the system against sudden frequency deviations and power disturbances. However, solar PV systems are connected via power electronics rather than rotating machinery, eliminating the natural inertia that has traditionally helped maintain frequency stability in interconnected grids (AEMO, 2025; IEA, 2024). As regions approach higher shares of inverter-based renewable energy, the absence of such inertia becomes increasingly problematic, exposing the grid to rapid rates of change of frequency, lower system strength, voltage instability, and a heightened risk of widespread outages.

To address these challenges, the industry has begun transitioning from conventional grid-following inverters to the more advanced grid-forming configurations. Grid-following inverters depend on a stable grid reference to

synchronise; they operate by locking onto the frequency and voltage provided by synchronous generators. As such, they cannot provide support during major disturbances or contribute meaningfully to frequency regulation beyond limited reactive power services. Grid-forming inverters, by contrast, can establish their own voltage and frequency references, effectively emulating the behaviour of synchronous machines through advanced control algorithms. These inverters generate what is often termed “virtual inertia,” enabling them to help arrest frequency decline, support black-start operations, and stabilise weak-grid regions where solar generation dominates. This technological shift marks a fundamental rethinking of the role of power electronics within the grid, positioning inverter-based resources as active providers of system services rather than passive energy sources (NREL, 2024).

Australia’s National Electricity Market (NEM) has emerged as a global testbed for demonstrating the real-world viability of grid-forming technologies. With some regions already operating at 80–90 percent instantaneous renewable penetration, Australia encounters stability challenges earlier and more intensely than most other power systems. For this reason, AEMO’s engineering pathways have consistently highlighted the need for grid-forming capabilities to maintain reliability as synchronous generation continues to decline (AEMO, 2025). Two high-profile Australian projects illustrate this transition in action. The Pelican Point Battery Energy Storage System (BESS) in South Australia is a 200 MW / 400 MWh installation equipped with Sungrow’s PowerTitan 2.0 platform, which incorporates sophisticated grid-forming controls. This system provides fast frequency response, synthetic inertia, and enhanced system strength, allowing South Australia to maintain operational stability even when gas generators operate at minimum output during periods of high solar production (SolarQuarter, 2025). The project not only validates the technological readiness of grid-forming batteries but also underscores their potential to anchor grid operations in regions with extremely high renewable penetration.

Similarly, the Koorangie Energy Storage System in Victoria demonstrates the capacity of grid-forming technologies to strengthen electrically weak regions of the network. This 185 MW / 370 MWh project, built using Tesla Megapacks, plays a pivotal role in stabilising the so-called “rhombus of regret,” a part of the Victorian grid notorious for transmission bottlenecks and low system strength. Through its virtual synchronous machine (VSM) capabilities, the Koorangie BESS enhances the thermal transfer capacity of transmission lines, mitigates voltage instability, and reduces renewable curtailment by enabling more consistent power flows from remote solar and wind farms. Importantly, it offers empirical evidence that inverter-based resources can operate autonomously in weak-grid environments while maintaining the quality and reliability of supply (PV Magazine, 2025).

Beyond stand-alone battery storage systems, inverter manufacturers are increasingly embedding grid-forming capabilities directly into their photovoltaic technologies. Huawei’s FusionSolar 9.0 platform, launched in late 2025, epitomises this shift. The system integrates artificial intelligence for real-time optimisation, incorporates grid-forming features into string inverters, and employs high-voltage AC architectures that reduce both cable losses and balance-of-system costs. These innovations transform solar plants from passive generators into actively stabilising grid assets capable of damping oscillations, regulating voltage, and supporting partial islanded operation during disturbances. As such, grid-forming functionality is becoming a standard expectation for next-generation solar deployments rather than a specialised add-on reserved for large storage plants (PV Magazine, 2025).

The growing complementarity between solar PV and battery storage further reinforces this technological shift. Hybrid solar–battery systems increasingly serve as the preferred architecture for new utility-scale projects because they combine the cost-effective generation of solar with flexible dispatchability and stability services provided by storage. Such hybrid systems reduce renewable curtailment, enhance the reliability of variable output, and replace the ancillary services traditionally supplied by fossil-fuel generators. With further cost declines expected for lithium-ion storage and advanced control systems, hybrid plants are projected to constitute the majority of new renewable power capacity by 2030 (IEA, 2024). Their widespread deployment marks a decisive transition in grid design, where the stability of the entire system gradually shifts from mechanical inertia to algorithmic control.

