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Recent Progress in Solar and Fuel Cell Materials: A Comparative Perspective on Efficiency and Commercialization

Neha Gharat[1] and Sayali Kamble[2]
Department of Chemistry,
Satish Pradhan Dnyanasadhana College, Thane, Maharashtra, India
Sanandkamble95@gmail.com

Abstract : *The global transition toward sustainable energy has intensified research into advanced materials for solar and fuel cell technologies, two of the most promising pathways for clean power generation. This review provides a comparative overview of recent developments in solar cell materials—including crystalline silicon, perovskite, perovskite–silicon tandem structures, and thin-film technologies (CdTe, CIGS)—alongside advances in fuel cell materials, particularly proton exchange membrane (PEM) and solid oxide fuel cell (SOFC) systems, with emphasis on membrane, electrode and catalyst materials. Key performance metrics such as efficiency, durability, and cost are discussed for each technology class, highlighting recent breakthroughs including tandem cell efficiencies exceeding 33% and emerging non-platinum catalyst alternatives for fuel cells. The review further examines shared challenges across both domains, such as material stability under operational conditions, scalability of manufacturing processes, and economic viability for widespread adoption. By juxtaposing solar and fuel cell material innovations, this work aims to identify synergies in materials research, such as overlapping needs in durable, low-cost, earth-abundant materials and outlines future research directions to accelerate the commercialization of both technologies. This comparative perspective offers insights valuable to researchers and policymakers working toward integrated renewable energy solutions.*

Key Words: Solar Cells; Fuel Cells; Advanced Materials; Perovskites; Silicon; PEMFC; SOFC; Electrocatalysts; Energy Efficiency; Sustainable Energy.

I. INTRODUCTION

Rising global energy demand, coupled with the urgency of decarbonizing the power and transport sectors, has placed materials innovation at the center of the clean-energy transition. Among the many renewable technologies under active development, solar photovoltaics and hydrogen fuel cells occupy a distinctive and complementary position: photovoltaics convert sunlight directly into electricity while fuel cells convert stored chemical energy most commonly hydrogen into electricity on demand offering the dispatchability that intermittent renewables lack. Both technology families are fundamentally materials-limited; their efficiency durability and cost are dictated by the semiconductors, membranes, electrodes, and catalysts from which the devices are built.

Over the past decade, both fields have experienced rapid materials-driven progress. In photovoltaics the emergence of halide perovskites and perovskite–silicon tandem architectures has pushed laboratory efficiencies well beyond the practical ceiling of single-junction silicon. In fuel cells, the search for catalysts that can replace or reduce reliance on platinum-group metals has intensified as proton exchange membrane and solid oxide systems move from niche to mainstream deployment. Despite being studied largely as separate disciplines solar and fuel cell materials research

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shares a common set of goals: higher conversion efficiency, longer operational lifetimes under real-world stress and lower reliance on scarce or expensive elements.

This review adopts a comparative lens, examining recent advances in solar cell materials (crystalline silicon, perovskite, perovskite–silicon tandems, and CdTe/CIGS thin films) alongside advances in PEM and solid oxide fuel cell materials (membranes, electrodes, and catalysts). Section 2 reviews solar cell material classes; Section 3 reviews fuel cell material classes; Section 4 presents a comparative analysis of efficiency, durability and cost; Section 5 discusses challenges common to both domains; Section 6 identifies synergies and future research directions; and Section 7 concludes.

II. SOLAR CELL MATERIALS: RECENT ADVANCES

2.1. Crystalline Silicon

Crystalline silicon (c-Si) remains the dominant commercial photovoltaic technology, accounting for the large majority of global module shipments. Advanced architectures such as tunnel oxide passivated contact (TOPCon) and silicon heterojunction (SHJ/HJT) cells have pushed single-junction silicon cell efficiencies toward 27–28%, approaching the practical limits set by the Shockley–Queisser theoretical ceiling for a single absorber. Continued gains are now incremental, driven by better surface passivation, thinner wafers and improved metallization, motivating interest in multi-junction approaches to surpass this ceiling.

2.2. Perovskite Solar Cells

Halide perovskites are solution-processable semiconductors whose tunable bandgap, strong light absorption, and low-temperature fabrication routes have made them the fastest-improving photovoltaic material class in history rising from roughly 3.8% efficiency at their first demonstration to a certified single-junction efficiency of about 27.3% within roughly a decade and a half. This rapid progress has, however, been accompanied by persistent concerns over long-term operational stability under heat, humidity and ultraviolet exposure, as well as the presence of lead in the most efficient compositions, both of which remain central research and regulatory issues.

