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REVIEW ARTICLE

Solar Cell Technology: Innovations and Challenges in Renewable Energy Conversion

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Abstract

Photovoltaic (PV) technology has evolved from a niche, high-cost energy source into the fastest-growing generation technology in the global electricity mix, with cumulative installed capacity surpassing the terawatt scale by the mid-2020s. This review synthesizes the state of the art across the major solar cell technology families—crystalline silicon (c-Si), thin films (CdTe, CIGS), and emerging concepts (perovskites, organic photovoltaics, dye-sensitized cells, quantum dots, and tandem architectures)—with attention to device physics, materials innovation, manufacturing scalability, and sustainability. Crystalline silicon, now dominated by passivated-contact architectures such as TOPCon and heterojunction (HJT) cells, continues to approach its practical efficiency ceiling near the Shockley–Queisser limit, while thin-film CdTe and CIGS modules offer lower embodied energy and complementary spectral and mechanical properties. The most consequential recent advances lie in perovskite photovoltaics, where single-junction laboratory efficiencies now exceed 26% and perovskite/silicon tandem cells have surpassed 33%, offering a credible pathway beyond the single-junction efficiency ceiling. Nonetheless, perovskites' operational stability, hysteresis, ion migration, and lead content remain unresolved barriers to bankable deployment at scale. Organic photovoltaics and dye-sensitized cells retain niche advantages in flexibility, transparency, and low-light performance but lag in efficiency and long-term durability. This review discusses the materials and interface engineering strategies—defect passivation, bandgap tuning, self-assembled monolayers, and two-dimensional capping layers—that have driven recent efficiency gains, alongside manufacturing innovations including roll-to-roll and slot-die coating, and integration concepts such as building-integrated photovoltaics (BIPV), agrivoltaics, and floating PV. Critical challenges are examined in depth: the efficiency–stability trade-off, supply constraints on indium, tellurium, and silver, degradation mechanisms and accelerated testing protocols, end-of-life recycling, and the soft costs that increasingly dominate total system economics. We conclude with an outlook on pathways toward >30–40% commercial module efficiencies via tandem and multi-junction architectures, the growing role of artificial intelligence and machine learning in accelerated materials discovery, and the research priorities that will determine whether photovoltaics can meet the multi-terawatt annual deployment rates required for a low-carbon energy system.

KEYWORDS:
Photovoltaic Technology; Solar Cell Technologies; Crystalline Silicon; Perovskite Solar Cells; Tandem Photovoltaics; Thin-Film Solar Cells; Sustainability

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1. Introduction

1.1 Global Energy Context and the Role of Photovoltaics

The global energy system is in the midst of its most rapid structural transformation since the industrial adoption of fossil fuels. Rising electricity demand, the need to decarbonize both power generation and, increasingly, transport and industry through electrification, and the falling cost of renewable generation have combined to make solar photovoltaics the single largest source

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of new electricity-generating capacity added worldwide in most years since the early 2020s. Unlike wind, hydropower, or nuclear energy, PV is modular at every scale—from milliwatt calculators to multi-gigawatt utility parks—and its cost has fallen along one of the steepest learning curves of any energy technology in history, a trajectory often described by "Swanson's Law," the photovoltaic analogue of Moore's Law, in which module prices have historically dropped by roughly 20% for every doubling of cumulative shipped capacity.

This cost decline has been driven by a combination of manufacturing scale-up, materials efficiency, and incremental device innovation rather than any single breakthrough. Yet the pace of new deployment now required to meet international climate targets—on the order of several terawatts of new PV capacity per year by the early 2030s—places unprecedented demands on manufacturing throughput, materials supply chains, land use, grid integration, and end-of-life management. Understanding where PV technology stands today, and where the remaining headroom for improvement lies, is therefore essential not only for materials scientists and device engineers but for policymakers and investors shaping the energy transition.

1.2 Historical Evolution of Solar Cell Technology

The modern solar cell traces its origin to the 1954 demonstration of a 6% efficient silicon p–n junction device at Bell Laboratories, which for the first time made photovoltaic conversion practically useful rather than a laboratory curiosity. Early applications were dominated by space satellites, where cost was a secondary concern relative to reliability and power density. Terrestrial deployment began in earnest during the 1970s oil shocks, and by the 1980s crystalline silicon had become the dominant commercial technology, a position it has never relinquished.

Thin-film technologies emerged in the 1980s and 1990s as a route to lower materials consumption, with amorphous silicon, CdTe, and CIGS all reaching commercial production, though only CdTe and CIGS have sustained significant market share into the 2020s. The most recent inflection point began around 2009 with the first reports of methylammonium lead halide perovskites as photovoltaic absorbers; within little more than a decade, perovskite single-junction efficiencies rose from roughly 3% to above 26%, the fastest efficiency ascent of any photovoltaic material class in the history of the field. This trajectory, combined with the compatibility of perovskites with low-temperature solution processing and their tunable bandgap, has made perovskite/silicon tandem architectures the most closely watched frontier in contemporary PV research.

1.3 Scope and Organization of This Review

This review covers the physical fundamentals of photovoltaic energy conversion, surveys the state of the art across established and emerging solar cell technologies, examines the materials and device innovations driving recent progress, and critically assesses the technical, economic, and sustainability challenges that stand between current laboratory and pilot-scale achievements and terawatt-scale deployment. Comparative technology and sustainability data are consolidated in two summary tables, and two schematic figures illustrate representative device architectures and the historical efficiency trajectory of the field. The review closes with an outlook on emerging directions, including the growing role of data-driven materials discovery.

