

# Recent Advances in Solar Photovoltaic Technology: Materials, Efficiency, and Applications

Hamod Ghorm Ali Alshomrani<sup>1</sup>, Abdullah F. Aljohani<sup>2</sup>, Nasser Yahya A. Alahmari<sup>2</sup>,  
Ahmed Baalghayth M. Alalyani<sup>2</sup>, Abeer Hdaddi<sup>3</sup>

<sup>1</sup>Saudi Electricity Company, Bisha, Saudi Arabia

<sup>2</sup>Renewable Energy Researcher, Bisha University, Bisha, Saudi Arabia

<sup>3</sup>Department of Physics, College of Science and Humanities, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia

Email: alrahal2000@hotmail.com, Abdullah-aljohani@hotmail.com, Alahmary306@gmail.com, ahmad.0976@hotmail.com, AbeerH@icloud.com

**How to cite this paper:** Alshomrani, H.G.A., Aljohani, A.F., Alahmari, N.Y.A., Alalyani, A.B.M. and Hdaddi, A. (2026) Recent Advances in Solar Photovoltaic Technology: Materials, Efficiency, and Applications. *Energy and Power Engineering*, 18, 73-87.

<https://doi.org/10.4236/epe.2026.182004>

**Received:** November 3, 2025

**Accepted:** February 1, 2026

**Published:** February 4, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

This paper surveys recent progress in solar photovoltaic (PV) technology, concentrating on fresh materials, higher efficiencies, and new use cases. Rising energy demand and accelerating climate impacts make affordable, clean solar power ever more vital. We compare well-established silicon panels with emergent options like perovskite and thin-film cells, weighing each systems efficiency, drawbacks, and life-cycle footprint. The review also considers advanced designs-multi-junction devices, bifacial modules, and building-integrated PV (BIPV) that push performance beyond heritage architectures. Together, these innovations are finding homes in residences, offices, farms, and even vehicles. Yet hurdles persist: grid fit, uneven policy support, and end-of-life waste remain pressing issues. Drawing on recent studies and comparative statistics, we propose actionable pathways for wider adoption and stronger governance around the world.

## Keywords

Solar Photovoltaic, Efficiency Enhancement, Perovskite Solar Cells, Thin-Film PV, Renewable Energy, Building-Integrated Photovoltaics (BIPV), Sustainability, Energy Transition

## 1. Introduction

Rising worldwide energy consumption, along with pressing environmental issues and finite fuel stocks, has steered policymakers and researchers toward renewable

energy options like never before. Within the broad portfolio of clean sources, solar photovoltaic (PV) technology stands out because it is flexible in scale, widely understood, and commercially reliable. The principle is straightforward: sunlight strikes special semiconductor layers that release electrons, turning rays into usable power. In 2024, PV installations have therefore climbed past 30 percent of total renewable electricity capacity, a milestone due to hardware improvements and supportive legislation [1].

Although harnessing solar rays is hardly a new idea, interest in PV systems has surged in the past few years. That acceleration stems from urgent climate targets, plummeting module prices, and breakthroughs in materials and design. Consequently, the Levelized Cost of Electricity (LCOE) for solar panels has fallen over 80 percent during the last decade, making them the least expensive generation option in much of the world [2]. Favorable economics have prompted intensified research and large-scale rollouts, especially in regions that receive abundant sunlight.

Solar photovoltaic (PV) technology is gaining traction because it can fit into almost any setting, from vast desert plants to roof tiles and even moving objects like solar cars. Still, hurdles-landed in tech, the environment, and social factors-remain before the units can reach their full promise. Each panel's output varies with the quality of its materials, temperature, shade, and where on the globe it sits. In addition, problems linked to recycling, storage, and supportive policy slow take-up most in poorer regions [3].

Materials lie at the heart of both efficiency and ecological footprint in PV systems. Silicon stays in first place, thanks to its wide availability, ruggedness, and an industry that knows how to scale it. New options such as perovskites, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) command attention because they promise higher yields at lower cost. Laboratory perovskite cells already flirt with over 25 percent efficiency when stacked in tandem [4]. Yet worries about their lifetime and toxicity keep them out of factories for now.

Efficiency remains a central concern in photovoltaic (PV) research. Conventional single-junction silicon cells reach a theoretical efficiency ceiling roughly set by the Shockley-Queisser limit, estimated at thirty-three percent. This is due to the fact that sub-bandgap photons are not absorbed and the high-energy photons dissipate their excess energy as thermal energy (thermalization). This therefore means that a single-junction cell can not make good use of the entire solar spectrum driving tandem and multijunction designs that divide the spectrum into layers to minimize these losses. To exceed this threshold, scientists are now exploring multi-junction and tandem architectures, refined light-trapping designs, and tighter surface passivation. Practical innovations-such as bifacial panels, concentrator PV (CPV), and intelligent tracking-also boost field performance [4].