2.3. Perovskite–Silicon Tandem Structures

Stacking a wide-bandgap perovskite top cell on a silicon bottom cell allows each layer to more efficiently harvest a different part of the solar spectrum, pushing combined efficiencies beyond what either material could achieve alone. Certified efficiencies for two-terminal monolithic perovskite–silicon tandems have advanced rapidly, reaching 34.85% in 2025 and recent work using peak-selective passivation strategies has demonstrated 32.9% certified efficiency with roughly 90% performance retention after 1,000 hours of continuous operation. These results place tandem cells well above the 27–28% ceiling of the best single-junction silicon and perovskite devices. Nonetheless, commercialization faces a stability-validation gap: the longest publicly reported operational stability data (on the order of 1,000 hours) remains far short of the 25-year field warranties expected of silicon modules, and additional barriers include lead-content regulation in some jurisdictions, unproven manufacturing yield at gigawatt scale, and continuing efficiency gains in competing silicon technologies that narrow the tandem's relative advantage.

2.4. Thin-Film CdTe and CIGS Technologies

Thin-film cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) technologies offer an alternative route to low-cost solar electricity through direct-bandgap absorbers that require only micron-scale material thicknesses. CdTe cell efficiency has progressed from about 16.5% in the early 2000s to 22.1% following innovations such as CdSeTe band-gap grading, refined $CdCl_2$ activation, and arsenic doping to improve carrier lifetime and open-circuit voltage; industry and national laboratory roadmaps target cell efficiencies exceeding 24% by the end of 2025 and 26% by 2030. CIGS cells have reached comparable laboratory efficiencies in the low-20% range. While thin-film technologies trail silicon and tandem architectures in peak efficiency, their lower material intensity, established gigawatt-scale manufacturing (led by First Solar for CdTe), and long field-performance track record make them commercially significant, cost-competitive options, particularly for utility-scale deployment.

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III. FUEL CELL MATERIALS: RECENT ADVANCES

3.1. Proton Exchange Membrane Fuel Cells (PEMFC)

PEM fuel cells rely on a perfluorosulfonic acid polymer membrane that conducts protons from anode to cathode while blocking electron transport, forcing the electrons through an external circuit. The catalyst layer, historically reliant on platinum or platinum-alloy nanoparticles to accelerate the sluggish oxygen reduction reaction (ORR) at the cathode, remains the single largest contributor to stack cost, motivating a large body of research into platinum-group-metal-free (PGM-free) alternatives. Atomically dispersed metal–nitrogen–carbon (M–N–C) catalysts, particularly those with iron–nitrogen (Fe–Nx) active sites, have emerged as the most promising non-platinum candidates, showing high intrinsic ORR activity and, in high-temperature PEMFC variants using phosphoric-acid electrolytes, useful tolerance to anion poisoning. The U.S. Department of Energy's 2025 performance target for PGM-free membrane electrode assemblies (44 mA cm^{-2} at 0.9 V, corrected for internal resistance) provides a widely used benchmark against which these catalysts are evaluated. The central unresolved challenge for non-PGM catalysts remains long-term durability: activity and stability under the acidic, oxidative operating environment of a PEMFC continue to trade off against one another, limiting practical deployment despite encouraging laboratory activity data.

3.2. Solid Oxide Fuel Cells (SOFC)

Solid oxide fuel cells use a dense ceramic electrolyte—commonly yttria-stabilized zirconia (YSZ), gadolinium- or samarium-doped ceria (CGO/CSO), or lanthanum strontium gallate magnesite (LSGM)—to conduct oxide ions between a nickel-cermet anode and a perovskite-type cathode, typically operating between 600 and 1,200 °C. Because ORR and fuel oxidation proceed rapidly at these temperatures, SOFCs do not require precious-metal catalysts, giving them a cost advantage over PEMFCs in this respect, and they achieve high electrical efficiencies (on the order of 60%) with fuel flexibility that extends beyond pure hydrogen to natural gas and other hydrocarbons. A major research thrust is the development of intermediate-temperature SOFCs (500–800 °C) to reduce thermal stress, material costs, and start-up time; lanthanum strontium cobalt ferrite (LSCF) perovskite cathodes, which exhibit high oxygen diffusivity and surface-exchange coefficients, have become the preferred choice for this regime, superseding strontium-doped lanthanum manganite (LSM) cathodes that perform poorly at reduced temperatures. Persistent challenges include thermal-expansion-coefficient mismatch between cells, cation segregation at electrode surfaces during long-term operation, and the sustainability of the rare-earth and doped-ceria compositions on which many high-performance electrodes depend.

IV. COMPARATIVE ANALYSIS: EFFICIENCY, DURABILITY, AND COST

Table 1 summarizes representative performance and status indicators across the solar and fuel cell material classes reviewed above. Several patterns emerge. First, efficiency gains in both domains increasingly come from architectural and interfacial engineering—tandem stacking in photovoltaics, atomically dispersed active sites in fuel cell catalysts—rather than from entirely new base materials. Second, durability under real operating stress, rather than peak efficiency, is now the principal barrier to commercialization for the newest material classes (perovskite tandems, non-PGM fuel cell catalysts), while more mature technologies (silicon, CdTe, SOFC) are limited more by incremental cost reduction and manufacturing scale-up. Third, cost structures differ in origin but converge in effect: solar technologies are cost-limited primarily by processing and balance-of-system expenses, whereas PEMFCs are cost-limited primarily by a single scarce catalytic element (platinum), a constraint SOFCs largely avoid at the expense of higher operating temperatures and more demanding ceramic processing.