1.4 Why Photovoltaics, and Why Now

Three structural features distinguish photovoltaics from other low-carbon generation technologies and help explain both its rapid growth and the technical questions that remain most pressing. First, PV's modularity means that manufacturing learning effects—cost reductions arising from cumulative production experience, equipment standardization, and supply-chain maturation—apply with unusual force, since a single manufacturing improvement can be replicated across billions of nominally identical cells rather than a handful of large, bespoke installations as in conventional thermal or nuclear power plants. Second, PV's short construction lead times relative to large thermal or hydroelectric plants allow capacity to be added incrementally and in close correspondence with observed demand growth, reducing the financial and planning risk associated with large, lumpy capital investments. Third, and most relevant to the remainder of this review, PV's dependence on continued materials and device innovation—rather than only manufacturing scale—means that the technology's future cost and performance trajectory remains, to an unusually large degree among mature energy technologies, an open scientific and engineering question rather than a purely economic or logistical one. It is this combination of manufacturing maturity in crystalline silicon alongside genuinely open materials-science frontiers in perovskites, tandems, and novel absorber chemistries that motivates the structure of this review.

2. Fundamentals of Solar Cell Operation

2.1 The Photovoltaic Effect

A solar cell converts incident photon energy into electrical energy through the photovoltaic effect: absorption of a photon with energy greater than the semiconductor bandgap (Eg) promotes an electron from the valence band to the conduction band, generating an electron–hole pair. A built-in electric field—typically established by a p–n or p–i–n junction, or by asymmetric selective contacts—separates these carriers before they can recombine, driving electrons and holes to opposite electrodes and

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producing a photocurrent under illumination.

The current–voltage (I–V) behavior of an illuminated solar cell is commonly described by the single-diode equation:

$$I = IL - I0\,[\exp(qV / n\,kB\,T) - 1] - V / Rsh$$

where IL is the light-generated current, I0 is the diode saturation current (governed by recombination), q is the elementary charge, n is the diode ideality factor, kB is Boltzmann's constant, T is temperature, and Rsh is the shunt resistance (series resistance Rs is typically incorporated as an additional term). This equation underlies the extraction of the key performance metrics discussed below from measured I–V curves.

2.2 Key Performance Metrics

- **Power Conversion Efficiency (PCE):** the ratio of electrical power output at the maximum power point to incident solar power, typically measured under the AM1.5G standard spectrum (1000 W/m², 25 °C).
- **Open-circuit voltage (Voc):** the voltage across the cell terminals at zero current, fundamentally limited by the bandgap and by non-radiative recombination losses; Voc deficits relative to the radiative limit are a key diagnostic of material and interface quality.
- **Short-circuit current density (Jsc):** the current density at zero applied voltage, determined by light absorption, carrier generation, and collection efficiency.
- **Fill factor (FF):** the ratio of maximum power to the product of Voc and Jsc, reflecting resistive losses and recombination near the maximum power point.
- **External quantum efficiency (EQE):** the fraction of incident photons at each wavelength that contribute to the collected photocurrent; integrating EQE over the solar spectrum yields Jsc.
- **Stability metrics:** commonly expressed as T80 or T90, the time under specified stress conditions (light, heat, humidity) for a cell or module to retain 80% or 90% of its initial performance, respectively.

2.3 Efficiency Limits: Shockley–Queisser and Beyond

The theoretical ceiling for a single-junction solar cell under unconcentrated sunlight is set by the Shockley–Queisser (S–Q) limit, derived from detailed-balance considerations of radiative recombination alone. For a given bandgap Eg, the limit balances two competing losses: photons with energy below Eg are not absorbed, while the excess energy of photons above Eg is lost as heat (thermalization). The S–Q analysis yields a maximum efficiency of approximately 33.7% for an optimal bandgap near 1.34 eV under the AM1.5G spectrum—close to the bandgaps of both crystalline silicon (1.12 eV) and many high-performing perovskites (1.5–1.6 eV), which explains why these materials are efficient absorbers despite non-ideal bandgaps.

Real devices fall short of the S–Q limit due to non-radiative recombination (Shockley–Read–Hall recombination at defects and interfaces, Auger recombination at high carrier densities), parasitic optical losses (reflection, parasitic absorption in non-photoactive layers), and resistive losses. Multi-junction (tandem) architectures circumvent the single-junction S–Q ceiling by stacking sub-cells of different bandgaps to more efficiently partition the solar spectrum; the detailed-balance limit for an infinite-junction stack under unconcentrated sunlight approaches roughly 68%, while practical two-junction tandems have a detailed-balance ceiling near 46%. This thermodynamic headroom is the principal motivation for the tandem architectures discussed later in this review.

3. Major Solar Cell Technologies – State of the Art

3.1 Crystalline Silicon (c-Si)

Crystalline silicon accounts for the large majority of global PV shipments and remains the industry's cost and reliability benchmark. Several passivated-contact architectures have succeeded the older aluminum back-surface-field (Al-BSF) design over the past decade:

- **PERC (Passivated Emitter and Rear Cell):** introduces a dielectric passivation layer and local rear contacts, reducing rear surface recombination. PERC became the dominant mainstream architecture through the early 2020s, with commercial module efficiencies typically in the 21–22% range, but it is now approaching its practical ceiling and is being displaced by higher-efficiency architectures.
- **TOPCon (Tunnel Oxide Passivated Contact):** employs an ultrathin tunneling silicon oxide layer beneath a doped polysilicon layer to achieve carrier-selective, low-recombination contacts on the rear (and increasingly the front) surface. TOPCon has become the new mainstream architecture, with commercial module efficiencies commonly in the 22–23.5% range and a manufacturing cost structure similar to PERC, easing its rapid market uptake.
- **Heterojunction (HJT/SHJ):** sandwiches a crystalline silicon wafer between thin intrinsic and doped amorphous silicon layers, achieving excellent surface passivation and among the highest Voc values reported for silicon cells. Laboratory HJT

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cells have reached efficiencies above 27%, and HJT's low-temperature processing and inherently bifacial structure also make it an attractive silicon "bottom cell" for perovskite/silicon tandems.

- **Interdigitated Back Contact (IBC):** places both electron- and hole-collecting contacts on the rear surface, eliminating front-side metallization shading and improving aesthetics and current collection. IBC cells have achieved some of the highest confirmed silicon single-junction efficiencies, though at a higher processing cost and complexity than TOPCon or PERC.
- These architectures are increasingly described as "tandem-ready," since TOPCon and HJT bottom cells with textured or planar front surfaces and appropriate transparent electrodes can serve directly as the silicon sub-cell in a perovskite/silicon tandem stack.

