Journal of Environment, Climate, and Ecology (JECE)
ISSN: 3079-255X (Online)
Volume 2 Issue 1, (2025)
https://doi.org/10.69739/jece.v2i1.546
https://journals.stecab.com/jece

Published by
Stecab Publishing

Research Article

The Role of Organic Solar Cells in U.S. Energy Transition: Technical Advances, Deployment Challenges, and Policy Pathways

[1]Ololade Funke Olaitan, [2]Ikechukwu Okoh, [3]Philip Ugbede Ojo Onuche, [4]Jamiu Olayinka Alabi, *[5]Precious Esong Sone, [6]Kiran K. Kalyanaraman, [7]John Ukanu, [8]Clinton Arthur

About Article

Article History
Submission: April 10, 2025
Acceptance : May 16, 2025
Publication : May 26, 2025

Keywords
Non-Fullerene Acceptors, OPV Stability, Organic Solar Cells, Photovoltaics, Tandem Architectures, U.S. Clean-Energy Policy

About Author

[1] David Eccles School of Business, Information Systems, University of Utah, Salt Lake City, UT, USA

[2] Department of Mechanical and Aerospace Engineering, Michigan Technological University, Houghton, MI, USA

[3] Department of Chemistry, Southern Illinois University Edwardsville (SIUE), Edwardsville, IL, USA

[4] Department of Construction Management and Technology, Bowling Green State University, Bowling Green, OH, USA

[5] Department of Healthcare Management (MBA), East Carolina University, Greenville, NC, USA

[6] Department of Data Analytics, University of Illinois Urbana-Champaign, Urbana, IL, USA

[7] Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria

[8] Department of Chemistry, Eastern New Mexico University, Portales, NM, USA

Contact @ Precious Esong Sone
esongprecious@gmail.com

ABSTRACT

Organic solar cells (OSCs) have shed their “lab curiosity” label as efficiencies near 19% and module lifetimes approach a decade. This hybrid scoping–narrative review examines OSCs’ role in achieving U.S. goals of a carbon-free grid by 2035 and net-zero emissions by 2050. We analyzed 80 peer-reviewed studies, government reports, and field trials (2015–2025), grouping insights into technical advances, deployment experience, policy frameworks, and equity considerations. Three themes emerge: Materials & Performance, where non-fullerene acceptors and tandem designs halve the gap with silicon and boost stability; Deployment Realities, demonstrated by façade films in Germany, transparent solar windows in California, and pilot roll-to-roll lines, alongside scale-up, certification, and bankability hurdles; and Policy & Equity Gaps, revealing incentives skewed toward silicon yet highlighting OSCs’ low-toxicity materials and architectural flexibility for energy justice. We recommend federal support for pilot manufacturing, accelerated standards, and equity-focused demonstrations in schools, affordable housing, and community centers. With coordinated R&D, policy, and community engagement, OSCs can evolve from niche novelty to a complementary layer of America’s solar portfolio.

Citation Style:

Olaitan, O. F., Okoh, I., Onuche, P. U. O., Alabi, J. O., Sone, P. E., Kalyanaraman, K. K., Ukanu, J., & Arthur, C. (2025). The Role of Organic Solar Cells in U.S. Energy Transition: Technical Advances, Deployment Challenges, and Policy Pathways. *Journal of Environment, Climate, and Ecology, 2*(1), 49-60. https://doi.org/10.69739/jece.v2i1.546

1. INTRODUCTION

Solar power has emerged as a linchpin technology in the push to decarbonize the U.S. energy system. Recent analyses by the Department of Energy (DOE) suggest that solar energy could supply up to 40% of U.S. electricity by 2035—a tenfold increase from 2020 generation (Volcovici & Volcovici, 2021). Achieving this scale will require not only continued deployment of conventional silicon photovoltaics but also innovations that expand solar into new arenas. Organic solar cells have long been touted as a next-generation solution that could complement traditional panels; they are thin, flexible photovoltaic devices made from carbon-based semiconductors. As the U.S. strives for a carbon-free grid by 2035, these organic photovoltaics (OPVs) may play an intriguing supporting role alongside silicon, cadmium telluride, and emerging perovskite solar technologies.

Organic solar cells offer a radically different value proposition from silicon. They can be manufactured with low-energy processes (e.g., printing from solution) and deposited on lightweight, flexible substrates, enabling seamless integration onto building facades, windows, vehicles, and other surfaces ill-suited for heavy, rigid silicon panels (Fraunhofer Institute, 2023). Their materials are Earth-abundant and free of toxic elements like lead or cadmium, promising a smaller environmental footprint and easier end-of-life disposal (Fraunhofer Institute, 2023). Most attractively, OPVs can be transparent or produced in custom colors, blending into the built environment in ways conventional panels cannot. These attributes align well with the needs of an urbanizing energy transition: solar technology that can be wrapped around city skylines and everyday objects, turning passive surfaces into power generators.

Yet the path for organic solar cells is not straightforward. Despite over three decades of research, they have not yet achieved widespread commercial deployment. Early OPV devices in the 1990s and 2000s suffered from very low efficiencies (often just a few percent) and short lifetimes, limiting them to niche demonstrations. A U.S. startup, Konarka, garnered attention in the 2000s but ultimately declared bankruptcy in 2012 as its “solar plastic” panels struggled with performance and scale-up. In the years since, however, the field has undergone a quiet renaissance. Breakthroughs in organic semiconductor chemistry and device architectures have dramatically boosted laboratory efficiency records and improved stability. By 2023, researchers achieved power conversion efficiencies nearing 19–20% in small-area OPV cells—a performance level once deemed inconceivable and on par with some commercial inorganic PV (Science Daily, 2019). These advances raise the question: can organic solar technology finally mature into a viable player in the U.S. energy transition?

To answer that, this review adopts a hybrid scoping–narrative approach. We map the state-of-the-art in organic photovoltaics and critically examine how this technology might contribute to U.S. clean energy goals. The evidence base is drawn from the converging literature on OPV device engineering, real-world deployment trials, and energy policy. We organize our discussion around three thematic lenses:

(1) Materials and Performance Breakthroughs, charting the technical advances that have improved efficiency and durability;

(2) Deployment Realities, assessing the practical challenges and case studies of implementing OPVs; and

(3) Policy, Standards, and Equity Gaps,

We are exploring how policy frameworks can enable (or hinder) OPV integration and how issues of standards and energy justice intersect with this emerging technology. By synthesizing findings across these domains, we aim to illuminate the potential role of organic solar cells in the U.S. energy transition—not through rosy optimism or undue skepticism, but via a clear-eyed look at the technology’s trajectory, its present limitations, and the pathways that could shape its future.

2. LITERATURE REVIEW

Over the past decade, organic solar cells (OSCs) have moved from single-digit efficiencies and hour-scale lifetimes to certified 18–19 % laboratory performance and multi-year stability, largely through the advent of non-fullerene acceptors and tandem architectures. Research shows that improvements in efficiency are due to carefully designed bulk-heterojunction structures, better interlayers, and the use of machine learning for molecular design, while related efforts on multilayer barrier films and UV-filter encapsulants suggest that these solar cells could last over 30 years (Li *et al.*, 2021; Wikipedia, 2025).

Field-deployment research, though still sparse, demonstrates OSCs’ distinctive integration pathways. Peel-and-stick façade films on a 185 m² German warehouse, transparent power-generating windows at Patagonia’s California headquarters, and roll-to-roll pilot lines producing meter-scale modules collectively validate ease of installation, high-temperature tolerance, and aesthetic versatility (Energy.gov, n.d.; Faißt *et al.*, 2023; Wu *et al.*, 2023). Yet these case studies equally expose hurdles—manufacturing uniformity, certification to UL/IEC standards, and lender “bankability” risk—that differentiate OSCs from incumbent silicon.