As innovations in grid-forming inverters and hybrid storage solutions continue to mature, regions like South Australia are beginning to experience periods of nearly 100 percent inverter-based operation. Until recently, such a scenario would have been considered technically infeasible due to concerns over frequency stability and the lack of synchronous machine inertia. Yet real-world performance in Australia demonstrates that inverter-based resources, when equipped with advanced grid-forming capabilities, can sustain stable grid operation and even

outperform conventional generation in certain stability metrics. This shift signals the emergence of a fundamentally new grid paradigm -one in which renewable energy does not merely displace fossil fuels in terms of generation capacity but also assumes full responsibility for maintaining power system stability and operational resilience (AEMO, 2025).

5. Results and Discussion: Environmental Lifecycle and Circular Economy

The unprecedented scale and speed at which solar photovoltaic (PV) systems are being deployed globally has brought renewed attention to their environmental lifecycle, resource intensity, and end-of-life (EoL) management. Although solar energy is widely celebrated as a clean and low-carbon technology, its environmental profile extends far beyond its operational phase. The sustainability of PV systems must therefore be evaluated across their entire lifecycle -from raw material extraction, manufacturing, transport, and installation to long-term maintenance, decommissioning, and final disposal. As global solar deployment accelerates toward multi-terawatt levels, the magnitude of these lifecycle impacts becomes increasingly significant, prompting pressing questions regarding carbon footprints, material circularity, recycling infrastructure, and regulatory coherence across regions (IEA-PVPS, 2024). Addressing these questions is essential to ensure that the solar sector evolves not only as a decarbonisation driver but also as a model for environmentally responsible industrial growth.

A key dimension of lifecycle sustainability concerns the embodied carbon of photovoltaic manufacturing. Traditional crystalline silicon modules, which continue to dominate the global market, require energy-intensive production processes, particularly during polysilicon purification and ingot crystallisation. These stages often involve extremely high temperatures -exceeding 1400°C -and, depending on manufacturing location, may rely heavily on coal-powered electricity. As a result, monocrystalline silicon modules typically exhibit an average carbon footprint of about 24.6 grams of CO₂-equivalent per kilowatt-hour of electricity generated over their lifetime (Cornell University, 2024). Although this figure is significantly lower than that of fossil fuel alternatives, it nonetheless highlights the embedded emissions associated with upstream operations. Improvements in energy efficiency, the use of renewable-powered manufacturing, and increasing reliance on hydro- or nuclear-based electricity grids in some regions have partially mitigated these impacts, yet silicon PV remains more carbon-intensive than emerging thin-film technologies.

In contrast, perovskite-based tandem solar technologies demonstrate a markedly lower environmental profile, positioning them as promising candidates for achieving deeper sustainability benchmarks. Perovskite-silicon tandems, which combine a perovskite absorber layer with a conventional silicon wafer, require far less energy during production due to low-temperature processing techniques. Their thin-film architecture reduces material consumption significantly, and the absence of energy-intensive wafer-slicing processes further reduces carbon intensity. Life cycle assessment studies indicate that these tandem designs yield carbon footprints as low as 10.7 grams of CO₂-equivalent per kilowatt-hour -less than half that of standard silicon modules (MDPI, 2024). Furthermore, perovskite tandems exhibit one of the shortest energy payback times among photovoltaic technologies. A perovskite tandem requires approximately 0.35 years to generate the amount of energy consumed during its manufacturing, compared to about 1.52 years for silicon modules. These figures underscore the substantial environmental advantages of tandem technologies and highlight their potential role in reducing the overall carbon intensity of future solar energy systems.

Beyond embodied carbon, one of the most significant environmental challenges facing the PV sector is the looming “waste tsunami,” a term used increasingly by researchers and policymakers to describe the anticipated surge in decommissioned solar modules over the coming decades. By 2030, global PV waste volumes are expected to reach several million tonnes, rising to more than 60 million tonnes by 2050 if current deployment and retirement trends continue (IEA-PVPS, 2024). This escalation in waste not only puts pressure on landfills but also represents a lost opportunity to recover valuable materials such as silver, silicon, copper, and high-quality glass. Without adequate recycling systems, the environmental benefits of solar could be compromised by the rising ecological costs of disposal and resource depletion. As such, the need for effective EoL management strategies has become central to discussions on sustainable solar expansion.