PV applications are growing quickly in cities, where seamless pairing with buildings and public works is essential. Building-integrated PV (BIPV) replaces ordinary cladding and glazing, generating power without extra footprint. Such

designs lower energy demand and shrink urban carbon footprints. In transport, solar modules feed electric vehicle (EV) charging stations and may soon cover car exteriors, furthering ambitions to decarbonize mobility [5].

Agrivoltaics interlace farming with on-site solar energy production, easing competition for scarce land in rural economies. Trials across Mediterranean vineyards and Southeast Asian fruit farms reveal that crops under filtered light can use water more sparingly and suffer less heat damage [6]. Such evidence portrays PV as a nimble tool able to serve both agriculture and energy needs when designed thoughtfully.

Still, photovoltaic uptake varies widely between nations and regions. Local income levels, public knowledge, clear regulations, and pathways to credit jointly influence how quickly panels cover rooftops and fields. Wealthy states typically ride the wave thanks to generous incentives and established supply chains. Many low and middle-income countries, by contrast, confront heavy capital costs, patchy grids, and scant policy backing [7].

Environmental factors now sit squarely at the heart of photovoltaic (PV) research. Although sunlight itself leaves no footprint, making and ultimately discarding solar panels can harm ecosystems. The presence of scarce or hazardous ingredients—such as lead in some perovskite blends or cadmium in CdTe—raises worries about poisoning soil and water. Researchers therefore chase greener production methods and workable recycling systems to curb those dangers [8].

Looking ahead, PVs will thrive only if engineers, ecologists, policymakers, and business leaders pull together. When solar arrays link with batteries, agile grids, and other smart tools, power becomes steadier and losses shrink. At the same time, artificial intelligence and data analytics sift vast operating records to tune performance, forecast repairs, and guide long-term planning [9].

This article presents a broad assessment of present-day solar photovoltaic (PV) technology, organized around three interrelated themes: new materials, higher efficiencies, and wider applications. By reviewing literature published between 2018 and 2025, the work collates recent findings, traces the rapid evolution of PV systems, and discusses both hurdles and promising pathways that researchers still confront. The goal is to equip a diverse audience—scholars, regulators, business executives, and environmental advocates—with an evidence-based understanding of how solar PV can help steer the world toward more sustainable energy.

## **2. Materials in Solar Photovoltaic Technology**

Materials lie at the heart of solar photovoltaic (PV) systems, shaping their efficiency, lifespan, ecological footprint, and bottom-line cost. Faced with rising demand for more powerful, affordable, and planet-friendly panels, researchers in materials science have hurried to test new semiconductors, novel layer designs, and fresh production methods. The following pages survey the core materials found in PV devices, highlight recent breakthroughs, and weigh the performance of promising contenders against established choices.

## 2.1. Silicon-Based Technologies

Crystalline silicon (c-Si) still powers roughly 90 % of the commercial solar market, making it by far the leading technology. This share stems from the material's relative abundance, time-tested reliability, mature supply chains and a cost-performance balance that continues to satisfy installers and buyers alike. Two principal cell formats exist, monocrystalline and polycrystalline. Monocrystalline devices usually deliver higher efficiencies, in the 19 to 22 percent range, and a longer operational lifespan but command a small price premium. Polycrystalline options are cheaper, yet grain boundaries lower their efficiency to roughly 15 to 18 percent.

Recent innovations have pushed c-Si farther. Passivated Emitter and Rear Cell (PERC) structures cut electron recombination losses, boosting yield, while bifacial modules, which harvest sunlight from front and rear, offer extra output in bright, reflective settings [10].

## 2.2. Thin-Film Technologies

Thin-film solar cells provide a lightweight, bendable option that fits well into building-integrated photovoltaics (BIPV), portable gadgets, and specialized uses. Key materials include cadmium telluride (CdTe), copper-indium-gallium-selenide (CIGS), and amorphous silicon (a-Si).

- **CdTe:** Characterized by low manufacturing costs and efficiencies around 15-18%, CdTe dominates many utility-scale projects. Yet toxic cadmium raises eco and end-of-life issues [11].
- **CIGS:** Delivers efficiencies of 13% - 20% and outperforms a-Si at higher temperatures, yet dwindling indium and gallium supplies hamper mass production.
- **Si:** Cheap and pliable, a-Si nonetheless delivers only 6% - 10% efficiency and degrades rapidly in sunlight, limiting it mostly to low-power devices.