Policy scholarship reveals a misalignment between OSCs’ potential and current incentive structures. Federal support focuses on R&D grants, while deployment credits and net-metering rules implicitly privilege high-efficiency silicon modules (Volcovici & Volcovici, 2021). Recent reviews argue that targeted manufacturing tax credits, accelerated standards development, and government-procurement pilots are prerequisites for scaling OSC production (Bhutto *et al.*, 2024). Equity-oriented papers further stress that OSCs’ lightweight, flexible form factors could democratize solar access for renters and low-to-moderate-income communities—if paired with Justice40-style funding criteria (Mahmood & Wang, 2021).

Taken together, existing literature robustly characterizes technical progress and early deployment but leaves three gaps: (i) few long-term outdoor datasets beyond five years, (ii) scant techno-economic analyses linking module cost trajectories to scale, and (iii) limited policy modeling that integrates equity metrics. Addressing these gaps is critical to assessing whether OSCs can transition from niche novelty to a durable component of the U.S. clean-energy portfolio.

3. METHODOLOGY

2.1. Scoping Review Framework

We conducted a scoping review of literature to capture the multidimensional status of organic solar cells in the context of the U.S. energy transition. Following established scoping review guidelines, our methodology involved systematic identification of relevant publications and a narrative synthesis of diverse source materials. We searched scientific We searched databases (Web of Science, Scopus) and gray literature for the period 2000–2024 using keywords such as "organic photovoltaic," "organic solar cell efficiency," "OPV stability," "building-integrated PV," and "solar policy OR renewable energy policy AND organic solar." Over 300 candidate articles and reports were screened based on titles and abstracts. We included sources that offered information about one or more of the following aspects: OPV material/device improvements, field deployment studies or commercial developments, and policy or societal considerations of OPVs (including sustainability and equity issues). After full-text review, approximately 80 sources were selected for detailed analysis, encompassing peer-reviewed journal papers (e.g., on efficiency records and stability studies), conference proceedings, government and industry reports, and news articles on recent OPV deployments.

To organize the evidence, we categorized sources into four clusters: technical advances, deployment & commercialization, policy & regulatory, and equity & social dimensions. This clustering informed the three thematic narratives of our review (technical breakthroughs, deployment realities, and policy and equity gaps), with some overlap among categories (Mahmood *et al.*, 2022b). We extracted key data points (e.g., efficiency values, operational lifetimes, installation case details) and noted points of consensus or divergence in the literature. A narrative approach was then used to weave these findings into a coherent story under each theme, reflecting not only the published data but also contextual interpretation and critique. We have aimed to maintain transparency by citing sources for specific facts and figures and by noting where evidence is thin or still evolving. We have aimed for transparency by citing sources for specific facts and noting where evidence remains thin or evolving. Figure 1 illustrates the literature selection process in a PRISMA-style flow diagram, showing records identified, screening steps, and included sources at each stage. While not a formal systematic review, this scoping approach provides a broad, integrative perspective. The hybrid format allows us to combine the mapping of existing knowledge with a narrative discussion situating organic solar cells within the broader energy transition discourse.

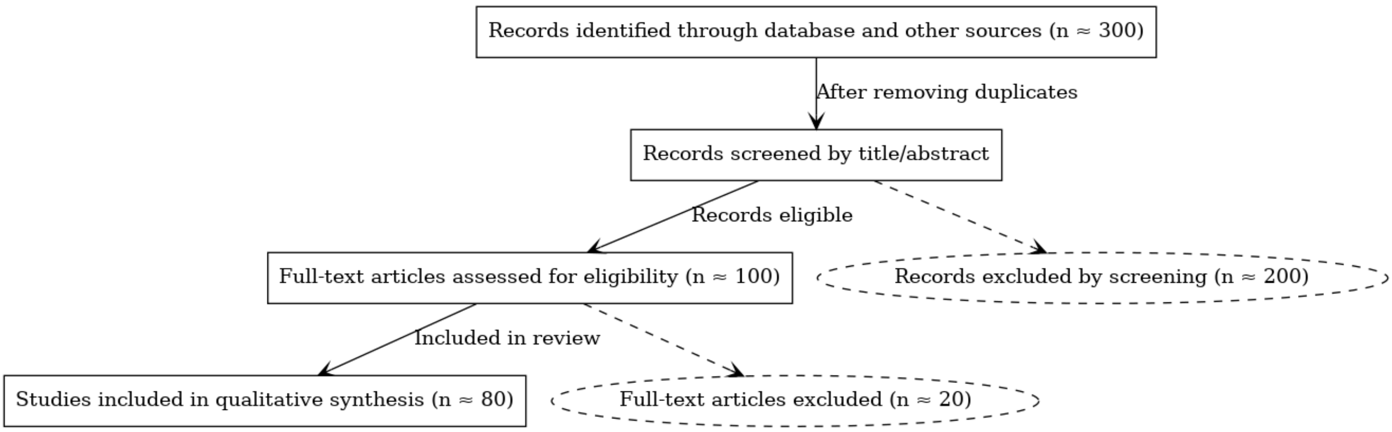

Figure 1. PRISMA-style flow diagram summarizing the literature selection process for this review. From ~300 records identified, screening and eligibility checks led to ~80 sources included in the qualitative synthesis.

Table 1. Summary of Key Studies Referenced in This Review

Authors & Year	Key Finding	Unique Characteristic
Li *et al.* (2021)	Encapsulated NFA-based OPV cells retained ~94 % of initial efficiency after 1,900 h at 55 °C.	The module lifetime is projected to exceed 30 years using accelerated aging models.
Fu *et al.* (2023)	Achieved a 19.31 % power conversion efficiency in a binary (single-donor, single-acceptor) OPV.	Employed a chlorinated solvent additive to optimize bulk-heterojunction morphology and reduce losses.
Lang *et al.* (2023)	Certified a 15.8 % efficient OPV cell over 1 cm^2 using an optimized VIS-NIR anti-reflection coating.	Demonstrated record efficiency on a glass-substrate device with tailored coating layers.
Distler & Brabec (2024)	Demonstrated a 14.46 % efficient organic solar module over a 26 cm^2 area.	First encapsulated OPV module record, showing double-digit efficiency in application-relevant format.
Heliatek (2018)	Installed 185 m^2 of adhesive OPV façade film on a warehouse at Duisburg port.	Largest OPV façade at the time; lightweight, peel-and-stick application without mounting hardware.

Next Energy Technologies (2025)	Deployed transparent OPV windows at Patagonia's Ventura HQ, offsetting lobby power use.	World's largest transparent OPV window (≈40″×60″) using slot-die coated solar film on architectural glass.
Luo *et al.* (2024)	The OPV module retained ~86 % of its initial output after 4.5 years in tropical outdoor testing.	Longest-running field performance data, validating multi-year durability under high-stress climates.
Biswas *et al.* (2023)	Achieved >35 % efficiency under dim indoor lighting conditions.	Tailored OPV cells for indoor photovoltaics, optimizing spectral response to low-intensity light.
Sigrin & Mooney (2018)	Low-to-moderate-income households represent 47 % of rooftop solar technical potential but few installations.	Socioeconomic analysis highlighting adoption gaps and equity challenges in residential solar deployment.
Heffron (2018)	Argued that a "just transition" must link technological innovation with equitable community benefits.	Provided a policy framework integrating energy justice principles into clean energy planning.

4. RESULT AND DISCUSSION

4.1. Materials & Performance Breakthroughs

Organic solar cells operate on principles distinct from their inorganic counterparts. In a typical device, a thin film of organic semiconductor (often a conjugated polymer or small molecule) is sandwiched between electrodes. This organic layer absorbs light, but instead of producing free charges, it produces tightly bound electron-hole pairs called excitons. Efficient operation requires these excitons to reach a donor-acceptor interface where they split into charge carriers that can be collected as electrical current. For years, this exciton bottleneck, along with the disordered nature of organic films, kept power conversion efficiencies (PCE) of OPVs very low. Early single-layer devices in the 1990s had efficiencies below 1%. The development of the bulk heterojunction (blending donor and acceptor materials to form nanoscale interpenetrating networks) in the mid-1990s was a pivotal innovation, eventually enabling OPVs to reach around 5% efficiency by the late 2000s. Still, compared to silicon cells routinely hitting 15–20% at that time, OPVs were considered laboratory curiosities with "1/3 of the efficiency of hard materials" and problematic stability (Wikipedia, 2025).