The European Union currently leads global efforts to establish a coherent regulatory framework for solar PV circularity. Under the Waste Electrical and Electronic Equipment (WEEE) Directive, PV panels are classified as

e-waste, subjecting them to stringent collection and recycling requirements. Producers are obligated to finance and organise the collection of 85 percent of decommissioned modules and ensure that at least 80 percent of their material content is recovered through recycling processes. These mandates have facilitated the development of a robust recycling ecosystem across member states. In France, for instance, the non-profit organisation Soren coordinates nationwide PV waste collection and partners with advanced recycling firms. Among these, ROSI stands out for its ability to recover high-purity silicon and silver using sophisticated pyrolysis and hydrometallurgical techniques, thereby reintroducing valuable materials back into the solar supply chain. The European model demonstrates that strong regulatory frameworks can both mitigate environmental harm and create new opportunities for industrial innovation and material circularity (Intersolar, 2024).

In contrast, the United States exhibits a far more fragmented policy landscape with respect to solar PV recycling. At present, no federal legislation governs the handling or recycling of solar modules, resulting in considerable variation in state-level approaches. Washington State remains the only state with a comprehensive, producer-funded stewardship programme for PV recycling, although implementation has been slower than anticipated. Other states, such as Texas, have recently passed laws requiring the responsible decommissioning and recycling of solar and wind infrastructure, but these regulations are still in the early stages of rollout (PV Magazine USA, 2025). In much of the country, low landfill disposal costs discourage recycling, leading to a scenario where economically viable recycling infrastructure struggles to develop without policy intervention. In response to these shortcomings, private-sector innovators have stepped in to fill the gap. SOLARCYCLE, a leading U.S.-based recycling firm, has developed advanced separation and recovery technologies that allow for the extraction of up to 95 percent of valuable materials from end-of-life solar modules. Despite such advances, the absence of nationwide policy means that recycling rates remain modest, and the economics of circularity depend heavily on voluntary participation and local market conditions.

Environmental concerns surrounding new photovoltaic technologies introduce additional layers of complexity. Emerging perovskite solar cells, while hailed for their high performance and environmental advantages during production, utilise lead-based compounds that raise legitimate questions about potential toxicity. If improperly handled, damaged perovskite modules could release soluble lead ions into soil or water systems. Recognising this concern, researchers have intensified efforts to develop robust containment and stabilisation strategies. Recent advances include the incorporation of polymer networks -often described as molecular “net bones” -that chemically bind to lead ions, thereby preventing their leakage even under mechanical stress or water exposure. Europium-based metal-organic frameworks (Eu-MOFs) have also demonstrated strong potential for immobilising migrating lead within the perovskite layer. Together with improved glass-glass encapsulation and durable barrier films, these innovations significantly reduce toxicity risks and help perovskite modules meet regulatory thresholds such as the Toxicity Characteristic Leaching Procedure (TCLP) standards (MDPI, 2024). As a result, environmental risks associated with perovskites are rapidly diminishing, paving the way for safer commercial deployment.

Taken together, these developments illustrate that the environmental sustainability of solar PV hinges not only on its ability to decarbonise electricity generation but also on the integrity of its supply chains, manufacturing processes, and end-of-life management. As the industry scales toward the multi-terawatt era, questions surrounding recycling capacity, material recovery, carbon reduction in manufacturing, and toxicity mitigation will become increasingly central to energy planning and policy design. The challenge for the next decade will be to ensure that solar growth is accompanied by parallel advancements in circular economy practices. Doing so will reinforce the environmental and economic benefits of photovoltaics while preventing the accumulation of waste and embodied emissions that could otherwise undermine the technology’s transformative potential.

6. Conclusion and Future Outlook

The global solar energy landscape in 2025 stands at a pivotal moment, shaped by a convergence of technological breakthroughs, economic transformations, and systemic integration challenges that together define the contours of the emerging “solar singularity.” As the world advances toward the ambitious goal of tripling renewable energy capacity by 2030, solar photovoltaics have positioned themselves not merely as an alternative source of energy but as the central pillar of the clean energy transition. The dramatic decline in the Levelized Cost of Energy (LCOE), reaching as low as \$38 per megawatt-hour in leading markets, has fundamentally altered investment

patterns, rendering solar the most economically viable option for new electricity generation even without subsidies (Lazard, 2025). This shift signifies that the global energy transition is no longer driven solely by environmental imperatives but increasingly by pure economic rationality. Solar PV now outcompetes fossil fuels, not only in new installations but in many cases even against the marginal operating costs of existing coal and gas plants, marking a definitive disruption of long-standing energy paradigms.