3.2 Thin-Film Technologies

Cadmium Telluride (CdTe) thin-film modules, produced predominantly using vapor-transport or close-spaced sublimation deposition on glass superstrates, have achieved commercial module efficiencies in the high teens, with laboratory cell efficiencies exceeding 22%. CdTe's near-ideal bandgap (~1.5 eV), low materials use (absorber layers only a few micrometers thick), lower embodied energy, and better high-temperature performance than silicon (a smaller power temperature coefficient) make it commercially significant, particularly for utility-scale deployment in hot climates. Toxicity concerns around cadmium are mitigated in practice by encapsulation and established recycling programs operated by major manufacturers, though public perception and end-of-life regulation remain relevant considerations.

Copper Indium Gallium Selenide (CIGS) cells use a direct-bandgap chalcopyrite absorber with a tunable bandgap (via the In/Ga ratio), enabling record laboratory efficiencies above 23%. CIGS modules offer good performance under diffuse and low light and can be deposited on flexible substrates, enabling lightweight and building-integrated applications. However, the multi-element composition (Cu, In, Ga, Se) complicates process control and yield at scale, and indium supply—shared with the display and electronics industries—is a long-term materials constraint.

Amorphous and Microcrystalline Silicon (a-Si:H, μc-Si:H) thin films, once a significant commercial technology, have declined in market share due to lower efficiencies and pronounced light-induced degradation (the Staebler–Wronski effect) in amorphous silicon. They remain relevant in niche applications (indoor/low-light photovoltaics, some BIPV products) and as component junctions in certain thin-film tandem stacks.

A further consideration for c-Si technologies is bifaciality: nearly all current TOPCon and HJT cells are inherently or readily configured as bifacial devices, capable of collecting reflected and diffuse light incident on the rear surface. Bifacial gains of 5–15% in energy yield are commonly reported for elevated, high-albedo installations (e.g., over light-colored ground cover or snow), and bifacial modules have consequently become the default configuration for new utility-scale silicon deployment.

3.2b Manufacturing Considerations for Crystalline Silicon

The crystalline silicon value chain—polysilicon refining (predominantly via the Siemens process or, increasingly, fluidized-bed reactor methods), ingot growth (Czochralski for monocrystalline material), wafering, cell processing, and module assembly—is now overwhelmingly concentrated in a small number of manufacturing regions, with associated implications for supply-chain resilience and embodied carbon that vary substantially depending on the electricity mix used at each processing stage. Diamond-wire wafer slicing, thinner wafers (increasingly below 130 μm), and larger wafer formats (M10, G12, and successors) have each contributed incremental reductions in silicon consumption per watt, partially offsetting rising demand from terawatt-scale deployment targets. Continued wafer thinning is constrained by cell breakage rates during handling and by the diminishing returns of thinner absorbers on light capture without accompanying advances in rear-side light trapping, illustrating how manufacturing and device physics considerations remain tightly coupled even within a mature technology platform.

3.3 Emerging and Next-Generation Technologies

Perovskite Solar Cells: Metal halide perovskites, with the general formula ABX_3 (commonly a mix of formamidinium/methylammonium/cesium on the A site, lead or tin on the B site, and iodide/bromide on the X site), combine strong, tunable absorption, long carrier diffusion lengths, and defect tolerance with the possibility of low-temperature solution or vapor processing. Single-junction perovskite laboratory cells have reached certified efficiencies above 26%, approaching the best crystalline silicon cells within little more than a decade of development. Compositional engineering (mixed-cation, mixed-halide formulations), additive engineering, and interface passivation have been central to this progress. Despite this remarkable efficiency trajectory, operational stability under heat, humidity, illumination, and applied bias remains the technology's central unresolved challenge.

Organic Photovoltaics (OPV): OPV cells use conjugated polymer or small-molecule donors paired with non-fullerene acceptors (NFAs) in a bulk-heterojunction active layer. The introduction of NFAs after roughly 2015 substantially improved OPV efficiency, with certified single-junction cells now exceeding 19–20% and tandem OPV devices reported above 20%.

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OPV's principal advantages are mechanical flexibility, semi-transparency, low-temperature roll-to-roll processing, and a favorable environmental profile compared with lead-halide perovskites, positioning it for niche applications such as flexible/wearable electronics, semi-transparent glazing, and indoor energy harvesting, rather than utility-scale deployment.

Dye-Sensitized Solar Cells (DSSC): DSSCs use a dye-sensitized mesoporous metal-oxide (typically TiO_2) photoanode paired with a redox electrolyte or solid-state hole conductor. Champion efficiencies remain around 13–14% for standard AM1.5G conditions, well below silicon or perovskite cells, but DSSCs retain a niche advantage in aesthetic, semi-transparent, and low-light/indoor photovoltaic applications due to their favorable spectral response under diffuse and artificial lighting.

Quantum Dot Solar Cells: Colloidal quantum dot (CQD) photovoltaics, based primarily on lead sulfide or perovskite nanocrystals, exploit size-tunable bandgaps and solution processability. Certified efficiencies have progressed steadily to the high teens for PbS CQD cells, aided by improved surface ligand chemistries that reduce trap-state density. Quantum dot technology also underpins interest in multiple exciton generation and intermediate-band concepts as routes to exceeding the S–Q limit.

Other Novel Concepts: Several device concepts aim explicitly to surpass single-junction thermodynamic limits or exploit non-traditional carrier physics: hot-carrier solar cells seek to extract photogenerated carriers before they thermalize to the band edges; intermediate-band solar cells introduce a partially filled band within the host bandgap to enable sub-bandgap photon absorption via two-step transitions; and singlet-fission materials can convert one absorbed high-energy photon into two triplet excitons, in principle enabling external quantum efficiencies above unity. These concepts remain largely at the fundamental research stage.