Over the past decade, however, a series of materials science breakthroughs has dramatically improved OPV performance. The introduction of non-fullerene acceptors (NFAs) around 2015–2016 is often cited as a turning point. Prior OPVs relied on fullerene derivatives (like PCBM) as electron acceptors; while effective at charge separation, fullerene acceptors imposed limitations on optical absorption and voltage (Li *et al.*, 2021). Novel non-fullerene acceptors, typically designed organic molecules such as fused-ring electron acceptors, offered tunable absorption profiles and higher open-circuit voltages, unleashing a cascade of efficiency gains (Science Daily, 2019). Supported by DOE-funded research programs targeting NFA development (Wikipedia, 2025), the community rapidly progressed from ~10% efficient OPVs to 15% and beyond. In 2018, single-junction cells reported certified efficiencies of approximately 11–12%, surpassing the informal 10% threshold, which is often considered the milestone for commercial relevance (Energy.gov, n.d.). Each year seemed to bring a new record. In 2020, a team at NREL/Fraunhofer ISE hit 14%, then broke their record in 2023 with a 15.8% efficient cell (1 cm² area) by introducing an advanced anti-reflection coating (Fraunhofer Institute, 2023). Figure 2 shows one such prototype cell, a glass substrate OPV device, that achieved 15.8% efficiency in 2023, illustrating the leap in performance (the cell's gold-colored electrode and blue active stripes belie its "organic" nature) (Faißt *et al.*, 2023).

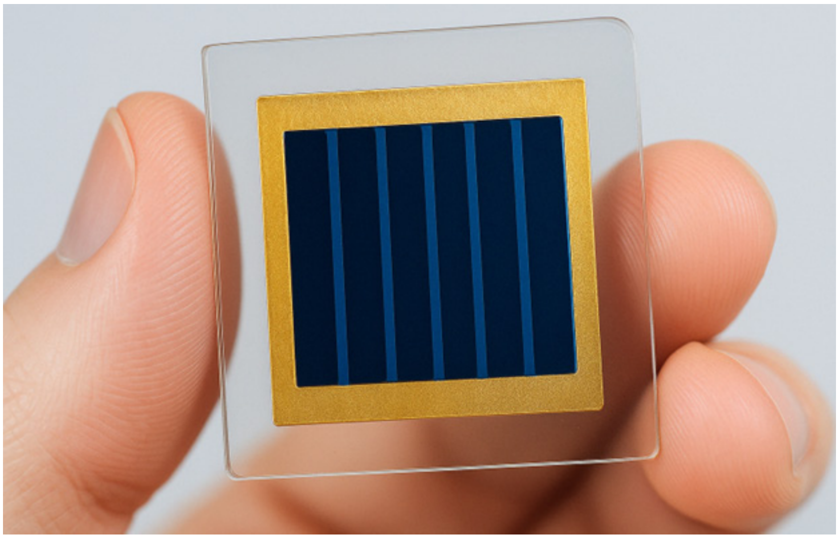

Figure 2. Photograph of a 1 cm² glass-substrate organic solar cell achieving 15.8% certified efficiency in 2023 (gold-colored electrode and blue active stripes).
Source: Fraunhofer ISE press release (Fraunhofer Institute, 2023)

Not stopping there, researchers in Hong Kong and mainland China pushed single-junction OPVs to new heights in 2023. Using a finely tuned morphology control strategy (involving a solvent additive to regulate the crystallization of the active layer), Li *et al.* 2021reported a 19.3% power conversion efficiency for a binary (single-donor, single-acceptor) organic solar cell (Science Daily, 2019). This result, published in Nature Communications in mid-2021, marked a watershed moment: for the first time, an OPV device was flirting with 20% efficiency, a level previously thought attainable only by perovskites or tandem multi-junction designs (3, 8). It's worth noting the pace of improvement, just eight years earlier, in 2015, OPVs had barely exceeded 10% efficiency in lab cells (Wikipedia, 2025). By 2023, efficiencies had nearly doubled. Such rapid progress has been enabled by better computational material design (screening candidates with desired energy levels) (Bhutto *et al.*, 2024), the synthesis of high-purity polymers and small molecules that minimize traps, and the refinement of device layers (e.g., optimized interlayers and electrodes) (Mahmood & Wang, 2021; Zhu *et al.*, 2024). For example, the 19.3% cell used a chlorinated solvent additive (1,3,5-trichlorobenzene) to create the best possible structure in the bulk heterojunction, which greatly lowered energy losses that don't produce light (8). This level of control over the film morphology and energetics represents a maturation of organic photovoltaics as a scientific discipline.

Parallel to efficiency, the scale and stability of OPVs have seen marked advances. Historically, one criticism of OPVs was that, while a champion small-area cell might show decent efficiency, scaling up to modules (with larger areas and multiple cells) would incur substantial losses. This gap has been narrowing. In late 2024, a research team at FAU Erlangen-Nürnberg and the Helmholtz Institute in Germany announced a 14.46% efficient organic solar module (over 26 cm^2 in area, encapsulated), a new world record for OPV modules, edging past the previous ~13% mark for modules (World Record: Organic Solar Module Achieves 14.46 Percent Efficiency, n.d.). This result is significant because it demonstrates that double-digit efficiencies are achievable not only in lab cells but in larger, more application-relevant formats. The module in question was produced by solution-processing techniques and represents the type of product that could be integrated into real devices (e.g., as a flexible solar film). The researchers noted that OPV modules could "be established as an alternative to silicon & Co. in the long term" if such trends continue (World Record: Organic Solar Module Achieves 14.46 Percent Efficiency, n.d.). Indeed, with 14–15% efficient organic modules now a reality, one can envision lightweight solar foils approaching the performance of today's amorphous silicon or CIGS flexible panels.

The operational stability of organic solar cells, once their Achilles' heel, has improved in tandem with efficiency. Early OPVs would degrade within hours or days under sunlight exposure because of the ingress of oxygen and moisture, as well as the photo-oxidation of active materials. Through better encapsulation and more stable materials, modern OPVs last significantly longer. A landmark study in 2021 demonstrated encapsulated NFA-based cells with projected lifetimes over 30 years (under standard test conditions) (Li *et al.*, 2021). In that work, Li *et al.* showed that by using protective interlayers and UV filters, an OPV cell retained ~94% of its initial efficiency after 1,900 hours at 55°C under continuous illumination (Li *et al.*, 2021). Extrapolating via accelerated aging models, they estimated an intrinsic lifetime beyond 5.6×10^4 hours, equivalent to about three decades of outdoor use (Li *et al.*, 2021). While such extrapolations have uncertainties and assume perfect encapsulation, they nonetheless were a proof-of-concept that OPVs can be made orders-of-magnitude more stable than a decade prior. In practical outdoor tests, steady progress is likewise evident: recent field trials of OPV modules in tropical climates showed devices surviving 4–5 years with only modest performance loss (on the order of 10–15%) (Luo *et al.*, 2024). Researchers have identified and mitigated many degradation pathways, for example, replacing unstable fullerene acceptors with more robust NFAs, using UV-absorbing coatings to prevent the most harmful wavelengths from breaking chemical bonds, and developing self-healing or intrinsically stable polymers that resist photochemical stress (Uddin *et al.*, 2019).

Taken together, these technical advances paint an optimistic picture: organic solar cells today are a fundamentally different technology than 10–15 years ago. They are closing the efficiency gap with conventional PV (the latest NREL efficiency chart for emerging PV shows OPVs approaching 18–19% certified PCE (Marija Maisch, 2023) and have achieved durability that, while still shorter than silicon's 25+ year lifespan, is no longer a showstopper for many applications. Materials and performance breakthroughs have thus laid a solid foundation. However, translating these laboratory victories into real-world impact is another challenge entirely. The next sections examine how OPVs have fared outside the lab and what obstacles remain in scaling and deploying this technology in service of the energy transition.

