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The Need for Fundamental Photovoltaics Research to Ensure Energy Security

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ABSTRACT

Despite the commercial maturity of photovoltaic (PV) technology, fundamental research remains essential for continued innovation, energy resilience, and strategic independence. The low cost and distributed nature of solar and wind power make them uniquely suited to deliver secure electricity without reliance on fuel supply chains. However, these strengths are the result of decades of foundational scientific inquiry, and continued progress depends on sustained support for such work. This paper outlines a future-oriented agenda for fundamental PV research, addressing challenges in materials, device architectures, characterization, and system integration. Drawing on discussions from the 53rd IEEE Photovoltaic Specialists Conference (PVSC) in Montreal, we critically examine the narrative that PV is a “solved” problem. We argue that deep scientific exploration is not only vital for unlocking next-generation technologies but also for training the skilled workforce required to maintain technological leadership and to support the reliable functioning of national energy infrastructure. We conclude with targeted recommendations for funding agencies and policymakers on how to structure research support to maximize long-term impact.

1 | Introduction

Solar photovoltaic (PV) power is the fastest growing energy source in history [1]. The cost reduction and growth in the market for PV panels have been remarkable and consistently underestimated by reputable forecasters since the first commercial PV panels were produced more than 50 years ago [2, 3]. It is the lowest cost way to generate electricity in a wide range of locations, and the cost continues to decline [4, 5]. The success of solar technology is built on decades of research in materials and device design. As the world increasingly shifts to electrical energy, the benefits of continuing the progress in PV technology

are clear. Low-cost electricity supports rising standards of living globally. Continuing support for fundamental research in PVs is essential to sustain the remarkable progress in this technology into the future.

Nevertheless, in recent years, perceptions have grown among a number of public and commercial funding bodies and policymakers that PVs is a “solved” problem, from a technological perspective at least, no longer requiring fundamental research and development. This view is a dangerous trend given that energy security is one of the cornerstones of modern, prosperous societies and is considered critical for national sovereignty [6].

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A secure and reliable energy supply ensures everything from economic growth to political stability and national defense. Without it, no country can safeguard its independence or sustain the well-being of its citizens.

In this context, solar energy has become the most cost-effective source of electricity in many regions [4, 5], thanks to rapid technological advances, manufacturing scale-up, and declining deployment costs. Beyond its economic advantage, it also offers a uniquely resilient form of power generation [7]. Its distributed nature and independence from global fuel markets reduce exposure to price volatility, supply disruptions, and geopolitical risk. Once installed, solar and wind systems require no imported fuels and operate with very low operational costs, making them less susceptible to market shocks or external control.

External control over a nation's energy supply becomes significantly less feasible when powered by distributed renewables, as disrupting generation would require widespread, simultaneous interference across many sites, unlike centralized fossil fuel or nuclear facilities, where a single point of failure can compromise large portions of the energy system [8–10]. This structural resilience extends to system-level performance provided that the infrastructure, particularly inverters and grid control systems, is robust against cyberattacks and unauthorized access. For example, during recent energy infrastructure disruptions in Ukraine, it was found that decentralized generation reduced recovery time to 3–6 h compared with 12–18 h for traditional power supply [11]. Moreover, solar and wind are inherently abundant and unmonopolizable resources. Unlike fossil fuels or uranium, they are not subject to extraction bottlenecks or international trade dependencies. Together, these qualities make solar energy not only economically attractive but also a cornerstone for secure, self-sufficient, and future-proof energy systems.

While silicon-based solar modules now achieve high efficiencies at low cost [12], this maturity should not be mistaken for the end of innovation. On the contrary, as this paper will show, substantial scientific and technological challenges remain, ranging from material stability and circularity to system integration, next-generation architectures, and entirely new application domains. These future breakthroughs, like past ones, depend on continued investment in foundational science and a research environment that fosters exploration and understanding. As the PV sector continues to scale, any new foundational science integrated in improved large-scale commercial deployments will have an outsized impact on the global energy economy.

History shows that declaring a field “solved” too early can be a strategic error. As one of many examples, in the early days of color television, RCA dominated the market and reaped large profits, viewing the technology as mature and diverting its research efforts elsewhere. Japanese competitors, who continued investing in improved solutions, eventually outpaced RCA and now flat panel displays have taken over the market [13]. This shows the importance to sustain foundational research and avoid complacency in a field that remains critical to global infrastructure and competitiveness.