3.4 Commercialization Status Snapshot

Translating the laboratory and pilot-line status summarized above into deployment reality, crystalline silicon (PERC transitioning to TOPCon and HJT) constitutes the overwhelming majority of new global shipments as of 2025–2026, with TOPCon having surpassed PERC as the leading mainstream architecture and HJT holding a smaller but growing premium-efficiency segment. CdTe holds a durable minority market share, concentrated among a small number of vertically integrated manufacturers primarily serving the utility-scale segment in North America and select international markets. CIGS occupies a narrower commercial niche, particularly in flexible and BIPV product lines. Perovskite single-junction and perovskite/silicon tandem technologies remain in pilot and early commercial-scale production, with several manufacturers having announced or begun limited-volume tandem module shipments; industry-wide consensus generally places broad commercial availability of tandem modules at meaningful scale in the latter half of the 2020s, contingent on the stability and yield challenges discussed later. OPV, DSSC, and quantum-dot technologies remain confined to specialty and niche commercial applications rather than mainstream grid-scale deployment.

4. Key Innovations Driving Progress

4.1 Materials Innovations

Progress across all PV technologies has been driven substantially by defect and interface engineering rather than by entirely new absorber chemistries. In silicon, hydrogenated amorphous silicon and doped polysilicon passivation layers (as used in HJT and TOPCon, respectively) suppress interface recombination velocity by orders of magnitude relative to earlier diffused-junction designs. In perovskites, a wide range of passivation strategies—organic ammonium salts, Lewis-base additives, and post-deposition surface treatments—reduce trap-state densities at grain boundaries and surfaces, directly increasing Voc toward the radiative limit. Bandgap engineering through halide (I/Br) and cation composition tuning allows perovskite absorbers to be tailored to specific roles as wide-bandgap top cells in tandem stacks. Two-dimensional (2D) perovskite or organic capping layers, applied atop 3D perovskite films, form a mixed 2D/3D architecture that improves both defect passivation and moisture resistance, addressing stability and efficiency simultaneously. Parallel efforts toward lead-free perovskites—based on tin, bismuth, or double-perovskite chemistries—aim to reduce toxicity concerns, though these alternatives currently lag well behind lead-based compositions in efficiency and stability.

4.2 Device and Interface Engineering

Beyond bulk absorber quality, charge-selective contact layers and their interfaces with the absorber are now recognized as central determinants of device performance. Self-assembled monolayers (SAMs) as hole-selective contacts in perovskite cells have enabled substantial gains in both efficiency and thermal stability relative to earlier organic hole-transport materials. Transparent conductive electrodes (indium tin oxide and emerging indium-free alternatives) and optimized anti-reflection and light-management schemes (textured surfaces, dielectric mirrors, photonic light-trapping structures) further reduce optical and resistive losses across silicon, thin-film, and perovskite devices alike.

4.3 Tandem and Multi-Junction Architectures

Tandem architectures pair sub-cells of different bandgaps—most commonly a wide-bandgap perovskite top cell (≈1.6–1.8 eV)

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atop a silicon or lower-bandgap perovskite bottom cell (≈1.1–1.2 eV)—to reduce thermalization losses and more fully harvest the solar spectrum. Perovskite/silicon tandem cells have progressed rapidly, with certified efficiencies surpassing 33%, substantially exceeding the practical ceiling of either constituent technology alone. All-perovskite tandems, pairing two perovskite absorbers of different bandgap, offer a potentially lower-cost, fully solution-processable alternative and have also achieved efficiencies in the high twenties to low thirties in laboratory demonstrations. III-V multi-junction cells (e.g., GaInP/GaAs/Ge and related stacks), though far too costly for terrestrial utility deployment, remain the efficiency leaders overall, with laboratory multi-junction and concentrator cells exceeding 39% (and above 47% under concentrated sunlight), and continue to serve as the benchmark technology for space and specialized high-value applications, as well as a proving ground for tandem device physics later adapted to lower-cost material systems.

4.4 Manufacturing and Scalability Advances

Translating laboratory tandem and thin-film efficiencies into bankable products requires manufacturing processes compatible with high throughput and yield. Roll-to-roll and slot-die coating methods, long used in OPV and increasingly explored for perovskite deposition, allow continuous, high-speed processing on flexible substrates at potentially lower capital cost than batch vacuum deposition. Scalable vapor-phase deposition methods for perovskites (co-evaporation, hybrid vapor–solution processes) offer improved thickness uniformity over large areas relative to solution coating, addressing one of the key scale-up bottlenecks identified in pilot-line studies. Module-level series interconnection and edge-sealing techniques, along with improved encapsulation materials (barrier films, glass–glass lamination), are equally critical to translating cell-level gains into durable, manufacturable modules. Recycling-compatible module design—delaminable encapsulants, reduced use of leaded solder and fluorinated polymers—is an emerging design consideration.

4.5 Integration Innovations

PV deployment is increasingly diversifying beyond ground-mounted utility arrays. Building-integrated photovoltaics (BIPV) incorporate PV directly into façades, roofing, and glazing, often exploiting the semi-transparency and color tunability achievable with thin-film, OPV, or perovskite technologies. Flexible and lightweight modules, enabled by thin-film and perovskite absorbers on polymer or ultrathin glass substrates, extend PV to curved surfaces, vehicles, and portable applications where the areal mass of conventional glass-encapsulated silicon modules is prohibitive. Agrivoltaics—the co-location of PV arrays with agricultural production—can improve combined land-use efficiency and, in some crops and climates, provide beneficial shading that reduces water stress. Floating PV (FPV), deployed on reservoirs and other water bodies, reduces land-use competition and benefits from evaporative cooling of modules, which can modestly improve energy yield relative to equivalent ground-mounted systems.

4.6 Characterization and Standardization Advances

Progress in device performance has been accompanied by parallel progress in the metrology needed to reliably report it. The historical tendency for early-stage perovskite cells to exhibit current–voltage hysteresis—apparent efficiency depending on scan direction and rate—prompted the adoption of stabilized power output measurement (tracking output at the maximum power point over an extended period, typically tens of seconds to minutes, rather than relying on a single I–V sweep) as a standard reporting requirement for certified efficiency records. Improved spectral mismatch correction, larger-area reference cells, and more rigorous inter-laboratory round-robin comparisons have similarly increased confidence in reported efficiencies across emerging technologies, an essential prerequisite for the credibility of the efficiency trends summarized in Figure 2.