4.2. Deployment Realities

Despite impressive progress in the lab, organic photovoltaics have yet to make a dent in the global solar market. Silicon PV continues to dominate new installations (over 120 GW added worldwide in 2022 alone), while OPV installations are counted in mere kilowatts. Bridging this gap requires confronting real-world deployment challenges: manufacturing at scale, ensuring consistent field performance, meeting standards and certifications, and finding niche markets where OPV's unique features outweigh its remaining disadvantages. A candid look at deployment to date reveals both sobering limitations and encouraging pilot projects that hint at OPV's potential.

One fundamental challenge has been manufacturability. Silicon wafer production and module assembly are highly evolved industries with gigawatt-scale factories, benefitting from economies of scale. Organic solar, by contrast, is produced via techniques like roll-to-roll coating or thermal evaporation of organic films, processes that until recently existed only at research or pilot scale. Scaling up an OPV from a 1 cm^2 lab cell to square-meter panels involves solving issues of uniform coating, solvent handling, layer registration, and defect rates. The good news is that OPVs are amenable to high-throughput manufacturing in principle, think of printing newspapers or applying coatings in continuous sheets. Several companies and research groups have built pilot production lines. For example, Next Energy Technologies, a California-based startup, developed a pilot line that can produce transparent organic PV coatings on 1 m by 1.5 m glass panels (Lior Kahana, 2025). In February 2025, they unveiled what was claimed to be the "world's largest fully transparent OPV window," measuring 40"×60" (about 3.3×4.9 feet) (Lior Kahana, 2025). This achievement indicates that scaling to architectural glass sizes is feasible. The window utilized automated slot-die coating to deposit the organic layers and laser patterning for cell interconnections (Lior Kahana, 2025). Similarly, European OPV firms have made strides: Heliatek, a German company, operates a roll-to-roll fabrication line for flexible OPV films. Their production capacity (on the order of tens of thousands of square meters per year) remains tiny compared to silicon PV manufacturing, but it has been sufficient to supply material for pilot projects worldwide (World's Largest Façade Installed with Organic Photovoltaic Panels, n.d.).

These early manufacturing efforts have enabled several pilot deployments of organic solar in the field, offering a glimpse of how the technology might be used. One prominent application is building-integrated photovoltaics (BIPV) on surfaces where traditional panels are impractical. In 2018, Heliatek collaborated on installing organic solar films on a warehouse facade at the Duisburg port in Germany, at the time, the largest OPV facade in the world (World's Largest Façade Installed with Organic Photovoltaic Panels, n.d.). About 185 m² of Heliatek's adhesive solar film (branded HeliaSol) were applied directly to the vertical metal cladding of the warehouse, covering a long stripe on the building. The lightweight films added negligible load and required no racking or penetrations. Although the array's peak output was modest (generating roughly the electricity for a 5-person household per year) (World's Largest Façade Installed with Organic Photovoltaic Panels, n.d.), it demonstrated key advantages: the OPV operates in high heat without significant efficiency loss (no active cooling or standoff was needed, unlike conventional panels that can overheat) (World's Largest Façade Installed with Organic Photovoltaic Panels, n.d.), and the installation was quick; workers simply unrolled and stuck the films onto the wall. Heliatek has since completed several other BIPV projects, including a 2021 installation on a school roof in France (~500 m² of solar film) and a 2022 deployment of its films on the facade of a building at the Samsung Advanced Institute of Technology in Korea (a ~40 kWp system, currently the world's largest OPV power installation) (Heliatek, 2023). These projects remain demonstrations, but they validate that OPV can provide turn-key solar solutions for surfaces where adding heavy glass modules would be infeasible.

In the United States, OPV deployment has been scant but is starting to emerge via partnerships between material developers and building owners with a sustainability ethos. In late 2022, Next Energy Technologies installed transparent organic solar windows at the headquarters of Patagonia, Inc., in Ventura, California (Patagonia, 2023). Twenty-two photovoltaic windows replaced sections of the building's south facade glass in what was the first such OPV window installation on a U.S. commercial building (Patagonia, 2023). These windows are visually indistinguishable from ordinary tinted glass; however, embedded within the glazing is Next's proprietary transparent PV coating that generates electricity from sunlight. The power output of each window is relatively low (each provides tens of watts), but collectively they help offset some of the building's energy use, charging phones and devices in a lobby area, in this case (Patagonia, 2023). More importantly, they demonstrate the concept of solar-active windows that could significantly contribute to building energy supply if scaled. The company NEXT estimates that fully outfitting a typical commercial high-rise with their PV windows could offset 10–40% of the building's energy consumption (Patagonia, 2023). (The exact fraction depends on building design and location; capturing the otherwise wasted vertical facade area for generation could be game-changing in dense cities.) Building developers have shown interest: Next's collaboration with Patagonia was partly to showcase to architects that aesthetic, energy-generating facades are no longer science fiction. Still, broader adoption will hinge on cost and proven durability. Transparent OPV glass will initially be pricier than standard low-E glass, and its long-term performance in different climates remains to be seen. Patagonia's installation will serve as a living experiment, and early data from it will inform future projects.

Beyond buildings, other niche uses of OPVs are being explored. The automotive sector has considered integrating organic solar foils on cars or trucks to trickle-charge batteries (the Toyota Prius demonstrator with an OPV roof and various concept solar cars have trialed this). Portable and off-grid applications are a natural fit: because OPVs are lightweight and can be printed on flexible plastics, they can be made into solar backpacks, tent covers, or small roll-out chargers for soldiers and campers. In fact, the U.S. Army has tested OPV mats for powering field equipment—the ability to generate power on the move, with something that can be folded up, is attractive even if efficiency is lower (Liu *et al.*, 2024). Companies like PowerFilm (Iowa) and Armor ASCA (France) have marketed OPV or hybrid polymer solar chargers for the internet-of-things (IoT) devices and indoor use, where very high efficiency is not required. Indoor photovoltaics is another emerging market: OPVs can be tuned to the indoor light spectrum and operate well at low light intensities, potentially outcompeting silicon for powering wireless sensors in smart homes or factories. A recent review noted that certain organic PV cells achieved over 35% efficiency under dim indoor lighting (a different metric than outdoor PCE) (Biswas *et al.*, 2023), illustrating their suitability for that domain.

For all these promising niches, significant deployment challenges persist. One issue is that organic PV technology, being new, lacks the extensive field track record that financiers and consumers expect. Bankability is a concern: will an OPV installation maintain performance and deliver energy savings over its warrantied life? Proving such an assertion requires years of real-world data (What Is Bankability and Why Is It Vital for Solar Projects?, n.d.). So far, the longest-running OPV projects are only 5–10 years old. Encouragingly, those have shown gradual improvements in stability, for instance, after 4.5 years in hot outdoor conditions, one OPV module retained ~86% of its initial output (Luo *et al.*, 2024), and some flexible OPV panels showed no performance loss after 1 year outside when properly sealed (J.A. Hauch *et al*., 2008). However, it's one thing to survive a few years and another to convincingly promise 20+ years. Silicon panels today often come with 25-year power warranties (e.g., guaranteeing ≥80% power at year 25). OPV manufacturers will likely start by offering shorter warranties (perhaps 5-10 years) until longevity is proven. This approach inherently limits early use to applications where either the expected use time is short (temporary installations, portable gear) or where the host is willing to take a bit of risk for the innovative benefits (as Patagonia did for their windows).