## 2.3. Perovskite Solar Cells (PSCs)

The direct impact of Perovskite materials, which are constructed on the formula  $ABX_3$  (A an organic or inorganic cation, B a metal and X a halide ligand), has redesigned photovoltaic activities due to strong light absorption, variable bandgap, and low cost of processing. Since their arrival in 2009, perovskite solar cells have recorded laboratory efficiencies above 25%, matching leading commercial silicon panels [12].

The main advantages of perovskite devices are:

- Very high absorption coefficients permitting thin active films.
- Seamless integration with flexible, transparent substrates.
- The option to form tandem stacks with silicon or Cu-In-Ga-Se.

Still, PSCs contend with stability over years, sensitivity to moisture, and the health risks tied to lead. Scientists are testing improved encapsulation, safer lead-free formulas, and large-area deposition methods to tackle these issues. The com-

mon dominant forms of degradation are the migration of halide and A-site cation ion under an electric field and light bias; interaction with moisture and oxygen forming a hydrated or oxidized phase; phase segregation in mixed-halide under light/thermal conditions; and diffusion at an electrode interface. Better encapsulation and interface design have the ability to overcome moisture/oxygen ingress and compositional tuning and additives can decrease the density of mobile-ions [13].

#### 2.4. Organic and Hybrid Photovoltaics

Organic photovoltaics (OPV) and dye-sensitized solar cells (DSSCs) mark a distinct class of next-generation devices, prized for their light weight, design flexibility, and fabrication at modest temperatures. Both approaches rely on organic polymers or small molecular dyes to harvest sunlight and produce electricity.

Even so, OPVs still yield lower efficiencies, generally ranging from 5 to 12 percent, than mainstream inorganic cells; promising progress in donor-acceptor chemistry, device layout, and protective encapsulation has begun to lift both stability and performance [14].

#### 2.5. Tandem and Multi-Junction Cells

To reach efficiencies beyond the Shockley-Queisser limit, scientists are now concentrating on tandem and multijunction designs. These systems layer materials with different band gaps so they can absorb a wider slice of sunlight.

One such combination, that theorists believe could be more than 30-percent efficient, is the silicon-perovskite tandem. Such a hybrid construction will combine the long-known stability of silicon and the high absorption of perovskites and presents a promising way forward in solar panels in the future, as described in **Table 1** [15] [16].

**Table 1.** Summary of key PV materials.

Material Type	Efficiency Range (%)	Advantages	Challenges	Reference
Monocrystalline Si	19 - 22	High efficiency, mature technology	Higher cost	IEA (2023), Khan <i>et al.</i> (2025)
Polycrystalline Si	15 - 18	Cost-effective, widely available	Lower efficiency	IEA (2023)
CdTe	15 - 18	Low-cost, good temperature behavior	Toxicity (cadmium), recyclability	Derin Gure <i>et al.</i> (2025)
CIGS	13 - 20	High efficiency, flexible	Rare materials, cost	Derin Gure <i>et al.</i> (2025)
Perovskite	18 - 25+ (lab)	High absorption, low cost, flexible	Stability, toxicity (lead)	Alnusairat & Abu Qadourah (2024), Khan <i>et al.</i> (2025)
Organic PV	5-12	Lightweight, printable	Low efficiency, degradation	Yang & Gong (2025)

Inventive materials still drive nearly all advances in solar photovoltaic technology. Although silicon rules the commercial sector, newer compounds like perovskites and CIGS are widening the performance envelope and enabling fresh appli-

cations. Future inquiry must weigh added efficiency against long-term stability, resource impact, and safety. Progress on those fronts will guide the next wave of meaningful breakthroughs in solar energy.

### 3. Efficiency Enhancement in Solar Photovoltaic Technology

Increasing the performance of solar photovoltaic (PV) systems stands as an enduring priority in renewable-energy research. When cells achieve higher performance, they generate more electricity from less area, conserving land, lowering installation costs, and quickening return on investment. The current section reviews principal strategies and recent breakthroughs toward that aim, from cell architecture and new materials to tighter integration with balance-of-system components.

#### 3.1. Advanced Cell Architectures

##### a. Passivated Emitter and Rear Cell (PERC)

PERC adds a passivation film to the back of a cell, improving light capture and cutting recombination losses. The modest change boosts module efficiency by roughly 1% - 2% over standard monocrystalline designs.

##### b. Heterojunction with Intrinsic Thin-layer (HIT)

HIT sandwiches thin amorphous silicon between crystalline wafers, producing higher efficiencies and better temperature behavior. The structure shines in hot regions where conventional cells suffer greater performance drop.