5. Critical Challenges

5.1 Efficiency vs. Stability Trade-Offs

The efficiency gains of perovskite and organic photovoltaics have generally outpaced improvements in operational stability. Perovskite degradation pathways include ion migration under electric field and illumination, moisture- and oxygen-induced decomposition, thermally driven phase segregation in mixed-halide compositions (which can cause photoinduced halide segregation and associated Voc losses), and interfacial reactions with adjacent charge-transport and electrode layers. While encapsulated perovskite cells have demonstrated T80 lifetimes extending to several thousand hours under standard accelerated test protocols—and some tandem and single-junction devices have shown promising results under extended damp-heat and light-soaking testing—these results still generally fall short of the multi-decade field lifetimes routinely achieved by crystalline silicon modules, which typically retain over 80% of rated power after 25 years of outdoor operation. Organic photovoltaics face analogous degradation mechanisms, including photo-oxidation of the active layer and morphological instability of the bulk-heterojunction blend, compounded by generally weaker intrinsic stability of the low-bandgap NFA components responsible for their highest efficiencies.

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5.2 Scalability, Cost, and Manufacturing Yield

Laboratory-scale efficiency records are typically achieved on cells of a few square millimeters to a few square centimeters; efficiency losses when scaling to full-size modules (hundreds to thousands of square centimeters) are a persistent and technology-specific challenge, arising from non-uniformities in thin-film deposition, resistive losses in series-connected interconnects, and reduced yield from defect-induced shunting. Perovskite modules in particular have historically shown a substantial "scaling gap" between small-area champion cells and commercial-format modules, though this gap has narrowed considerably as deposition uniformity and interconnect design have matured. Manufacturing yield, capital expenditure for new production lines, and the availability of specialized deposition equipment further determine whether a given technology can achieve cost parity with incumbent crystalline silicon, whose manufacturing base benefits from decades of accumulated process optimization and enormous economies of scale.

5.3 Materials Sustainability, Toxicity, and Critical Raw Materials

Several leading and emerging PV technologies rely on elements subject to toxicity concerns, geological scarcity, or geopolitically concentrated supply. Lead (Pb) in the dominant perovskite compositions raises environmental and regulatory concerns despite its typically small absolute mass per module and the demonstrated efficacy of encapsulation in limiting leakage risk under normal and even damaged-module conditions in laboratory leaching studies; nonetheless, public and regulatory acceptance of lead-based perovskites remains an open question that will shape commercialization pathways. Cadmium (Cd) in CdTe modules is similarly subject to toxicity regulation, managed through encapsulation and established end-of-life recycling programs. Indium (In), used in CIGS absorbers and in indium tin oxide transparent electrodes across multiple technologies, and tellurium (Te), used in CdTe, are both relatively scarce elements with demand shared across the electronics and display industries, raising long-term supply concerns if PV deployment reaches multi-terawatt annual scale. Silver, used extensively in silicon cell metallization, similarly faces long-term supply and cost pressure at projected terawatt-scale silicon deployment, motivating industry-wide efforts to reduce silver loading or substitute copper-based metallization.

5.4 Long-Term Outdoor Reliability, Degradation Mechanisms, and Accelerated Testing

Even mature crystalline silicon technology exhibits degradation mechanisms that continue to be studied and mitigated, including light- and elevated-temperature-induced degradation (LeTID) associated with boron–oxygen defect complexes, potential-induced degradation (PID) arising from leakage currents under high system voltage bias, and microcrack- or corrosion-related power loss. For emerging technologies, standardized accelerated testing protocols (damp heat, thermal cycling, humidity-freeze, and light-soaking tests, largely adapted from IEC 61215-series silicon module standards) are still being refined to adequately capture perovskite- and OPV-specific degradation modes, and the correlation between accelerated indoor testing and real-world outdoor field performance over decade-plus timescales remains an active area of investigation and a prerequisite for bankability in project finance.

5.5 Recycling, Circular Economy, and End-of-Life Management

As the first large cohorts of crystalline silicon modules installed during the 2000s and 2010s approach end-of-life, module recycling infrastructure remains underdeveloped relative to anticipated waste volumes. Current recycling processes can recover glass, aluminum framing, and, with more advanced processes, silver and silicon, but economically efficient, high-purity material recovery—particularly for the encapsulant-embedded silicon wafer and specialty metals—remains technically and economically challenging at present energy and labor costs, and most recovered material streams remain economically marginal without policy support. CdTe manufacturers have implemented relatively mature take-back and recycling programs, partly in response to cadmium-related regulatory scrutiny. Perovskite and thin-film modules present distinct recycling challenges and opportunities: perovskite absorbers can in principle be dissolved and reprocessed at lower thermal budgets than crystalline silicon, but industrial-scale recycling processes for perovskite and tandem modules are not yet established. Design-for-recycling principles—delaminable encapsulants, reduced adhesive use, and material substitution—are increasingly discussed as a means of easing future end-of-life management, though they remain more prevalent in the research literature than in current commercial module design.

5.6 Policy, Grid Integration, and Soft Costs

Beyond hardware, "soft costs"—permitting, customer acquisition, installation labor, inverter and balance-of-system hardware, and financing costs—now constitute a majority of total installed system cost in many mature residential and commercial markets, even as module prices have fallen dramatically. At high PV penetration, grid integration challenges intensify: the well-documented "duck curve" phenomenon, in which net electricity demand dips sharply during peak solar hours and ramps steeply in the evening, requires increased dispatchable capacity, storage, demand response, or curtailment to maintain grid stability. Policy frameworks—net metering design, interconnection standards, storage incentives, and domestic manufacturing incentives

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(such as those embedded in recent industrial policy in the United States, European Union, and China)—increasingly shape not only deployment rates but also which technologies and supply chains gain market share, making policy a first-order variable in the practical trajectory of PV technology alongside the materials science discussed elsewhere in this review.