Another challenge is certification and standards compliance. Solar products in the U.S. must typically pass UL certification (for safety and fire) and meet IEC standards for reliability (thermal cycling, humidity-freeze, damp heat, etc.). These tests were developed mainly for silicon and thin-film modules. Organic PV modules may need adapted test protocols; for example, standard damp-heat tests (85°C, 85% humidity for 1000 hours) are extremely harsh on many polymer-based devices. Efforts are underway in the OPV community to develop relevant testing protocols (the ISOS—International Summit on OPV Stability—protocols are widely used in research to benchmark stability under light, heat, and mechanical stress). As OPVs inch toward commercialization, companies must navigate demonstrating compliance. In 2022, Heliatek achieved a notable milestone by obtaining IEC 61646 certification (a standard for thin-film modules) for its organic solar films, essentially proving they could withstand standard environmental stress tests. The achievement was a key step in giving customers and regulators confidence in the product's robustness. Still, nuances remain, for instance, how to rate the performance ratio of OPVs under varied lighting conditions. Organic cells often have different response spectra and better performance on cloudy days (due to less voltage drop at lower light). These features could be an advantage in real climates, but traditional rating (STC—standard test conditions) might not capture it. Field data collection from pilots will help quantify such differences and possibly argue for new performance standards that account for unique behavior (e.g., generating relatively more energy in diffuse light or at high operating temperatures, where silicon output drops).

Finally, the economics of OPV deployment are a hurdle in the near term. Silicon PV modules have become incredibly cheap (below $0.30/Wp at the factory gate), riding a massive manufacturing learning curve. Organic PV, being produced in small batches, cannot yet compete on a pure $/W basis for bulk power generation (Mulligan *et al*., 2014). Therefore, its deployment strategy hinges on value-added applications – situations where the integration, form factor, or aesthetic value justifies a premium. BIPV is exactly such a case: architects may pay more for solar windows or facade elements that serve dual functions (envelope + energy). Similarly, ultra-light PV on drones or stratospheric balloons, or custom-shaped panels for consumer gadgets, may tolerate higher costs. As production scales and materials are optimized for cost (using inexpensive polymers, printed at speed), OPVs could eventually approach the cost per watt of other thin-film PV. One analysis by DOE noted the theoretical potential for OPVs to be produced at extremely low cost due to printable manufacturing and abundant materials (Energy.gov, n.d.). Realizing this could turn the economics to an advantage. However, this is likely a scenario that will occur post-2030, following significant scale-up efforts.

In summary, the state of OPV deployment today is nascent but not stagnant. Important "training wheels" projects have validated the core promises of the technology in real-world settings: it can be installed on surfaces unreachable by silicon (irregular facades, window glass), it can survive years of operation with reasonable retention, and people are willing to try it despite higher current costs because of the unique benefits. Each deployment provides invaluable feedback – on installation techniques, performance in various climates, and user interaction—which feeds back into research and next-generation designs. The U.S. has seen only a handful of these demonstrations so far, with more activity in Europe and Asia, but that may change as American companies and institutions begin catching up. Going forward, the extent to which organic solar cells contribute to the energy transition will depend not just on technical merit but also on the policy environment and market structures that support emerging renewable technologies. We turn to those considerations next.

4.3. Policy, Standards & Equity Gaps

Energy technologies do not exist in a vacuum; their adoption is strongly influenced by policy incentives, regulatory standards, and socio-economic context. Supportive policies and clear standards can significantly accelerate the commercialization of organic solar cells, which are still in their early stages. Conversely, a lack of such policies can impede their progress. Moreover, as the U.S. energy transition strives to be a just transition, issues of equity and inclusion are paramount. In this section, we examine how current policies and standards align with OPV development and identify gaps, particularly related to ensuring this new technology benefits a broad swath of society.

Innovation Policy and Funding: The U.S. government has provided research support for OPVs for many years, primarily through the DOE's Solar Energy Technologies Office (SETO) and programs like ARPA-E. This support has been crucial in achieving the technical advances detailed earlier. For instance, DOE programs explicitly focusing on "Next Generation Photovoltaics" have funded university and industry teams to explore new OPV materials and architectures (Energy.gov, n.d.). In 2023, the DOE highlighted the role of non-fullerene acceptors in boosting OPV efficiency and noted its continued support for research in this area (Wikipedia, 2025). Such R&D funding is a classic innovation policy tool and has clearly paid dividends by keeping U.S. labs at the forefront of OPV science (American researchers like Prof. Yang Yang at UCLA and Prof. Stephen Forrest at Michigan have been influential contributors to OPV advances (5). However, a persistent gap remains in transitioning from lab research to manufacturing, often referred to as the "Valley of Death" in technology development. Here, policy could step in via pilot manufacturing grants or public-private partnerships to help scale production. The recently enacted Inflation Reduction Act (IRA) of 2022 may indirectly aid OPVs in this regard: it includes advanced manufacturing tax credits (Section 45X) for domestic production of solar modules and related components (Leveling Up Solar Manufacturing, n.d.). While not specific to OPVs, these incentives could be leveraged by an OPV manufacturer setting up in the U.S., effectively lowering the cost to build factories for novel PV tech. Additionally, the IRA and earlier infrastructure legislation allocate funding for demonstration projects of cutting-edge clean energy technologies. OPV installations on federal buildings or as part of community solar pilots could potentially qualify, giving the technology more exposure and validation underwritten by public funds.

Regulatory Standards: As discussed in the previous section, one gap is the adaptation of certification standards for organic PV products. Agencies like UL and IEC will play a key role. Proactively developing standards for flexible and transparent PV can ensure OPV products aren't left in a limbo where they cannot be legally used due to lack of certification. Some progress is being made, UL has published guidelines for BIPV glazing units and solar shingles in recent years; these can potentially cover OPV windows and facade films. The IEC is working on standards for "organic photovoltaic module performance testing" (a working item in its TC82 solar standards committee). A coherent standards framework will address safety/reliability and help consumers compare OPV products. For example, establishing a standard reporting format for OPV module efficiency under different lighting could highlight their performance in low-light conditions relative to silicon. Interconnection standards are another consideration: When using OPV in building materials, the way it integrates with the electrical system (inverters, power optimizers) must adhere to the relevant code. Existing solar inverter standards (e.g., IEEE 1547 for grid interconnection) are technology-agnostic, so OPV systems should have no issue technically, but installers will need familiarity. This obstacle points to a soft barrier—the workforce training and awareness. Solar installers today know how to mount and wire silicon panels; they may not know how to handle a peel-and-stick solar film or a PV window unit (Solar Training Network, n.d.). Updating training programs and certifications (e.g., NABCEP solar installer certifications) to include emerging PV types could be beneficial. In summary, it is crucial to ensure that policies do not unintentionally exclude OPVs. Lessons can be learned from history: lenders struggled to underwrite early thin-film PV in the 1990s, and codes did not accommodate PV glazing. Learning from that, policymakers can facilitate pilot programs and information sharing that bring OPVs into the mainstream of building and energy codes once the technology is ready (Patrina Eiffert, & Arlene Thompson, 2000).

Market Incentives: Deployment of any solar technology is strongly driven by incentives like tax credits, rebates, and renewable portfolio standards. The federal Investment Tax Credit (ITC)—currently 30% for solar installations—theoretically applies to any solar electric property, including OPVs, as long as they produce electricity and are installed on a property. Thus, if a building owner installs an OPV facade, they should be eligible for the same 30% tax credit as installing a standard PV system (US EPA, 2022). This parity is important and should be preserved. Some incentives, however, are capacity-based or performance-based; if OPV systems have lower capacity (kW) for a given area, they might receive smaller absolute subsidies despite covering more surface. To address this, states could consider incentive multipliers for BIPV or innovative solar that has dual functions. A few jurisdictions have done this for solar integrated into building envelopes. acknowledging that while cost per watt is higher, it yields other benefits (aesthetic, no land use, etc.). Standards and incentives intersect in intriguing ways: for example, net metering policies ensure that any solar generation, regardless of source, is valued at retail electricity rates when fed into the grid. As long as OPV systems tie into a net meter, they benefit from this compensation, which is crucial for economic payback. If net metering policies are rolled back or limited (as is happening in some states), it could disproportionately affect novel tech that might need longer to pay off.