##### c. Interdigitated Back Contact (IBC)

IBC traps all contacts behind the cell, removing shading and raising overall efficiency. Although fabrication is challenging, commercial modules routinely exceed 23%.

#### 3.2. Multi-Junction and Tandem Cells

Multi-junction cells stack layers with tuned bandgaps, harvesting a wider slice of the solar spectrum. Silicon-perovskite tandems illustrate the approach, pairing robust silicon with a perovskite layer that absorbs light even better.

Fresh laboratory data show tandem cells reaching efficiencies above 30% and suggest a commercial rollout could begin by 2030. Such thin, powerful devices suit settings with tight real estate or-demanding power, including aircraft and city rooftops [17].

#### 3.3. Light Management Strategies

##### a. Anti-Reflective Coatings

Anti-reflective coatings (ARCs) cut down surface glare so more sunlight passes into the active cell layer. Recent multilayer designs lift overall light capture by roughly three to five percent across the full solar spectrum.

##### b. Surface Texturing

Submicron and nanostructured patterns on the cell surface bend incoming rays,

forcing them to reflect internally several times before escaping. This tactic has become standard in high-efficiency monocrystalline devices.

### c. Light-Trapping Structures

Novel elements such as photonic crystals, plasmonic nanoparticles, or simple rear mirrors aim to push absorbed light toward the junction. Presently still in the lab, these features sketch the horizon for next-generation PV modules.

## 3.4. Bifacial and Tracking Systems

### a. Bifacial Panels

Bifacial panels harvest photons on both the front and rear faces, turning stray or diffuse light into extra current. Trials show field gains of five to twenty percent, with yield tied closely to ground reflectance and mounting height.

### b. Solar Trackers

Single- and dual-axis trackers pivot to keep panels aimed at the moving sun throughout the day. Pairing this motion with bifacial technology can, under ideal skies, boost annual output by more than thirty percent.

## 3.5. System-Level Efficiency Improvements [18]

### a. Maximum Power Point Tracking (MPPT)

MPPT strategies continuously modify the electrical load so that photovoltaics operate at their peak power point. Contemporary inverters now embed these advanced routines, yielding 5 to 10 percent more energy with each sunny day.

### b. Cooling and Thermal Management

Heat squanders output; elevated cell temperatures depress efficiency. Researchers trial both passive and active cooling—such as fin arrays, micro-water circuits, and phase-change media—to maintain stable module temperatures and boost yield. Performance improvements are outlined in **Table 2**.

**Table 2.** Summary of efficiency enhancement techniques.

Technique	Efficiency Gain (%)	Application Stage	Reference
PERC	+1 - 2	Commercial	Khan <i>et al.</i> (2025)
HIT	+2 - 3	Commercial	Yang & Gong (2025)
IBC	+3 - 4	Limited Commercial	IEA (2023)
Tandem Cells	+5 - 10 (lab)	Experimental	Khan <i>et al.</i> (2025)
Anti-Reflective Coatings	+3 - 5	Widely Used	Bao <i>et al.</i> (2020)
Surface Texturing	+1 - 2	Widely Used	IEA (2023)
Light-Trapping Structures	+3 - 8	Experimental	Chisale <i>et al.</i> (2025)
Bifacial Modules	+5 - 20 (field)	Growing Adoption	Derin Gure <i>et al.</i> (2025)
Solar Tracking	+15 - 30	Commercial	IEA (2023)
MPPT	+5 - 10	Standard	IEA (2023)
Thermal Management	+2 - 6	Experimental	Ghaleb <i>et al.</i> (2023)

Improving the efficiency of solar photovoltaics requires a layered strategy that merges advances in materials, devices, and system design. Although today's commercial panels already exhibit impressive performance and durability, ongoing investigations into tandem cells, novel optical components, and adaptive thermal management still promise compelling avenues for future gains. Integrating these innovations will therefore be crucial for maximizing energy capture while driving down the long-term cost of solar power.

Green and blue rays are distinguished by the capacity to ameliorate optical loss. The design of the breakthrough is to replace silicon with a highly absorbent layer of thin perovskite, having in a single package the benefits of low-cost flexibility and high absorbency.

Recent lab reports document tandem cell efficiencies topping 30%, and investigators predict commercial deployment as early as 2030. Such high-density sources are vital where real estate is scarce or energy loads soar, such as in aircraft, satellites, and dense urban rooftops [11].

## **4. Applications of Solar Photovoltaic Technology**

Once limited to conventional rooftops, solar photovoltaic (PV) technology now stretches into nearly every corner of daily life, from homes and businesses to farms and even vehicles. This chapter reviews these growing roles and shows how shrinking prices and flexible design have made seamless use in so many settings possible. For each topic, benefits, hurdles, and outlook are considered.