5.7 Water, Land, and Broader Environmental Considerations

Beyond materials toxicity and supply, terawatt-scale PV deployment raises broader environmental and land-use considerations that are gaining increasing research and policy attention. Utility-scale ground-mounted arrays compete with agricultural and natural land uses in some regions, motivating interest in agrivoltaics, floating PV, and rooftop/BIPV deployment as land-conserving alternatives. Water use in module manufacturing (particularly silicon wafer cleaning and CIGS/CdTe wet-chemical processing) and in some module cleaning practices at utility-scale sites in arid, high-irradiance regions represents a secondary but non-trivial resource consideration, though PV's operational water intensity remains far lower than that of thermal generation technologies requiring cooling water. Life-cycle greenhouse gas emissions from PV, dominated by manufacturing-stage energy use, are substantially lower than fossil generation on a per-kWh basis across all major PV technologies, and continue to decline as manufacturing electricity supply itself decarbonizes—though this also means that embodied carbon accounting for PV modules is increasingly sensitive to where and how the module supply chain is powered.

6. Comparative Analysis

Figures 1 and 2 and Tables 1 and 2 consolidate the comparative technical, performance, and sustainability data discussed throughout this review.

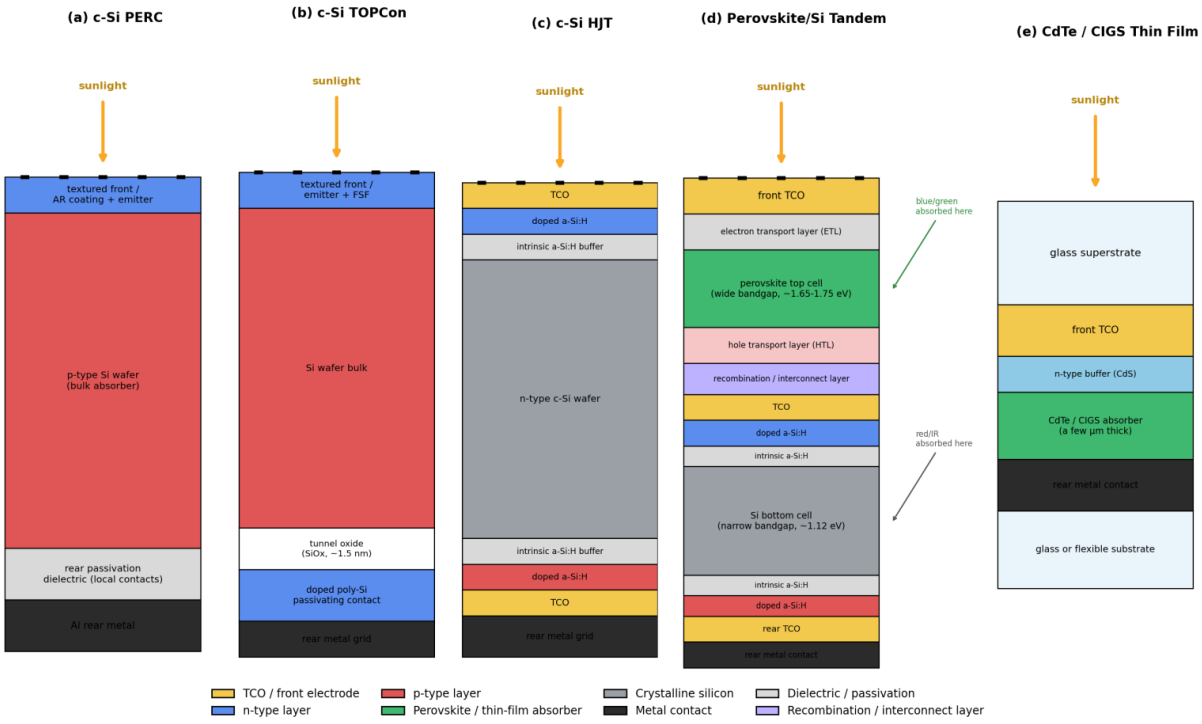

Figure 1: Schematic comparison of five major solar cell device architectures showing layer stacks for (a) c-Si PERC, (b) c-Si TOPCon, (c) c-Si HJT, (d) Perovskite/Si tandem, and (e) CdTe/CIGS thin-film cells. Color key: yellow = TCO/front electrode; blue = n-type layer; red = p-type layer; green = perovskite/thin-film absorber; gray = crystalline silicon; light gray = dielectric/passivation; black = metal contact; purple = recombination/interconnect layer.

As shown in Figure 1, the progression from panel (a) to (c) illustrates the evolution of silicon cell architectures toward increasingly sophisticated passivated contacts, while panel (d) illustrates how a wide-bandgap perovskite top cell is stacked atop a conventional silicon bottom cell to reduce thermalization losses, and panel (e) illustrates the comparatively simple, thin-absorber structure of established thin-film technologies.