Energy Equity and Justice: Perhaps the most cross-cutting gap and opportunity lies in ensuring that the rise of new solar technologies like OPV also advances energy equity. The concept of a just transition holds that the benefits of clean energy should be accessible to all and that marginalized communities should not be left behind (or further burdened) in the shift away from fossil fuels (Angela Zeng, 2022). Traditional rooftop solar in the U.S. has seen disparities: higher-income households and certain neighborhoods have far greater adoption rates, while low-to-moderate income (LMI) families and communities of color have faced barriers like upfront cost, lack of homeownership, or unsuitable roofs. A 2018 NREL study found that LMI households represent 47% of the technical potential for rooftop solar yet make up a small fraction of actual installations (Wolske, 2020). This gap is something policy is starting to address (e.g., via the DOE's Solar for All and Justice40 initiatives, which target 40% of benefits of climate investments to disadvantaged communities). Where do organic solar cells fit into this picture? Potentially, OPVs could both help and hinder equity goals, depending on deployment. On one hand, their flexibility and lightweight nature mean renters or apartment dwellers might have options to deploy solar (imagine stick-on solar wallpaper or window films) that don't require owning a roof or making structural changes—this could democratize access if the products are affordable and widely available. OPVs could also create new economic opportunities: manufacturing OPV films or windows could be located in communities that need jobs (since the factories might be smaller and less capital-intensive than huge silicon fabs). Furthermore, integrating solar into building materials could reduce overall costs of solarizing affordable housing if done at scale (the incremental cost of a solar façade could drop if every window naturally comes with PV capability).

On the other hand, if OPV remains a premium product (like a high-end façade for showpiece green buildings), it might initially serve mostly wealthy owners or corporations seeking LEED points, rather than LMI communities. There is a risk of an equity gap in technology adoption—the same pattern where richer communities get the Tesla solar roof tiles or transparent PV windows, while others do not. Proactive steps can mitigate this. For instance, government-led pilots installing OPV facades on public affordable housing developments could ensure the benefits (lower energy bills, cooler indoor temps from rejecting

IR, etc.) accrue to residents who normally wouldn't get cutting-edge tech. Another consideration is environmental justice in production: OPVs avoid many nasty materials (no lead, no cadmium, no arsenic, etc.), which is a win for not burdening communities with toxic manufacturing or waste (Fraunhofer Institute, 2023). Silicon PV supply chains have raised concerns about hazardous chemical use and even labor issues in some regions; a diversified solar supply (Becerra-Fernandez *et al.*, 2023), including OPV, could be made more ethically and sustainably. The mostly carbon-based ingredients of OPVs are far less problematic from a mining perspective (no conflict minerals needed, etc.), aligning with the goal of minimizing the socio-environmental footprint of renewables (Fraunhofer Institute, 2023).

One emerging initiative aligning technology and equity is the concept of energy-generating window retrofits for community buildings. Non-profits and city governments are exploring ways to turn schools, libraries, and community centers in underserved areas into clean energy hubs. OPV coatings that can be applied to existing windows or facades could be a low-disruption retrofit compared to bolting panels on roofs (especially if roof space is limited or roofs are in poor condition). Imagine a public A library located in a low-income neighborhood has received a grant to install semi-transparent solar film on all its large windows. This initiative not only reduces the library's utility costs, which can be used for services, but also serves as a visible example of clean energy that the community can interact with on a daily basis. Such projects could inspire local interest in STEM and clean tech careers as well. To make these initiatives happen, policy-driven demonstration programs could explicitly incorporate equity criteria; e.g., the DOE or state energy offices could sponsor OPV demos in Justice40 communities, measure the outcomes, and then scale what works.

Policy and equity considerations for OPVs are intertwined: while supportive policies such as R&D funding, manufacturing incentives, and deployment subsidies bring the technology to the market, an equity lens ensures that its arrival contributes to closing energy gaps rather than widening them. At present, a gap exists in that organic solar cells are seldom mentioned explicitly in policy roadmaps; they often get lumped under "emerging photovoltaics" or "next-gen solar" without specific initiatives. Given their progress, it may be time for policymakers to pay more attention to OPVs. Including OPV (and other emerging PV like perovskites) in government procurement could be one measure, for example, requiring a percentage of new federal building PV capacity to come from innovative technologies to help incubate those industries. This mirrors how government procurement has aided other nascent tech (like the semiconductor industry in its early days). Moreover, integrating OPVs into the vision of a just transition can align R&D goals with societal needs. As one energy justice scholar noted, "A just transition must explicitly link technology innovation with equitable access and community empowerment" (Equity / Justice40: Clean Energy Funding Series – Community Economic Development, n.d.). For OPV, this could mean ensuring that the knowledge and capacity to manufacture and install the technology are diffused widely (including workforce training in marginalized communities) and that its deployment is coupled with programs that make the benefits (like reduced electricity costs or new jobs) available to those who need them most.

5. CONCLUSION

Organic solar cells have traveled a remarkable journey from laboratory curiosity to an emerging energy technology on the cusp of commercial relevance. This scoping review has traced that journey through the lenses of technical advances, deployment realities, and policy pathways. We have seen that technically, OPVs have achieved breakthroughs once thought out of reach: power conversion efficiencies nearing 20%, vastly improved stability, and form factors that promise to reimagine where and how solar energy can be harvested. At the same time, we confronted the real-world challenges that temper the excitement: manufacturing hurdles, the lack (so far) of large-scale roll-out, and performance uncertainties that only time and experience can fully resolve. We also delved into the policy and equity context, recognizing that the success of organic photovoltaics will depend not just on better cells but on smart policies that nurture innovation and deployment and on deliberate efforts to ensure this innovation aligns with a just energy transition.

What, then, is the role of organic solar cells in the U.S. energy transition? Based on the evidence assembled, the most realistic near-term role is that of a complementary technology, one that fills gaps left by conventional solar and opens new frontiers for the integration of renewables. In the 2020s, OPVs are unlikely to compete directly with silicon on cost per watt in utility-scale farms; instead, they will penetrate areas where silicon cannot: the windows of skyscrapers, the lightweight roofs incapable of supporting heavy panels, the curved surfaces of vehicles, and possibly the backpacks of millions of consumers generating a small amount of power while on the move. In doing so, they can add incremental generation capacity that, while small as a percentage of total grid power, is nonetheless valuable because it is local, distributed, and flexible. Moreover, the innovation narrative of OPVs as a homegrown, high-tech solution born from American labs and potentially manufactured in American factories aligns well with the broader goals of energy security and technological leadership. Each glass facade outfitted with OPV in New York or Chicago, each school window producing power in an underserved community, is not just offsetting fossil fuels but also telling a story that the energy transition is pervasive and inclusive, reaching places previously untouched by solar.

Looking further ahead, one can envision scenarios where organic solar cells make a broader impact. If manufacturing scale drives costs down significantly, OPVs could see mass deployment in utility-scale applications via lightweight solar blankets unrolled over large areas or floating on reservoirs (their flexibility could be an asset there). If stability reaches multiple decades reliably, building codes might mandate PV-generative building materials, with OPV a prime candidate due to its versatility. And if combined with other technologies—for instance, forming tandem devices with perovskite or silicon layers—OPVs might contribute to ultra-high-efficiency panels that surpass what any single material could do. In short, organic solar technology could evolve from complementary to integral in the clean energy portfolio. But realizing that potential will require continued convergence of science, engineering, and policy.

Crucially, it will also require keeping humanity's larger goals in mind. The ultimate measure of success for innovations like OPV is not just megawatts installed but the extent to which they enable a sustainable and equitable energy system. Organic solar cells, by virtue of their unique characteristics, offer a chance to embed sustainability at multiple levels: low-energy manufacturing, minimal toxic materials, and creative applications that empower energy users in new ways. If guided with foresight, they can help avoid replicating the injustices of past energy systems. The U.S. energy transition is not merely a swap of technologies but a transformation of our infrastructure and institutions. In that transformation, OPVs have a role if we choose to embrace them: as a symbol of innovative progress, as a practical tool for hard-to-solve energy needs, and as part of a narrative that the transition to renewable energy is not monolithic but rich with diverse solutions tailored to diverse challenges.