In addition to driving innovation, foundational research plays a vital role in cultivating a highly skilled and adaptable workforce.

Even if today's technologies were fully optimized, maintaining technical excellence and resilience over time, particularly in the face of global disruption, supply chain shifts, and evolving system requirements, depends on the availability of researchers and engineers who are deeply trained in the basic scientific principles of energy technologies.

In response to growing concerns that fundamental renewable energy research is being de-emphasized in the funding landscape [14–16], the session *Focus on Fundamentals* was held at the 53rd IEEE Photovoltaics Specialists Conference (PVSC) 2025 in Montreal, Canada. The event convened scientists, students, and industry experts to articulate why fundamental PV research remains indispensable and to discuss how it can be reasserted within the broader scientific and policy agenda. The ideas presented here emerged from that interactive forum and have been refined into a broader perspective on the role of foundational science in the future of PVs.

In what follows, we clarify what constitutes fundamental research in the context of PVs and we then present a forward-looking agenda, highlighting key scientific and technological frontiers. This includes the study of fundamental limits, novel materials and architectures, advanced characterization, and system-level integration. We further discuss how fundamental research supports workforce development and technological resilience, and we conclude with concrete recommendations for policymakers and funding agencies on how to structure support for PV research in ways that maximize long-term impact, scientific return, and strategic value.

2 | Defining the Role and Scope of Fundamental Research in PVs

Defining what constitutes “fundamental research” in PVs is not straightforward. In solar energy, there is nearly always an application in mind, even when the work is exploratory. However, the key distinction is often in the timeframe and intent. Research may be fundamental when it does not lead to commercial implementation within a foreseeable period but rather focuses on building a deeper understanding of materials, processes, or phenomena that may later prove essential to innovation. A practical definition is that fundamental research is aimed at understanding a specific problem or technology space, rather than immediately solving it or developing a market-ready product. This kind of inquiry values understanding for its own sake, which often becomes the foundation for later technological progress. This interpretation is consistent with earlier definitions of basic and fundamental research, as summarized by the National Academies of Sciences, Engineering, and Medicine, which emphasize the pursuit of understanding without immediate consideration of specific commercial applications [17].

Fundamental research also includes the exchange of concepts across disciplines. Emerging areas such as thermophotovoltaics, laser power conversion, thermoradiative diodes (or “night-time solar”), and quantum-enhanced energy systems are examples of how curiosity-driven science can open new directions for PVs. Similarly, concepts from biology, photonics, and quantum information may yield fresh insights into solar conversion and

vice versa. This interplay between fields has historically driven disruptive innovation, but it requires long-term investment and freedom to explore without immediate constraints.

3 | Future Directions for Fundamental Research in PVs

Historically, some of the most impactful innovations in PV have emerged from foundational scientific insights. Theoretical breakthroughs such as the detailed balance limit or the $4n^2$ light-trapping formulation were not driven by immediate product development, but they enabled entire generations of device optimization and performance gains. However, while these examples remain valuable, the future of PV science cannot be justified solely by past successes. We must ask what kinds of foundational research will underpin the next wave of progress.

In what follows, we focus explicitly on the underlying scientific questions that remain unresolved in PV. While many of these questions are motivated by technological challenges, the emphasis here is on the fundamental physical, chemical, and materials principles that must be understood to enable future progress.

A central pillar of this foundation is the continued study of thermodynamics, reciprocity relations, and efficiency limits. These concepts define what is physically achievable and provide essential guidance for materials discovery and device design. Understanding entropy constraints, loss mechanisms, and nonideal behaviors is key to identifying pathways for improved performance, both in conventional devices and in advanced conversion schemes such as hot carrier systems [18], intermediate band materials [19], and photon up- or down-conversion [20]. This line of inquiry bridges theoretical insight with material science, ensuring that research efforts are grounded in physical reality.