### **4.1. Residential Sector**

Home solar kits remain the public's most familiar renewable option, offering freedom from fluctuating power bills and a smaller carbon footprint over time. New inverters, batteries, and smart meters boost performance while guiding owners through daily use.

Building-integrated photovoltaics, or BIPV, are now standard in award-winning subdivisions, turning façades and rooftops into sleek power plants. Generous net metering in many states still pays families for surplus sun, strengthening the business case [19].

### **4.2. Commercial and Industrial Applications**

Large, mostly unshaded roofs make most commercial buildings natural candidates for solar panels. Many firms are moving fast to cut overhead and polish public images with on-site generation. At bigger industrial sites, the same logic drives both rooftop and ground-mounted arrays that match heavy daytime loads.

In modern cities, architects now place photovoltaic (PV) cells in building façades, sunshades, and even skylights. Semi-transparent solar glass in windows absorbs sunlight yet lets in enough daylight to keep rooms bright. Certification bodies like LEED actively urge designers to weave these solar features into green projects [20].

### 4.3. Agricultural Sector

Agrivoltaics links food production and power generation by installing panels above working fields or orchards. The slight shade lowers air temperature and slows soil moisture loss while still letting sunlight reach plants. Crops that tolerate shade e.g., herbs (basil, cilantro), brassicas, leafy greens (lettuce, spinach, kale), berries, and pasture grasses are usually viable in to partial shading that is characteristic of Agri voltaic designs [21].

Field trials in Jordan, India, and several European nations report stronger yields and smarter land use underneath solar canopies. Off-grid farms also gain reliability from PV-fed pumps and climate-controlled, energy-independent greenhouses.

### 4.4. Transportation and Mobility

Another frontier is embedding solar technology into transport systems and vehicles themselves. Solar EV charging pads and self-shading rest areas now pop up along highways and in urban hubs to ease emissions from driving.

Vehicle-integrated photovoltaics (VIPV) lay flexible modules on roofs, hoods, or windows of cars, buses, and trucks. Although limited by surface area and cell efficiency, these systems stretch battery range and lessen reliance on public plugs [22].

### 4.5. Rural Electrification and Off-Grid Systems

Stand-alone photovoltaic (PV) units, which provide an essential service in remote or underserved locations where the central grid is absent, are used in these locations. Phones, a few small appliances, and lighting can be enabled using solar home systems (SHS), small community mini-grids and portable kits [23].

Worldwide, NGOs and public projects have rolled out these units across Sub-Saharan Africa and South Asia, powering schools, clinics, and safe-water pumps. Modular hardware paired with pre-paid meters also makes each scheme easier to scale and cheaper for households. Real-world deployments are summarized in **Table 3** [3] [4].

**Table 3.** Applications of PV technology across sectors.

Sector	Application Example	Benefits	Challenges	Reference
Residential	Rooftop systems, BIPV	Energy savings, autonomy	Aesthetic, regulation, roof orientation	Alnusairat & Abu Qadourah (2024)
Commercial	Facades, solar carports	Cost reduction, green branding	High upfront cost, design complexity	Noorzai <i>et al.</i> (2023)
Agriculture	Agrivoltaics, solar irrigation	Dual land use, water efficiency	Infrastructure, shading management	Chisale <i>et al.</i> (2025)
Transport	EV chargers, VIPV	Reduced emissions, energy reuse	Limited area, low yield	Yang & Gong (2025)
Off-grid Areas	SHS, mini-grids, solar lanterns	Access to electricity, low cost	Maintenance, financing, policy support	Derin Gure <i>et al.</i> (2025)

Photovoltaic technology is proving itself adaptable across numerous sectors

and stands poised to reshape energy systems worldwide. Whether mounted on suburban rooftops, spread over farm fields, or embedded in electric cars, solar panels deliver versatile, clean power that is falling steadily in price. Realising this potential requires concerted work to lift technical, financial, and policy hurdles so that solar benefits reach everyone fairly [6].

## 5. Challenges and Limitations of Solar Photovoltaic Technology

Although solar photovoltaic (PV) technology is being adopted far and wide, its roll-out still faces a mix of technical, economic, environmental, and social roadblocks that threaten both immediate use and long-term viability. This section highlights the main hurdles confronting PV systems and briefly reviews the strategies now under investigation to ease them [7]-[9].

### 5.1. Technical Challenges

#### a. Intermittency and Reliability

Because solar power hinges on sunlight, its availability swings with clouds, nighttime, weather fronts, and the latitudinal position of the installation. Without proper safeguards, these fluctuations can jolt electric grids that already host large volumes of solar generation.