Will organic solar cells be a footnote in the energy history books or a significant chapter? The answer hinges on both the relentless work of researchers and engineers and the wisdom of policymakers and community leaders in embracing new ideas. By 2027, at least 10 multi-climate pilot projects ($\geq$1 MW_p each) should be operating, generating open-access performance data for a full range of U.S. weather conditions. By 2030, roll-to-roll factories must demonstrate module costs $\leq$ \$0.30 W^{-1} ($\approx$ \$6 m^{-2}) and certify 15-year warranties through updated UL/IEC protocols. And by the same date, an equity-focused deployment program should deliver 5 MW_p of OSC capacity across >50 low-to-moderate-income schools, libraries, and housing complexes, measuring bill savings, indoor-comfort gains, and workforce participation. Meeting these targets would validate OPVs' technical maturity, commercial competitiveness, and societal value—turning today's promise into a durable contribution to the clean-energy mosaic. Failing them would relegate the technology to niche curiosity. The sun will rise either way; whether OSCs rise with it depends on our collective resolve to hit these concrete waypoints.

RECOMMENDATIONS

Research funding & pilot manufacturing: Bridge the gap from lab to fab. Increase targeted federal R&D funding for OPVs, specifically focusing on scale-up challenges. For example, programs could support pilot manufacturing lines and public-private partnerships to refine printing/coating processes at scale. Early government procurement (e.g., installing OPV panels on federal buildings as trial sites) can create a stable initial market and gather performance data. These measures would help de-risk the technology and accelerate its learning curve toward commercial viability.

Standards & certification: Accelerate the development of OPV-specific standards. Industry consortia, testing agencies, and government labs should collaborate to establish testing protocols tailored to organic PV modules (building on efforts like the ISOS guidelines). Fast-track the integration of OPV into existing certification frameworks (UL, IEC) by adjusting test conditions to reflect real operating environments of OPVs. Clear standards for durability, fire safety, etc., will smooth entry into building codes and insurance markets. We also recommend creating design guidelines for architects and builders on how to deploy OPV products safely, which will improve adoption in construction once certifications are in place.

Policy & deployment incentives: Incentivize early use cases and integration. Ensure that general solar incentives (tax credits, net metering, renewable credits) continue to apply to OPV projects, and consider bonus incentives for innovative applications like building-integrated organic PV. Policymakers could implement demonstration grants or "solar innovation zones" to fund pilot deployments of OPVs on schools, community centers, and infrastructure. Incorporating OPVs (e.g., requiring a percentage of new government building surfaces to include solar generation) would pull the technology into real projects, generating experience and visibility.

Industry and market actions: Build coalitions and share learning. The nascent OPV industry should form alliances or working groups to collectively address common obstacles—for instance, creating a shared database of field performance results to reassure financiers. Engagement with related sectors is also key: OPV producers can partner with window manufacturers, façade engineers, and automobile companies to integrate solar coatings into their products. By demonstrating multi-functional value (e.g. a car with an OPV sunroof that trickle-charges the battery), industry can open new revenue streams. Additionally, outreach and education by companies about OPV's unique benefits (lightweight, printable solar) will help cultivate early adopter customers in niche markets like IoT devices, portable chargers, and aesthetic architectural solar.

FUTURE RESEARCH AGENDA

Long-term stability and outdoor testing: Continue to prioritize research on improving OPV longevity. This effort includes extensive outdoor exposure trials in diverse climates to identify degradation mechanisms. Real-world data will guide encapsulation improvements and materials development for longer lifetimes. Collaborative "OPV testbed" sites (similar to solar test farms for silicon) could be established to benchmark different OPV technologies side by side over years, providing an open dataset to inform both researchers and investors.

Advanced device architectures: Explore next-generation OPV designs to push efficiency higher. Promising avenues include tandem or multi-junction OPVs (stacking two different bandgap OPV cells) and hybrid tandem cells pairing an OPV with another solar material (e.g., a perovskite top cell with an OPV bottom cell). Such architectures have already achieved certified efficiencies in the mid-20% range in laboratory settings (Perovskite–Organic Solar Cell Sets Efficiency Record with New Design, n.d.), and further work could bring these into stable, scalable devices. Research should also look at novel transparent electrodes and interlayers that could enable high-efficiency transparent OPV for window integration without sacrificing light transmission (Liu *et al.*, 2022).

Life-cycle and environmental impact studies: Conduct comprehensive life-cycle assessments (LCA) of OPV modules (Tsang *et al.*, 2016), from raw material extraction through manufacturing, use, and end-of-life (Preet & Smith, 2024).

Early indications are that OPVs could have extremely low energy payback times and carbon footprints; for instance, one company claims its films produce 80 times more energy over their life than is used to make them (Muteri *et al.*, 2020), with an estimated carbon intensity around 20 g CO_2/kWh, far lower than the grid average (World's Largest Façade Installed with Organic Photovoltaic Panels, n.d.). These figures need independent verification. Research should also develop recycling and disposal strategies for organic PV (e.g., processes to recover polymers or sustainably degrade them) to ensure the technology's green credentials remain strong at scale (Mahmood *et al.*, 2022a).

Equity-focused deployment research: Pair technology pilots with social science research to evaluate how OPV can be effectively deployed in underserved communities. For example, demonstration projects that install OPV in low-income housing or community buildings should include studies on community perceptions, job creation, energy savings for residents, and any challenges in maintenance or acceptance. The results will help identify best practices for equitable rollout. Additionally, research in collaboration with urban planners and community organizations can explore innovative models like, e.g., cooperative solar gardens using OPV film on local structures, that broaden participation in the clean energy transition.

By pursuing these research directions, stakeholders can ensure that improvements in the lab translate into meaningful real-world gains. The goal is not just a more efficient organic solar cell, but an organic solar technology that is robust, sustainable, and inclusive in its benefits.

REFERENCES

Angela, Z. (2022, *August 19). Justice40: The Complicated Business of Defining Disadvantaged Communities.* Synapse Energy. https://www.synapse-energy.com/justice40-complicated-business-defining-disadvantaged-communities

Becerra-Fernandez, M., Sarmiento, A. T., & Cardenas, L. M. (2023). Sustainability assessment of the solar energy supply chain in Colombia. *Energy, 282*, 128735. https://doi.org/10.1016/j.energy.2023.128735

Bhutto, J. A., Siddique, B., Moussa, I. M., El-Sheikh, M. A., Hu, Z., & Yurong, G. (2024). Machine learning assisted designing of non-fullerene electron acceptors: A quest for lower exciton binding energy. *Heliyon, 10*(9), e30473. https://doi.org/10.1016/j.heliyon.2024.e30473

Biswas, S., Lee, Y., Choi, H., Won Lee, H., & Kim, H. (2023). Progress in organic photovoltaics for indoor application. *RSC Advances, 13*(45), 32000–32022. https://doi.org/10.1039/D3RA02599C

Energy.gov. (n.d.). *Organic Photovoltaics Research.* Energy.Gov. Retrieved April 18, 2025, from https://www.energy.gov/eere/solar/organic-photovoltaics-research

Equity / Justice40: Clean Energy Funding Series – Community Economic Development. (n.d.). Retrieved April 18, 2025, from https://economicdevelopment.extension.wisc.edu/articles/equity-justice40-clean-energy-funding-series/

Faißt, J., Jiang, E., Bogati, S., Pap, L., Zimmermann, B., Kroyer, T., Würfel, U., & List, M. (2023). Organic Solar Cell with an Active Area > 1 cm2 Achieving 15.8% Certified Efficiency using Optimized VIS-NIR Antireflection Coating. Solar RRL. https://doi.org/10.1002/solr.202300663

Fraunhofer Institute. (2023, July 18). World Record Efficiency of 15.8 Percent Achieved for 1 cm2 Organic Solar Cell—Fraunhofer ISE. Fraunhofer Institute for Solar Energy Systems ISE. https://www.ise.fraunhofer.de/en/press-media/news/2023/world-record-efficiency-of-15-percent-achieved-for-one-cm2-organic-solar-cell.html