One critical area is the exploration and advancement of new PV materials and architectures. While silicon continues to dominate the commercial market, next-generation technologies such as ultrathin III–V [21–23], two-dimensional semiconductors [24], and tandem devices [25, 26] promise significant efficiency gains, reduced weight, and new application possibilities. These materials offer exceptional optoelectronic properties but come with challenges in terms of cost, fabrication scalability, and integration. Other promising directions include novel heterojunctions, nitrides [27], sulphides [28], intermediate band structures [19, 29], up- and down-conversion systems [20], singlet fission [30, 31], and hot carrier devices [18]. Many of these concepts remain at an early stage, requiring extensive research to understand their mechanisms and to evaluate their viability. Addressing these challenges calls for foundational work in epitaxy, defect control, quantum efficiency, and interface design.

At the same time, the field is expanding toward more chemically and structurally complex materials, including metal halide perovskites [32] and organic semiconductors [33]. These materials deviate substantially from the idealized, stable systems on which traditional semiconductor models are based. Understanding their behavior, particularly with respect to long-term reliability, degradation mechanisms, ion migration, defect tolerance, and

nonradiative recombination, demands fresh theoretical and experimental insights beyond our current understanding of materials and device physics.

Closely tied to these material challenges is the development of advanced characterization techniques. As devices become more complex and multifunctional, there is a growing need for in situ and in-operando methods, high-resolution multimodal microscopy, ultrafast spectroscopy, and nondestructive imaging to probe materials and interfaces in realistic conditions. Importantly, even in industrial settings, significant gains can still be made through improved in-line manufacturing analytics enabling real-time quality control, defect detection, and process optimization at scale. Foundational research in instrumentation and measurement science will play a decisive role not only in unlocking the potential of emerging PV technologies but also in making their production more efficient and robust.

Another pressing frontier is the strategic reduction of reliance on critical raw materials. As PV deployment scales globally, material availability and supply chain resilience become central to its long-term viability. Foundational research can support the development of strategies that enhance performance with less material input. These may include advanced light-management techniques, thinner absorber layers, high-performance encapsulation, or the substitution of rare elements with earth-abundant alternatives. Equally important is improving long-term reliability. The longer PV systems operate without failure, the less frequently they need to be replaced, reducing overall material demand and mitigating the environmental and logistical burden of manufacturing and end-of-life handling. These efforts are tightly coupled with the development of recyclable module designs and circular manufacturing approaches, both of which require a fundamental understanding of material interactions over the full lifecycle of a solar device.

In addition to improving conventional PV devices, foundational science can help open entirely new PV applications. Fields such as thermophotovoltaics, thermoradiative diodes, laser power converters, and photoelectrochemical fuel generation represent adjacent domains where the principles of PV conversion are applied in novel ways. These areas pose their own set of fundamental questions related to photon and heat management, nonequilibrium processes, and device architecture.

As low-cost and scalable materials manufacturing capabilities expand, III–V semiconductors hold promise for a wider range of terrestrial applications. Their high efficiencies and design flexibility make them attractive for emerging use cases in transportation, architecture, portable systems, and possibly also for utility-scale, building and agriculture-integrated PV. Realizing this potential will require foundational advances in cost-effective manufacturing methods based on scalable epitaxy, substrate recycling, and the integration of these materials into unconventional environments such as unmanned aerial vehicles and automobiles.

Fundamental research also plays a vital role in enabling systemic integration of PV with broader infrastructure and energy systems. This includes efforts to reduce the mismatch between solar production and seasonal demand, hybridize generation with

agriculture, connect PV to long-duration storage, and improve the resilience of energy systems. Such advances require insights that extend beyond device-level efficiency and tap into system integration, thermal management, and energy storage principles. An instructive historical analogy is the early days of electrification and communication, when power and data transmission lines were visibly strung across streets. Today, energy and communication systems are largely hidden or delivered wirelessly. In the same way, PV could evolve toward seamless, aesthetically integrated forms embedded into buildings, vehicles, and public infrastructure. Realizing this vision demands not only engineering progress, but also new scientific insights into materials, form factors, and system-level dynamics.

Taken together, these areas define a forward-looking agenda for foundational PV research. They reflect not only the scientific richness of the field but its continued relevance in shaping resilient, secure, and inclusive energy systems for the decades to come.