Lithium-ion batteries and other energy-storage systems (ESS) are the standard fix, holding surplus power for use after the sun sets, yet they inflate project budgets and need replacement every few years. Researchers also investigate smarter grid software and hybrid set-ups that pair solar with wind, hydro, or demand-response models to tighten reliability at lower expense [1].

#### b. Efficiency Losses

Mother Nature and everyday grime can chip away at the output of even the best PV modules. When outside air is hot, a typical silicon panel may lose 0.3% to 0.5% of its rated efficiency for every degree Celsius above 25. Dust, pollen, and other airborne particles settle on surfaces in dry climates, sometimes denying up to 20% of the expected energy harvest [18].

#### c. System Integration

Adding solar panels to old buildings or dense city grids often demands careful design work and extra funding, whether the homes are historic landmarks or just narrow streets. In many developing nations, the local grid can't absorb vast new solar feeds, and cables, transformers, and meters may all need an upgrade before commercial arrays can even turn on. Decentralized community microgrids that combine PV with storage and smart controls can relieve feeder congestion and improve reliability where central grids are weak. These architectures align with the off-grid and mini-grid pathways discussed in Section 4.5, enabling phased upgrades while expanding energy access [19].

### 5.2. Economic and Financial Constraints

#### a. High Initial Investment

Even though panels cost far less than a decade ago, the full package-inverters, racking, batteries, cables, and labor-brings a bill most low-income families and small shops still cannot meet. Grants, popular feed-in rates, or tax offsets ease the pain in wealthier markets, yet those same financial cushions are scarce or tangled in bureaucracy the moment a project crosses a national border [14] [15].

#### **b. Uneven Access to Financing**

Cheap loans, upfront grants, or lease deals appear in some regions overnight and vanish a few miles down the road; without them, community cooperatives and smallholder buyers force savings that stretch years. In many off-grid villages the absence of bank accounts or collateral-worthy income chains makes formal credit impossible, so hopeful owners end up relying on informal money-lenders who charge steep premiums.

### **5.3. Environmental and Health Concerns**

Certain thin-film cells like cadmium telluride or the newest lead-rich perovskites contain heavy metals that present real hazards during production, repair, or end-of-life recycling. When shards, dust, or old stacks slip into local streams or pit latrines, the slow seep of poison harms plants, livestock, and eventually the very people who hoped solar energy would deliver them from fossil fuels.

As early-generation solar panels reach the end of their operational lives, mounting volumes of photovoltaic waste have emerged as a troubling issue. In large parts of the world, recycling networks are still in their infancy, and the technical and economic hurdles of reclaiming precious metals like silver, useful silicon, and rare-earth materials are also high. Global PV end-of-life wastes are expected to become on the order of 6078 million tonnes at a point around 2050, demonstrating the pressing need of scalable collection and recycling systems [20] [24].

### **5.4. Policy and Regulatory Issues**

#### **a. Policy Instability**

Repeated revisions of national solar incentives, tariffs, and rules shake investor confidence, obstruct long-term planning, and slow market expansion. Divergent requirements from central governments and local authorities also jam the permitting and grid-connection pipelines.

#### **b. Lack of Standardization**

The absence of country-wide or regional norms for module design, installation practice, and upkeep weakens quality control and makes performance volatile, especially in fast-growing markets with little experience.

### **5.5. Social and Behavioral Barriers**

#### **a. Public Awareness and Acceptance**

Limited public understanding-or outright myths-about solar system benefits, upkeep, and safety deters uptake in some communities. Local traditions, aesthetic values, and fears of change can further color decisions about roof space [7].

### **b. Workforce and Technical Expertise**

Building and servicing solar arrays depend on trained technicians and engineers. When that talent is absent, particularly in rural or isolated regions, installation shortcuts and poor maintenance can shorten system life and undercut output.

Though solar photovoltaic technology promises a cleaner energy future, capturing that promise depends on confronting several interrelated hurdles. These include advancing affordable storage, designing safe recyclable materials, widening access to capital, and reinforcing sensible regulation. Tackling those tasks will demand a broad, inclusive partnership among policymakers, businesses, and local communities [2] [8].

## **6. Conclusion and Recommendations**

Solar photovoltaic (PV) panels lie at the heart of the worldwide push for cleaner, renewable power. This study shows that better materials, efficiency gains and new uses have already boosted solar systems potential and made them easier to install. Whether it is monocrystalline silicon or the latest perovskite layers, fresh chemistry keeps raising output and broadening applications. At the same time, modern building design, multi-junction cells, bifacial modules and tracking rigs let PV arrays squeeze extra kilowatt-hours from almost every setting.