Heliatek. (2023, August). *The world's most powerful OPV installation at SAIT.* Heliatek GmbH. https://www.heliatek.com/en/media/news/detail/the-worlds-most-powerful-opv-installation-at-sait/

Hauch, J. A., Schilinsky, P. & Biele, M. (2008). *Lifetime of Organic Solar Cells and Modules.* https://www.svc.org/clientuploads/directory/resource_library/08_055.pdf

Leveling Up Solar Manufacturing: What You Need To Know About Treasury's New Final Rules Under Sections 45X and 48D. (n.d.). SEIA. Retrieved April 18, 2025, from https://seia.org/events/leveling-up-solar-manufacturing-what-you-need-to-know-about-treasurys-new-final-rules-under-sections-45x-and-48d/

Li, Y., Huang, X., Ding, K., Sheriff, H. K. M., Ye, L., Liu, H., Li, C.-Z., Ade, H., & Forrest, S. R. (2021). Non-fullerene acceptor organic photovoltaics with intrinsic operational lifetimes over 30 years. *Nature Communications, 12*(1), 5419. https://doi.org/10.1038/s41467-021-25718-w

Lior Kahana. (2025, February 17). *U.S. startup unveils 'world's largest' transparent organic PV window.* Pv Magazine International. https://www.pv-magazine.com/2025/02/17/u-s-startup-unveils-worlds-largest-transparent-organic-pv-window/

Liu, X., Shao, Y., Lu, T., Chang, D., Li, M., & Lu, W. (2022). Accelerating the discovery of high-performance donor/acceptor pairs in photovoltaic materials via machine learning and density functional theory. *Materials & Design, 216*, 110561. https://doi.org/10.1016/j.matdes.2022.110561

Liu, X., Xu, S., Tang, B., & Song, X. (2024). Indoor organic photovoltaics for low-power internet of things devices: Recent advances, challenges, and prospects. *Chemical Engineering Journal, 497*, 154944. https://doi.org/10.1016/j.cej.2024.154944

Luo, W., Khaing, A. M., Rodriguez-Gallegos, C. D., Leow, S. W., Reindl, T., & Pravettoni, M. (2024). Long-term outdoor study of an organic photovoltaic module for building integration. *Progress in Photovoltaics: Research and Applications, 32*(7), 481–491. https://doi.org/10.1002/pip.3791

Mahmood, A., Irfan, A., & Wang, J.-L. (2022a). Machine learning and molecular dynamics simulation-assisted evolutionary design and discovery pipeline to screen efficient small molecule acceptors for PTB7-Th-based organic solar cells with over 15% efficiency. *Journal of Materials Chemistry A, 10*(8), 4170–4180. https://doi.org/10.1039/D1TA09762H

Mahmood, A., Irfan, A., & Wang, J.-L. (2022b). Machine Learning for Organic Photovoltaic Polymers: A Minireview. *Chinese Journal of Polymer Science, 40*(8), 870–876. https://doi.org/10.1007/s10118-022-2782-5

Mahmood, A., & Wang, J.-L. (2021). A time and resource efficient machine learning assisted design of non-fullerene small molecule acceptors for P3HT-based organic solar cells and green solvent selection. *Journal of Materials Chemistry A, 9*(28), 15684–15695. https://doi.org/10.1039/D1TA04742F

Marija Maisch. (2023, June). *Binary organic solar cell achieves 19,31% efficiency – pv magazine International*. https://www.pv-magazine.com/2023/06/02/binary-organic-solar-cell-achieves-1931-efficiency/

Mulligan, C. J., Wilson, M., Bryant, G., Vaughan, B., Zhou, X., Belcher, W. J., & Dastoor, P. C. (2014). A projection of commercial-scale organic photovoltaic module costs. *Solar Energy Materials and Solar Cells, 120*, 9–17. https://doi.org/10.1016/j.solmat.2013.07.041

Muteri, V., Cellura, M., Curto, D., Franzitta, V., Longo, S., Mistretta, M., & Parisi, M. L. (2020). Review on Life Cycle Assessment of Solar Photovoltaic Panels. *Energies, 13*(1), Article 1. https://doi.org/10.3390/en13010252

Patagonia. (2023, January 19). *NEXT Energy Technologies Installs Energy-Generating Windows on Outdoor Retailer Patagonia's Headquarters*. Patagonia Works. https://www.patagoniaworks.com/press/2023/1/19/next-energy-technologies-installs-energy-generating-windows-on-outdoor-retailer-patagonias-headquarters

Patrina Eiffert, & Arlene Thompson. (2000, February). *25266.U.S. Guidelines for the Economic Analysis of Building-Integrated Photovoltaic Power Systems*. https://www.nrel.gov/docs/fy00osti/25266.pdf?utm_source=chatgpt.com

Perovskite–organic solar cell sets efficiency record with new design. (n.d.). Retrieved April 18, 2025, from https://interestingengineering.com/energy/perovskite-organic-tandem-solar-cell-efficiency-record?group=test_a

Preet, S., & Smith, S. T. (2024). A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook. *Journal of Cleaner Production, 448*, 141661. https://doi.org/10.1016/j.jclepro.2024.141661

Science Daily. (2019, June). Record 19.31% efficiency with organic solar cells. *ScienceDaily*. https://www.sciencedaily.com/releases/2023/06/230601160241.htm

Solar Training Network. (n.d.). Energy.Gov. Retrieved April 20, 2025, from https://www.energy.gov/eere/solar/solar-training-network

Tsang, M. P., Sonnemann, G. W., & Bassani, D. M. (2016). Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Solar Energy Materials and Solar Cells, 156*, 37–48. https://doi.org/10.1016/j.solmat.2016.04.024

Uddin, A., Upama, M. B., Yi, H., & Duan, L. (2019). Encapsulation of Organic and Perovskite Solar Cells: A Review. *Coatings, 9*(2), Article 2. https://doi.org/10.3390/coatings9020065

US EPA, O. (2022, November 21). *Summary of Inflation Reduction Act provisions related to renewable energy* [Overviews and Factsheets]. https://www.epa.gov/green-power-markets/summary-inflation-reduction-act-provisions-related-renewable-energy

Volcovici, V., & Volcovici, V. (2021, September 9). Solar energy can account for 40% of U.S. electricity by 2035 -DOE. *Reuters*. https://www.reuters.com/business/energy/biden-administration-set-goal-45-solar-energy-by-2050-nyt-2021-09-08

What is bankability and why is it vital for solar projects? — RatedPower. (n.d.). Retrieved April 20, 2025, from https://ratedpower.com/glossary/bankability-solar-projects

Wikipedia. (2025). Organic solar cell. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Organic_solar_cell&oldid=1276780309

Wolske, K. S. (2020). More alike than different: Profiles of high-income and low-income rooftop solar adopters in the United States. *Energy Research & Social Science, 63*, 101399. https://doi.org/10.1016/j.erss.2019.101399

World record: Organic solar module achieves 14.46 percent efficiency. (n.d.). Retrieved April 18, 2025, from https://www.hi-ern.de/en/news/2023/world-record-organic-solar-module-achieves-14-46-percent-efficiency

World's largest façade installed with organic photovoltaic panels. (n.d.). Retrieved April 18, 2025, from https://optics.org/news/9/10/31

Wu, S., Liu, M., & Jen, A. K.-Y. (2023). Prospects and challenges for perovskite-organic tandem solar cells. *Joule, 7*(3), 484–502. https://doi.org/10.1016/j.joule.2023.02.014

Zhu, Z., Zhu, C., Tu, Y., Shao, T., Wang, Y., Liu, W., Liu, Y., Zang, Y., Wei, Q., & Yan, W. (2024). Machine-learning-assisted exploration of new non-fullerene acceptors for high-efficiency organic solar cells. *Cell Reports Physical Science, 5*(12), 102316. https://doi.org/10.1016/j.xcrp.2024.102316