4 | Training a New Generation of Innovators

A less tangible but equally vital outcome of fundamental research is the cultivation of scientific minds. Graduate training grounded in fundamental inquiry equips researchers with the capacity to ask deep questions, navigate uncertainty, and adapt across disciplinary boundaries. These skills are not only essential in academia but are strongly valued in industry, government, and entrepreneurship.

PhD training should not be viewed as job-specific technical instruction, but as a rigorous development of critical thinking, creativity, and problem-solving. Many of today's industrial innovators began their careers exploring seemingly abstract scientific problems. Funding foundational research is therefore also an investment in the intellectual infrastructure of the clean energy industry and other deep tech economies.

Equally important, we must guard against a situation in which we have the technologies in place but lack the personnel to operate, maintain, upgrade, or innovate them. The risk is real: By letting skills atrophy, whether because of shrinking training programs, workforce attrition, or shifting institutional priorities, we risk developing the kind of “tech illiteracy” depicted in dystopian fiction, where we can no longer competently manage the systems we rely on. Germany offers a cautionary example. With the closure of its last three nuclear power plants in April 2023, many industry voices raised concern that the lack of sufficient skilled and trained workforce makes any future restart or redevelopment far more complex [34, 35].

In short, maintaining a highly trained, adaptable workforce is not just a matter of future-proofing innovation; it is a matter of national resilience, technological sovereignty and long-term system reliability.

5 | Communicating Impact and Securing Support

To effectively advocate for fundamental PV research, the community must improve how it communicates its impact. Rather

than appealing solely to long-term technological potential, it is also important to highlight the broader societal and educational returns of such endeavors. Training metrics, open-source software, public engagement, and interdisciplinary collaborations are concrete outcomes that resonate with funding agencies and the public. Participants stressed that even when fundamental research does not result in direct applications, it reshapes how the community thinks and operates. As one contributor noted, astronomy has justified its public investment not through immediate utility but through inspiration and education. Similarly, PV research can justify its fundamental pursuits by demonstrating broader intellectual and cultural value.

Successful cases of policy engagement, such as efforts in the Netherlands to quantify workforce development benefits in grant applications [36], demonstrate that clear narratives can influence funding priorities. Scientists must actively participate in shaping these narratives and educating decision-makers about the enduring value of curiosity-driven research.

At the same time, it is important to recognize that there is no single, monolithic “PV community.” The field encompasses diverse technologies, architectures, and research traditions, and healthy scientific debate is both inevitable and valuable. However, internal competition should not devolve into diminishing alternative approaches or framing progress as a situation in which the success of one technology must come at the expense of another. Especially in times of constrained funding, it is essential to foster a culture of mutual respect and intellectual openness that seeks to strengthen the entire field rather than defend narrow positions. A unified and optimistic narrative reinforces the shared goal of advancing solar energy for societal benefit.

5.1 | Future Research in PV Should Be Increasingly Interdisciplinary

As PV adoption scales, it intersects with agriculture (agrivoltaics [37–40]), the built environment (BIPV), water conservation (aquavoltaics and floatovoltaic [41, 42]), the circular economy (recycling and reuse), social sciences (public perception and adoption [39, 43]), and energy systems (storage and integration). These cross-cutting domains require a foundational understanding to enable transformative, context-aware solutions.

At the same time, the PV research community must also consider its messaging strategy. While environmental motivations have historically justified support for solar energy, they are unlikely to sway stakeholders who remain unconvinced of the urgency of climate action. For these audiences, often those making key funding decisions, it is more effective to emphasize solar energy's contributions to economic competitiveness, national resilience, and energy independence. In today's funding landscape, arguments grounded in economic strength and national resilience are not just more persuasive; they are essential if we want PV research to remain a priority in the eyes of those shaping science and innovation policy.

6 | Recommendations for Funding Bodies

To ensure continued innovation in PVs, funding bodies should adopt a long-term, strategic view that recognizes the critical role of foundational inquiry. During the discussions at PVSC, community leaders noted that 20% of fundamental effort can yield 80% of the key insights needed to direct the remaining engineering and implementation work. This emphasizes the absolute necessity for fundamental understanding to achieve progress. It is the same logic that drives the world's most successful companies, which consistently invest in research and innovation to secure their future growth [44, 45]. Governments should adopt the same approach, recognizing that sustained support for fundamental PV research is a strategic necessity rather than an optional expense.