Today the technology powers homes, offices, farms, vehicles and even remote camps after disasters. Its reach across such varied markets gives solar an image of a one-size-fits-all remedy for the energy and climate problems of our time. Still, growth stalls whenever technical, financial, regulatory or ecological hurdles appear. Issues such as supply interruptions, efficiency losses, steep upfront costs, panel waste and shifting policies all slow widespread roll-out.

## **7. Recommendations**

To unlock the full potential of solar photovoltaics and guide the energy switch toward fairness and long-term resilience, the authors offer the following action steps:

### **1. Support Materials Research and Development:**

Sustained funding for clean, durable, and recyclable inputs-especially lead-free perovskites and substitutes for rare thin-film metals-should remain a top priority.

### **2. Enhance Grid Integration and Storage Solutions:**

Incorporating affordable batteries and agile grid controls with every array can ease output fluctuations and direct power where it is most needed.

### **3. Expand Financial Access:**

Broadening ownership paths through micro-loans, leases, and community-shared projects will help households and small businesses in low-income areas enter the market.

### **4. Strengthen Policy and Regulatory Frameworks:**

Caretakers at all levels must write stable, long-term rules and predictable incentives so that innovators and investors can plan with confidence.

### 5. Promote Public Awareness and Workforce Development:

Ongoing outreach, hands-on curricula, and clear career pathways are vital for building public trust and equipping technicians with up-to-date skills.

### 6. Scale Circular Economy Practices:

New collection networks and recycling lines, paired with product designs meant to recover metals and cut landfill volume, will limit future waste and preserve resources.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

- [1] Abreu, J., Wingartz, N. and Hardy, N. (2019) New Trends in Solar: A Comparative Study Assessing the Attitudes Towards the Adoption of Rooftop PV. *Energy Policy*, 128, 347-363. <https://doi.org/10.1016/j.enpol.2018.12.038>
- [2] Abu Qadourah, J., AL-Falahat, A.M. and Alrwashdeh, S.S. (2022) Assessment of Solar Photovoltaics Potential Installation into Multi-Family Building's Envelope in Amman, Jordan. *Cogent Engineering*, 9, Article ID: 2082059. <https://doi.org/10.1080/23311916.2022.2082059>
- [3] Al-Falahat, A.M., Qadourah, J.A., Alrwashdeh, S.S., khater, R., Qatlama, Z., Alddibs, E., et al. (2022) Energy Performance and Economics Assessments of a Photovoltaic-Heat Pump System. *Results in Engineering*, 13, Article ID: 100324. <https://doi.org/10.1016/j.rineng.2021.100324>
- [4] Wael Albadaineh, R. (2023) Energy-Passive Residential Building Design in Amman, Jordan. *Energetika*, 68, 43-67. <https://doi.org/10.6001/energetika.v68i1.4857>
- [5] Albattah, M. and Attoye, D.E. (2021) A Quantitative Investigation on Awareness of Renewable Energy Building Technology in the United Arab Emirates. *Sustainability*, 13, Article 6665. <https://doi.org/10.3390/su13126665>
- [6] Ali, H., Alnusairat, S. and Hijazi, H. (2023) Green Urban Evaluation Index for the Central Districts of Cities in Developing Countries: Case of Jordan. *Urban Design International*, 28, 234-251. <https://doi.org/10.1057/s41289-023-00228-x>
- [7] Alnusairat, S. and Abu Qadourah, J. (2024) Moving to Green Technologies: Acceptance and Perception of Architectural Solar Photovoltaic Technology for Residential Buildings. *Architectural Engineering and Design Management*, 21, 338-355. <https://doi.org/10.1080/17452007.2024.2361819>
- [8] Alnusairat, S., Abu Qadourah, J. and Khattab, R. (2023) Assessing the Future City Post COVID-19: Linking the SDGs, Health, Resilience, and Psychological Impact. *Sustainability*, 15, Article 811. <https://doi.org/10.3390/su15010811>
- [9] Ariff Azizan, S. and Ahmad Sayuty, A.N.A. (2022) Social Acceptance of Green Electricity: A Case Study in Putrajaya. *Journal of KATHA*, 18, 56-72. <https://doi.org/10.22452/katha.vol18no1.4>
- [10] Baldwin, E. (2021) Solar Design: How Architecture and Energy Come Together. *ArchDaily*. <https://www.archdaily.com/933697/solar-design-how-architecture-and-energy-come-together>
- [11] Derin Güre, P., Zırh, B.C., Erdil, E., Topal, Y.E., Yazici, E., İpek, E., et al. (2025) A