Technology	Best Certified Efficiency	Key Durability Metric	Commercialization Status
Crystalline Si (TOPCon/HJT)	26–27.8% (cell)	25-year warranties standard	Mature, dominant (~90% market share)
Single-junction perovskite	~27.3% (NREL)	Sensitive to moisture/heat/UV; encapsulation improving	Pre-commercial; stability-limited

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Perovskite–Si tandem	34.85% (LONGi, 2025)	~90% retention after 1,000 h reported	Pilot-scale; first modules (~24–28%) emerging 2026
Thin-film CdTe	22.1% (cell, First Solar)	Long field record (>20 yr fleets)	Commercial, GW-scale (First Solar)
Thin-film CIGS	~22–23% (cell)	Good field stability	Commercial but smaller market share
PEMFC (Pt/C)	~60% (system, theoretical)	Pt dissolution/carbon corrosion limit life	Commercial (transport, backup power)
PEMFC (non-PGM, Fe-N-C)	Approaching DOE 2025 activity target	Durability under acidic/oxidative stress still limiting	Lab/pilot stage
SOFC	~60% electrical (system)	Thermal-cycling and TEC-mismatch degradation	Commercial for stationary CHP; niche scale

Table 1. Comparative summary of efficiency, durability, and commercialization status across solar and fuel cell material classes discussed in this review.

V. SHARED CHALLENGES ACROSS SOLAR AND FUEL CELL MATERIALS

Despite their different operating principles, solar and fuel cell materials face a strikingly similar set of obstacles on the path to widespread adoption.

Material stability under operational conditions: Perovskite absorbers degrade under prolonged heat, humidity, and UV exposure, much as fuel cell catalysts and ceramic electrodes degrade under sustained electrochemical and thermal cycling. In both cases, the mechanisms of degradation—ion migration, interfacial delamination, and nanoparticle agglomeration or ripening—are analogous even though the driving forces differ.

Scalability of manufacturing: Moving from record laboratory cells to gigawatt-scale modules, or from single fuel cell buttons to multi-kilowatt stacks, introduces yield, uniformity, and reproducibility challenges that are rarely visible at small scale. Perovskite tandem manufacturers and non-PGM catalyst developers alike face an unproven transition from pilot-scale to mass production.

Economic viability and critical materials: Both fields depend on elements that are scarce, geographically concentrated, or increasingly regulated—indium and gallium for CIGS, tellurium for CdTe, platinum-group metals for PEMFCs, and rare-earth dopants for SOFC electrodes. Lead in high-efficiency perovskites and cadmium in CdTe raise parallel environmental and regulatory concerns to the toxicity and end-of-life questions associated with certain fuel cell materials.

VI. SYNERGIES AND FUTURE RESEARCH DIRECTIONS

Viewed together, solar and fuel cell materials research point toward several shared priorities. Both fields would benefit from earth-abundant, non-toxic replacements for their most constrained materials—platinum-free catalysts in fuel cells and lead-free, indium/gallium-free, or tellurium-free absorbers in photovoltaics—motivating shared interest in computational materials screening and machine-learning-guided discovery to accelerate the search. Both fields also share an interest in accelerated stress-testing protocols and standardized durability metrics that can shorten the gap between laboratory demonstration and bankable, field-warrantied products. Finally, the physical coupling of the two technologies in integrated renewable energy systems—photovoltaic-powered electrolysis feeding hydrogen back through fuel cells for dispatchable power—creates a practical incentive for coordinated materials research, since the overall system efficiency and cost depend jointly on advances in both solar absorbers and fuel cell electrodes. Future work that treats these two device classes as parts of a single materials research agenda, rather than as separate specialties, is likely to accelerate progress toward integrated, low-carbon energy infrastructure.

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VII. CONCLUSION

This review has compared recent materials advances in solar photovoltaics and fuel cells, two technology families that are often studied in isolation but that face closely related scientific and commercialization challenges. Perovskite–silicon tandem solar cells and non-platinum fuel cell catalysts represent the most active frontiers in their respective fields, each promising substantial efficiency or cost improvements but each still constrained by durability under real-world operating stress. Thin-film CdTe/CIGS photovoltaics and solid oxide fuel cells illustrate the value of mature, already-commercial technologies that continue to improve incrementally while newer alternatives close the durability gap. By highlighting the overlapping need for stable, low-cost, earth-abundant materials, this comparative perspective aims to encourage cross-disciplinary research collaboration that can accelerate the commercialization of both solar and fuel cell technologies as complementary pillars of an integrated renewable energy future.

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