Yet the economic promise of solar PV exists alongside profound structural tensions in the upstream manufacturing sector. The global oversupply crisis, concentrated largely in China's massive production ecosystem, has resulted in unprecedented price collapses, financial losses, and accelerated industry consolidation (PV Magazine, 2025). While this oversupply benefits developers and consumers by lowering system costs, it raises serious questions about the long-term sustainability of the manufacturing ecosystem that underpins the solar revolution. Geopolitical responses from the United States, India, and the European Union -ranging from domestic incentives to strict trade barriers -illustrate that solar manufacturing has become as much a matter of industrial policy and national security as economic competitiveness. The decade ahead will likely see intensified fragmentation of global supply chains as nations attempt to secure local production capacity while navigating complex global trade dynamics.

From a technological perspective, the rapid displacement of p-type PERC technology by more advanced n-type architectures marks one of the most significant transitions in the history of solar PV. The rise of TOPCon, with its superior efficiency, durability, and production compatibility, positions it as the industry's dominant architecture for the foreseeable future. Even more transformative, however, is the ascent of perovskite-silicon tandem technologies, which have pushed laboratory efficiencies beyond 34 percent and opened a clear pathway toward commercial modules surpassing the long-assumed performance ceiling of traditional silicon (LONGi, 2025). Advances in interface engineering, passivation techniques, and material stability indicate that the scientific barriers once thought insurmountable for perovskites are rapidly dissolving. If the remaining challenges around long-term durability and lead toxicity are resolved at scale, tandem architectures may well define the next generation of solar power, enabling higher energy yields with substantially lower material and environmental footprints.

At the systems level, the shift from synchronous, inertia-based grids to inverter-dominated renewable networks represents an equally profound transformation. The deployment of grid-forming (GFM) inverters, hybrid solar-battery plants, and advanced control systems demonstrates that inverter-based resources can now assume essential stability functions once exclusively provided by fossil-fuel generators (AEMO, 2025). Real-world case studies from Australia offer compelling evidence that high-renewable grids can function reliably and autonomously when supported by advanced power electronics and storage. These developments mark the beginning of a new operational paradigm in which algorithmic stability supersedes mechanical inertia, reshaping the technical foundations of grid architecture. As more regions confront similar challenges, grid-forming technologies will become indispensable tools for managing deep decarbonisation and ensuring secure, flexible, and resilient electric power systems.

The environmental implications of the expanding solar industry highlight the need for an equally ambitious evolution in circular economy practices. Although solar PV offers substantial reductions in greenhouse gas emissions compared to fossil fuels, its long-term sustainability depends on responsible material management, recycling infrastructure, and the reduction of embodied carbon in manufacturing. The European Union's leadership in establishing comprehensive recycling frameworks demonstrates the feasibility and necessity of robust producer responsibility models, while the fragmented regulatory environment in the United States underscores the risks of policy inaction (IEA-PVPS, 2024). As the world braces for the large-scale retirement of early-generation PV modules in the coming decades, the ability to recover high-value materials and prevent waste accumulation will play a critical role in maintaining the net environmental benefits of the technology. Emerging solutions for mitigating lead leakage in perovskite modules further indicate that environmental innovation must accompany technological innovation to ensure sustainable growth.

Taken together, the findings of this analysis reveal that the solar sector is entering a period of both unprecedented opportunity and heightened responsibility. The coming five years will determine whether solar PV solidifies its place as the backbone of the global energy system or whether unresolved challenges undermine its long-term potential. Realising the promise of solar energy will require coordinated advancements across market design,

technological development, regulatory frameworks, and environmental governance. It will also demand a more holistic approach that integrates manufacturing sustainability, grid modernisation, and circular economy principles into every stage of the solar value chain. If these elements converge successfully, the 2025–2030 period may indeed mark the moment when solar energy becomes not just the most significant generation technology of the century but a foundational pillar of a more equitable, resilient, and sustainable global energy system.