- Systematic Review of Socio-Economic Impact Assessments of Solar Energy and Photovoltaic (PV) Technologies: Network Dynamics, Societal Problems and Policy Implications. *Innovation: The European Journal of Social Science Research*.  
<https://doi.org/10.1080/13511610.2024.2445176>
- [12] Bao, Q., Sinitskaya, E., Gomez, K.J., MacDonald, E.F. and Yang, M.C. (2020) A Human-Centered Design Approach to Evaluating Factors in Residential Solar PV Adoption: A Survey of Homeowners in California and Massachusetts. *Renewable Energy*, 151, 503-513. <https://doi.org/10.1016/j.renene.2019.11.047>
- [13] Raju, T.D., Murugadoss, V., Nirmal, K.A., Dongale, T.D., Kesavan, A.V. and Kim, T.G. (2025) Advancements in Perovskites for Solar Cell Commercialization: A Review. *Advanced Powder Materials*, 4, Article ID: 100275.  
<https://doi.org/10.1016/j.apmate.2025.100275>
- [14] Cang, T. (2025) Comprehensive Exploration of Solar Photovoltaic Technology: Enhancing Efficiency, Integrating Energy Storage, and Addressing Environmental and Economic Challenges. *Applied and Computational Engineering*, 123, 10-16.  
<https://doi.org/10.54254/2755-2721/2025.19565>
- [15] Canul-Reyes, D.A., Rodríguez-Hernández, O., Barragán-Peña, M.E. and del Rio, J.A. (2025) Analysis of Offshore Wind Energy and Solar Photovoltaic Production and Its Relationship with Regional Electricity Demand in the Yucatan Peninsula. *Ener-gy*, 314, Article ID: 134060. <https://doi.org/10.1016/j.energy.2024.134060>
- [16] Huang, J. and Mao, L. (2025) A Review on Perovskite/Silicon Tandem solar Cells: Current Status and Future Challenges. *Energies*, 18, Article 4327.  
<https://doi.org/10.3390/en18164327>
- [17] Chisale, S.W., Lee, H.S., Soto Calvo, M.A., Jeong, J., Aljber, M., Williams, Z., et al. (2025) Advanced Solar Energy Potential Assessment in Malawi: Utilizing High-Resolution WRF Model and GIS to Identify Optimal Sites for Solar PV Gen-eration. *Renewable Energy*, 239, Article ID: 122084.  
<https://doi.org/10.1016/j.renene.2024.122084>
- [18] Corrado, C., Holt, E., & Schambach, L. (2022) Barriers to Solar Photovoltaic (PV) Adoption on a National Scale in the United States. 2022 IEEE 49th Photovoltaics Specialists Conference (PVSC), Philadelphia, 5-10 June 2022, 1110-1117.  
<https://ieeexplore.ieee.org/document/9938533>
- [19] do Nascimento, F.M., Mairesse Siluk, J.C., de Souza Savian, F., Bisognin Garlet, T., Renes Pinheiro, J. and Ramos, C. (2020) Factors for Measuring Photovoltaic Adoption from the Perspective of Operators. *Sustainability*, 12, Article 3184.  
<https://doi.org/10.3390/su12083184>
- [20] Ghaleb, B., Abbasi, S.A. and Asif, M. (2023) Application of Solar PV in the Building Sector: Prospects and Barriers in the GCC Region. *Energy Reports*, 9, 3932-3942.  
<https://doi.org/10.1016/j.egy.2023.02.085>
- [21] Dupraz, C. (2024) The Agronomy of Crops in Agrivoltaic Systems. *Agrivoltaics: Technical, Ecological, Commercial and Legal Aspects*, The Institution of Engineering and Technology, 181-216. [https://doi.org/10.1049/PBPO245E\\_ch5](https://doi.org/10.1049/PBPO245E_ch5)
- [22] Haghghi, Z., Angali Dehnavi, M., Konstantinou, T., van den Dobbelsteen, A. and Klein, T. (2021) Architectural Photovoltaic Applications: Lessons Learnt and Perceptions from Architects. *Buildings*, 11, Article 62.  
<https://doi.org/10.3390/buildings11020062>
- [23] Chow, J.T. (2010) Assessment of Solar Home Systems (SHS) for Isolated Rural Communities in Vanuatu Using Project Lifecycle/Sustainability Framework. Doctoral dissertation, Michigan Technological University).

- [24] Khakpour, S., Luu, L.Q., Nocera, F., Latteri, A. and Cellura, M. (2025) The Solar Waste Challenge: Estimating and Managing End-of-Life Photovoltaic Panels in Italy. *Energies*, 18, Article 2219. <https://doi.org/10.3390/en18092219>.