Rather than reinforcing a binary opposition between “fundamental” and “applied” research, funding frameworks should instead focus on clarity of purpose, scientific rigor, and relevance to long-term progress. Fundamental research, when assessed primarily through the lens of short-term application, risks being distorted by unrealistic promises or diluted objectives. Instead, such work should be valued for its contribution to understanding, and for the knowledge it generates within the scientific community. Curiosity-driven inquiry, motivated by the desire to understand how things work rather than to immediately build them, has consistently led to transformative advances.

Funding criteria should therefore recognize and support work that seeks to understand core scientific mechanisms, explore new material systems, or unlock entirely new conceptual and technological spaces, even when direct applications may be distant or uncertain. Purpose, in this sense, refers not to product development, but to the thoughtful framing of a problem and the depth of insight brought to its exploration.

It is equally critical that agencies ensure scientific integrity during the evaluation process. Importantly, the scope of fundamental research in PV must also include thermodynamic constraints. Funding agencies and investors should ensure rigorous vetting of project proposals by involving reviewers who understand thermodynamics and basic energy systems, preferably solar-trained scientists. This avoids misdirected investments [46] and promotes scientifically sound innovation.

6.1 | International Collaboration and Interdisciplinary Coordination Should Also Be Upheld as *Nonnegotiable Principles*

The pace of discovery increases when knowledge is shared openly, redundancies are avoided, and complementary expertise is integrated across borders. One of the most striking examples of this principle is the long-standing US–Russian cooperation on the International Space Station, where scientific collaboration persisted even during periods of significant political tension. Unfortunately, for various reasons funding for international research projects across the scientific community has been eroded over the last 10–20 years, and mechanisms to strengthen and build such engagements should be actively sought and developed.

7 | Conclusion

This paper outlines why fundamental research remains essential for the continued advancement and societal value of PV technologies. Despite PV's commercial maturity, multiple unresolved challenges persist across materials science, device design, characterization, reliability, recyclability, and system integration. The examples discussed show that foundational research is not only a driver of long-term innovation but also central to enabling more resilient, secure, and sustainable energy systems.

We have proposed a refined view of what constitutes “fundamental” research in the context of PV, emphasizing that such work is often motivated by the need to understand rather than to immediately solve. We also highlighted future research directions where fundamental science is expected to make high-impact contributions, including advanced conversion schemes, new material systems, and seamless integration of PV into broader infrastructure.

Beyond its technical contributions, fundamental research plays a critical role in developing and sustaining a skilled and adaptable workforce. Graduate and postdoctoral training rooted in fundamental inquiry cultivates critical thinking, creativity, and problem-solving skills. These are essential not only for scientific innovation but also for maintaining industrial competitiveness, technological resilience, and the ability to respond to unforeseen challenges in a rapidly evolving energy landscape. Without continuous investment in such training, the knowledge base required to operate, maintain, and advance complex energy systems will erode over time, ultimately weakening national and global capacity to innovate and secure a resilient energy future.

Finally, we provide targeted recommendations for how funding agencies and policymakers can structure research support to maximize its impact. This includes recognizing the long-term value of foundational inquiry, ensuring scientific rigor in proposal evaluation, supporting international collaboration, and reducing artificial boundaries between applied and fundamental work.

Sustained, strategic investment in fundamental PV research is not only justified; it is necessary to ensure continued progress in global energy innovation.

Author Contributions

Rebecca Saive: Conceptualization; writing – original draft; writing – review and editing; supervision; project administration. Ian R. Sellers: Conceptualization; writing – review and editing; supervision. Gavin Conibeer, Lisanne Einhaus, Jean-François Guillemoles, Koami Soulemane Hayibo, Karin Hinzer, Jacob J. Krich, Martha Lenio, Michael P. Nielsen, Frederick U. Nitta, Daniel Suchet, Eric Tervo, Tom Tiedje, and Jelle Westerhof: Conceptualization; writing – review and editing. All authors contributed to the development of ideas during the IEEE PVSC session and subsequent discussions and approved the final manuscript.

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The authors declare no conflicts of interest.

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