7. Bibliographic Analysis

The reference base supporting this study reflects a diverse and interdisciplinary body of literature drawn from international energy agencies, photovoltaic research laboratories, peer-reviewed journals, industry reports, and real-world deployment case studies. Broadly, the works cited fall into four major thematic clusters: (1) global energy and economic assessments, (2) photovoltaic technology innovations, (3) grid integration and system stability, and (4) environmental lifecycle and circularity frameworks. Together, these sources provide a comprehensive understanding of the solar industry's transformation between 2024 and 2025 and help situate the present research within contemporary scholarly and industry discussions.

A significant proportion of the references come from global energy institutions such as the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and SolarPower Europe. These organisations provide authoritative projections on global solar deployment, Levelized Cost of Energy (LCOE) trajectories, manufacturing capacity, and renewable energy policy frameworks. Their reports contribute macro-level insights into the economic forces shaping the solar market and the geopolitical tensions emerging from supply-chain concentration. The reliance on such high-credibility sources ensures that the study's economic and market analysis reflects consensus outlooks from leading global authorities.

Another major cluster of references focuses on photovoltaic materials science and technological breakthroughs, derived from peer-reviewed journals (e.g., MDPI, Science, Nanomaterials) and research institutions such as NREL, Fraunhofer ISE, and LONGi R&D laboratories. These sources are central to documenting the shift from p-type PERC to n-type TOPCon architectures and the rapid advancement of perovskite–silicon tandem cells. Laboratory efficiency records, interface engineering breakthroughs, and stability enhancement strategies are all grounded in empirical research. The presence of multiple NREL-verified efficiency reports further strengthens the reliability of technological claims made within the study. These references form the scientific backbone of the paper's discussion on material physics and performance innovation.

A third thematic group comprises references addressing grid integration and the evolution of power electronics, especially grid-forming inverters and hybrid solar-battery systems. Case studies drawn from Australia's National Electricity Market (NEM), including the Pelican Point BESS and the Koorangie Energy Storage System, illustrate real-world deployments of advanced inverter technologies. Industry news platforms such as PV Magazine, SolarQuarter, and Energy-Storage.news contribute timely information regarding system performance, project commissioning, and grid operator strategies. While these sources are not academic in the traditional sense, they offer indispensable, up-to-date technical and operational insights that reflect the fast-paced nature of renewable integration and power electronics development.

Environmental and circular-economy references constitute the fourth cluster, encompassing life cycle assessments, recycling frameworks, and toxicity mitigation strategies. Studies from MDPI, the U.S. International Trade Commission, the Washington State Department of Ecology, and Intersolar Europe provide robust analyses of photovoltaic waste, material recovery potential, and regulatory approaches. These sources highlight regional disparities in recycling infrastructure between Europe, the United States, and Asia while also addressing environmental concerns associated with emerging perovskite technologies. Their inclusion ensures that the study situates technological growth within broader discussions of sustainability and ecological responsibility.

Overall, the references collectively balance high-level policy analysis, rigorous scientific research, engineering case studies, and practical industry insights, creating a multidimensional foundation for examining the solar sector. The bibliographic structure reflects the inherently interdisciplinary nature of solar research, where market economics intersect with materials science, and grid engineering intersects with environmental policymaking. The diversity of sources used in this paper enables a holistic examination of the solar singularity, ensuring that conclusions drawn are informed by credible evidence across multiple domains.

Table 2 Bibliographic Summary

| Category | Key Sources | Role in Study | Strength of Evidence |
|---------------------------------------|--|--|---|
| Global Energy & Economics | IEA, IRENA, Lazard, SolarPower Europe | LCOE trends, deployment forecasts, market asymmetries | High – authoritative institutions |
| PV Technology & Material Science | NREL, MDPI, Fraunhofer ISE, LONGi, JinkoSolar | Efficiency records, tandem breakthroughs, stability research | High – peer-reviewed/lab-verified |
| Grid Integration & Power Electronics | AEMO, PV Magazine, Energy-Storage.news | GFM inverter case studies, hybrid plant performance | Moderate to High – technical/industry validated |
| Environmental Lifecycle & Circularity | MDPI, USITC, Intersolar Europe, Washington State Ecology | Waste management, LCA studies, recycling frameworks | High – empirical policy and LCA reports |

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