

Research and Development Challenges in Contemporary Solar Cell Architectures for a Sustainable Energy Transition

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Abdelkader Djelloul*

Research Center in Semiconductor Technology for Energetics (CRTSE), 02 Bd Frantz Fanon, BP 140, 7 Merveilles, 16000, Algiers, Algeria

***Corresponding Author:** Abdelkader Djelloul, Research Center in Semiconductor Technology for Energetics (CRTSE), 02 Bd Frantz Fanon, BP 140, 7 Merveilles, 16000, Algiers, Algeria.

The continuously increasing global demand for energy, driven by population growth, rapid urbanization, and ongoing digital transformation, necessitates the adoption of sustainable, clean, and universally accessible energy sources. In this context, solar energy, as an abundant and renewable resource, stands out as one of the most promising solutions to address these challenges. The Earth receives an immense amount of solar radiation, yet only a small fraction is currently harnessed. Indeed, the solar irradiance reaching the Earth's surface has the theoretical potential to meet global energy demands.

A solar cell is a device that converts solar radiation directly into electrical energy through the photovoltaic effect. Photovoltaic technologies are among the most significant technological advancements, given that the sun represents a clean and virtually inexhaustible energy source. Consequently, the development of efficient and cost-effective solar cells constitutes a central pillar in global efforts to mitigate energy shortages and environmental pollution. However, conventional photovoltaic technologies, particularly those based on crystalline silicon (c-Si), continue to face several limitations, including high production costs, efficiency losses under variable illumination conditions, and environmental concerns associated with manufacturing processes.

The conventional classification of solar cells into successive "generations" (from wafer-based silicon (Si) to emerging nanostructured devices) remains a useful heuristic but should not obscure the increasing convergence between these categories. Each category has its own advantages and inherent challenges related to efficiency, stability, scalability and environmental impact. For example, advanced silicon architectures such as TOPCon and heterojunction cells already integrate concepts traditionally associated with next-generation devices, blurring the boundaries between generations. This convergence signals a shift from linear technological evolution to hybridized innovation pathways.

Emerging solar cells technologies, particularly perovskite-based systems, tandem architectures, and Earth-abundant absorbers such as kesterites, have attracted significant attention due to their potential to surpass the efficiency limits of single-junction devices. However, their scientific and technological challenges are often underestimated. In perovskite solar cells (PSC), the apparent defect tolerance coexists with intrinsic chemical and structural instability under operational conditions. Similarly, kesterite materials (CZTS) are constrained by persistent voltage deficits linked to cation

disorder and band tailing, while quantum dot systems face fundamental limitations related to carrier transport and surface recombination. These issues represent deep, unresolved physical and chemical constraints that continue to limit scalability.

Looking forward, the future of cutting-edge solar cell technologies will likely be shaped by the convergence of several strategic directions. First, tandem and hybrid architectures, particularly silicon-perovskite combinations, are expected to dominate high-efficiency pathways, provided stability and scalability challenges are resolved. Second, the development of environmentally benign and earth-abundant materials will become increasingly important in response to sustainability constraints. Third, advanced characterization techniques, data-driven optimization (including machine learning approaches), and digital manufacturing are anticipated to accelerate innovation cycles. Finally, the integration of photovoltaic systems into flexible, wearable, and building-integrated applications will expand the functional scope of solar energy technologies.

Therefore, next-generation solar cells are not only expected to meet current energy demands but also to enable a sustainable, resilient, and inclusive energy transition, particularly in developing regions. However, realizing this vision requires sustained interdisciplinary research, robust industrial partnerships, and supportive policy frameworks. This editorial calls for a renewed focus on bridging the gap between laboratory-scale innovation and industrial-scale deployment, ensuring that technological breakthroughs translate into tangible societal impact.