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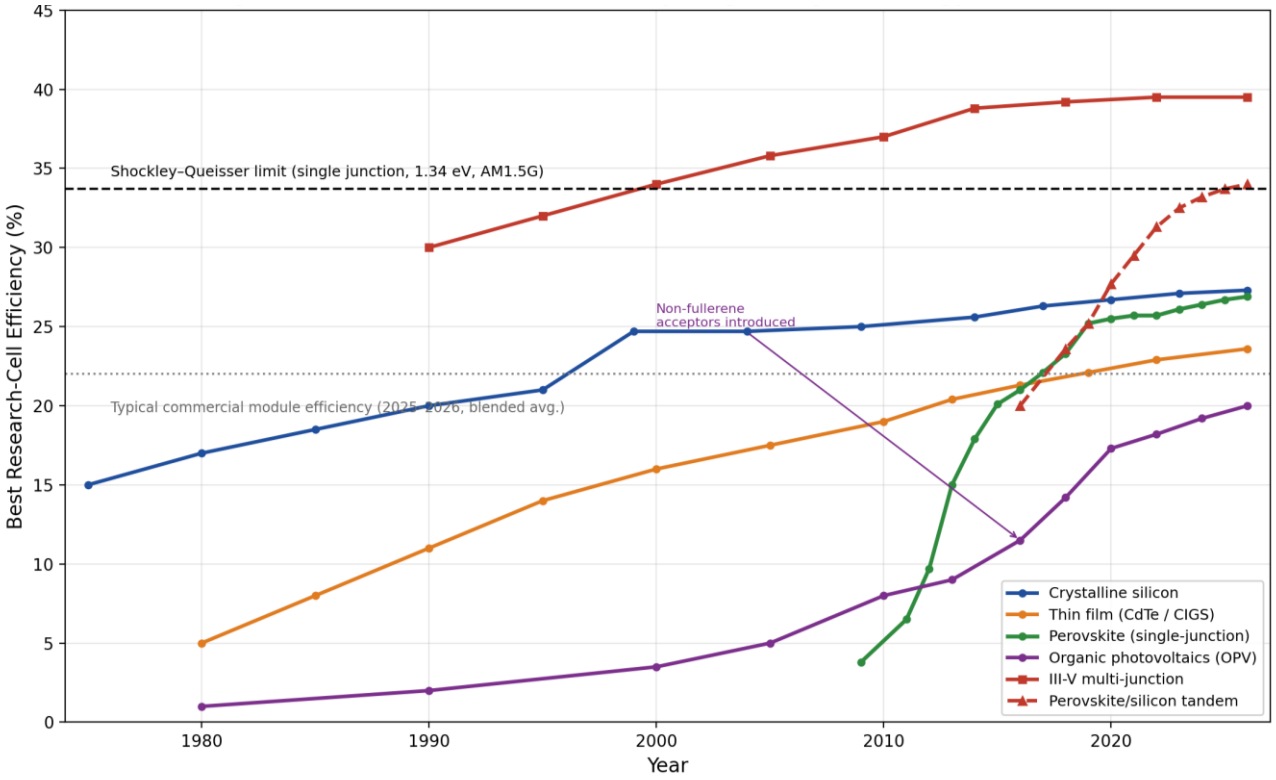

Figure 2: Best research-cell efficiency progress by technology (1975–2026). The Shockley–Queisser limit (≈33.7%) for a single-junction cell and typical commercial module efficiency (≈22%) are marked for reference. Perovskite and perovskite/silicon tandem curves show the steepest recent ascent.

As shown in Figure 2, the historical efficiency trajectory highlights three distinct patterns: the slow, incremental maturation of crystalline silicon over five decades; the comparatively rapid rise of thin-film and organic technologies over two to three decades; and the exceptionally steep ascent of perovskite and perovskite/silicon tandem technologies within little more than a decade, alongside the persistent gap between record laboratory efficiencies and typical commercial module efficiencies.

Table 1: Comparative Performance Metrics of Leading Solar Cell Technologies (2025–2026)

Technology	Record Lab PCE (%)	Typical Comm. Module PCE (%)	Stability (T80 / Outdoor)	Key Advantages	Key Challenges	TRL
c-Si PERC	~24 (cell)	20–21	>25 years field-proven	Mature, low-cost, bankable	Approaching efficiency ceiling	9
c-Si TOPCon	~26 (cell)	22–23.5	Field data emerging; strong lab durability	Best cost/efficiency balance	LeTID/LID mitigation still maturing	9
c-Si HJT	>27 (cell)	22–24	Excellent lab durability; limited long-term field data	High Voc, low temp. coeff., tandem-ready	Higher processing cost; indium TCO	8–9
CdTe (thin film)	>22 (cell)	18–19	Field-proven >20 years	Low embodied energy; hot-climate performance	Cadmium regulatory/perception concerns	9
CIGS (thin film)	>23 (cell)	17–19	Field-proven, module-dependent	Flexible; good diffuse-light response	Complex process; indium supply	8–9
Perovskite (SJ)	>26 (cell)	Not yet commercial at scale	Thousands of hours (accelerated);	Rapid efficiency gains; low-	Long-term stability, ion migration, Pb	5–6

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			limited field data	temp processing		
Perovskite/ Si tandem	>33 (cell)	Pilot-scale only	Improving but below Si benchmark	Highest realistic near-term efficiency	Scale-up, stability, interconnect losses	5–6
OPV	~19–20 (cell)	Niche products only	Moderate; improving with encapsulation	Flexible, semi-transparent, low-light	Lower efficiency; photo-oxidative degradation	5–7
DSSC	~13–14 (cell)	Niche/BIPV products	Good in low-light/indoor niches	Aesthetic; diffuse/indoor light performance	Low efficiency for outdoor utility use	6–7
Quantum dot (PbS)	~18–19 (cell)	Not commercial	Improving with ligand engineering	Tunable bandgap; solution processing	Efficiency and stability behind peers	3–4
III-V multi-junction	>39 (non-conc.); >47 (conc.)	Space/niche only	Excellent (space-qualified)	Highest efficiency of any PV technology	Very high cost; not viable for utility scale	9 (space)

Table 2: Sustainability and Economic Comparison of Leading Solar Cell Technologies

Technology	**Energy Payback (years)**	**Est. LCOE (USD/kWh)**	**Critical Materials / Toxicity**	**Recyclability / Circular Potential**	**Scalability Outlook**
c-Si (PERC/TOPCon/HJT)	1.0–1.8	0.02–0.06	Silver (metallization); high-purity polysilicon energy intensity	Moderate; glass/Al recovered; Si/Ag recovery improving	Excellent; largest existing manufacturing base
CdTe	0.5–1.0	0.02–0.05	Cadmium toxicity (regulated); tellurium scarcity	Good; established manufacturer take-back programs	Good; constrained longer-term by Te supply
CIGS	0.8–1.5	0.03–0.07	Indium scarcity/shared demand; Ga/Se supply risk	Moderate; less mature recycling than CdTe	Moderate; indium is binding long-term constraint
Perovskite (SJ)	<0.5 (projected)	Not yet established	Lead toxicity/regulatory uncertainty; solvent use	Potentially high (low-temp reprocessing) but unproven	Uncertain; depends on stability and scale-up
Perovskite/Si tandem	0.6–1.2 (projected)	Not yet established	Combines silicon and perovskite material concerns	Complex multi-material stack; recycling undeveloped	Promising but contingent on yield and stability

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OPV	0.3–0.8 (projected)	Not cost-competitive for utility	Generally low toxicity; limited NFA/solvent data	Potentially favorable (polymer/solution processing)	Niche (flexible, BIPV, indoor) rather than utility
DSSC	0.4–0.9	Niche pricing only	Generally low toxicity; iodine-based electrolytes	Favorable; simple materials set	Niche (BIPV, indoor/low-light)
III-V multi-junction	2–4 (space); N/A utility	Very high (>0.20 terrestrial)	Ga, Ge, As supply and cost constraints	Limited; small production volumes	Confined to space/specialized concentrator

7. Future Outlook and Emerging Directions

7.1 Pathways to >30–40% Commercial Modules

The near-term route to commercial module efficiencies exceeding 30% runs through perovskite/silicon tandems, where laboratory cell efficiencies already exceed 33% and pilot-line manufacturers have announced roadmaps targeting commercial tandem module efficiencies in the high 20s to low 30s percent range within the latter half of the 2020s. Reaching this target at the module (rather than cell) level requires simultaneous progress on large-area perovskite deposition uniformity, low-loss recombination/interconnect layers between sub-cells, UV- and moisture-stable encapsulation compatible with the perovskite top cell, and manufacturing yield comparable to existing silicon lines. Beyond tandems, three-terminal and mechanically stacked multi-junction architectures, along with continued incremental gains in III-V concentrator systems, represent longer-horizon pathways toward the 40%+ regime, though at correspondingly higher system complexity and cost, likely restricting near-term deployment of such ultra-high-efficiency devices to specialized or space applications rather than mainstream terrestrial utility markets.

7.2 Role of AI/ML in Materials Discovery and Process Optimization

Machine learning methods are increasingly integrated across the PV research and manufacturing pipeline. High-throughput computational screening, informed by density functional theory and increasingly by machine-learned interatomic potentials, has accelerated the identification of candidate perovskite compositions and lead-free alternatives with favorable stability and bandgap characteristics. Bayesian optimization and active-learning frameworks, coupled to automated synthesis and characterization platforms ("self-driving laboratories"), are being used to navigate the large compositional and processing parameter spaces relevant to perovskite film formation far faster than traditional one-variable-at-a-time experimentation. On the manufacturing side, machine-learning-based process control and in-line defect detection (e.g., using electroluminescence or hyperspectral imaging analyzed by convolutional neural networks) are improving yield and enabling faster fault diagnosis on production lines, while data-driven degradation modeling is beginning to improve the fidelity of accelerated stability testing protocols.

7.3 Hybrid Energy Systems and Sector Coupling

As PV penetration rises, its value increasingly depends on integration with complementary technologies rather than on module efficiency alone. Co-located battery storage, PV–electrolyzer systems for green hydrogen production, and PV-plus-thermal hybrid systems are all active areas of technology and market development, aimed at smoothing the variability challenges of high PV penetration (the duck curve) and extending the effective utilization of PV-generated electricity into sectors—industrial heat, transport fuels, chemical feedstocks—not directly served by grid electricity. Vehicle-to-grid and behind-the-meter storage integration, alongside demand-response technologies, are similarly positioned to increase the effective value of PV generation at high penetration levels.

7.4 Research Priorities for the Next Decade

Drawing together the challenges identified throughout this review, priority research directions include:

(1) Resolving the intrinsic and extrinsic degradation mechanisms limiting perovskite and tandem device lifetimes, including the development of standardized, field-correlated accelerated testing protocols;
(2) Closing the efficiency gap between small-area champion cells and full-size commercial modules for perovskite and tandem technologies;
(3) Reducing reliance on scarce elements (indium, tellurium, silver) through materials substitution and reduced loading;

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(4) Developing economically viable, industrial-scale recycling processes for silicon, thin-film, and emerging PV technologies ahead of anticipated end-of-life waste volumes; and
(5) Continued reduction of soft costs and improved grid-integration frameworks to ensure that hardware-level efficiency and cost gains translate into deployed, dispatchable low-carbon electricity at the multi-terawatt annual scale required for global decarbonization pathways.

8. Conclusions

Solar photovoltaic technology has progressed from a costly, low-efficiency niche technology to the leading source of new electricity-generating capacity worldwide, underpinned by decades of incremental innovation in crystalline silicon and, more recently, by the remarkably rapid maturation of perovskite photovoltaics. Crystalline silicon, now dominated by TOPCon and heterojunction architectures, continues to approach its practical single-junction efficiency ceiling near the Shockley–Queisser limit, while thin-film CdTe and CIGS technologies offer complementary advantages in embodied energy, high-temperature performance, and mechanical flexibility. Perovskite and perovskite/silicon tandem cells represent the most consequential recent development in the field, with laboratory efficiencies now substantially exceeding those achievable by any single-junction technology, but their path to bankable commercial deployment remains contingent on resolving persistent operational stability challenges, closing the module-scale efficiency gap, and addressing lead-content concerns. Organic photovoltaics, dye-sensitized cells, and quantum dot technologies, while unlikely to challenge silicon or perovskite tandems for utility-scale deployment, retain meaningful roles in flexible, transparent, and low-light niche applications. Across all technologies, the challenges of materials sustainability, critical raw material supply, long-term reliability under real-world conditions, and end-of-life recycling are becoming as central to the field's trajectory as headline efficiency records. Meeting the multi-terawatt annual deployment rates implied by global decarbonization pathways will require not a single technological breakthrough but sustained, parallel progress across device physics, materials engineering, manufacturing scale-up, recycling infrastructure, and the policy and grid-integration frameworks that determine how effectively hardware-level gains translate into deployed, reliable, low-carbon electricity.

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