Building Sustainable Solar Futures: Policy Pathways for Transforming Energy Access

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TEA@ SUNRISE – 2026

Acknowledgments

TEA@SUNRISE is enabling sustainable, affordable, next-generation solar photovoltaics to be manufactured locally in countries in Africa, Asia, and the Indo-Pacific. The project is part of the Transforming Energy Access platform funded by UK aid from the UK Government to support the technologies, business models, and skills needed to enable an inclusive, clean energy transition.

This material has been funded by UK aid from the UK government; however the views expressed do not necessarily reflect the UK government's official policies.

Executive Summary

Solar photovoltaics (PV) have become the fastest-growing source of renewable electricity worldwide, surpassing 1.4 TW of installed capacity in 2023. Current deployment models have delivered rapid cost and scale gains with tangible environmental benefits, but now face sustainability challenges related to coal-intensive manufacturing, supply-chain concentration, and end-of-life management. These risks, environmental, economic, and social, are particularly acute for low- and middle-income countries (LMICs), where energy access goals intersect with systemic vulnerabilities.

This report provides evidence-based guidance for the Transforming Energy Access (TEA@SUNRISE) initiative to accelerate PV adoption in LMICs while safeguarding environmental integrity, economic resilience, and social justice. It evaluates incumbent crystalline silicon technologies alongside emerging platforms such as perovskite and organic photovoltaics, identifying risks and opportunities across three pillars of sustainability:

Environmental: PV delivers major climate benefits, but coal-heavy production can extend carbon payback times to a decade. Circular design and clean manufacturing are essential to mitigate the environmental harms that are implicit in any manufacturing process.

Economic: Solar is now the lowest-cost source of electricity globally, yet over 80% of modules and 95% of wafers originate from a single country, creating systemic vulnerability. Material bottlenecks—silver, indium, tin—must be addressed through substitution and recovery.

Social: Forced labour risks in upstream supply chains pose serious reputational, regulatory, and legitimacy challenges to the energy transition. Next-generation PV offers pathways for localised production and inclusive industrial strategies, provided ethical standards and technology transfer are embedded early.

Without decisive action, the world risks locking in new forms of avoidable environmental harm, supply dependency, and social injustice. By contrast, strategic interventions now can deliver a solar future that is not only low-carbon but truly sustainable.

Key Policy Actions

To achieve a just and resilient solar transition, governments and development partners should act immediately across five fronts:

Diversify and decarbonise supply chains: Support regional manufacturing powered by clean electricity and transparent labour practices.

Embed circularity from the outset: Mandate design-for-disassembly standards, extended producer responsibility (EPR), and invest in recycling infrastructure.

Mandate ethical sourcing and traceability: Eliminate forced labour risks through independent audits and enforceable social safeguards.

Accelerate innovation in next-generation PV: Target R&D funding for scalable, low-toxicity processing and material substitution to reduce reliance on critical raw materials.

Leverage procurement and finance for sustainability: Reward sustainable designs, create markets for secondary materials, and enable local manufacturing in LMICs.

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List of Acronyms

a-Si	Amorphous Silicon: A thin-film photovoltaic technology using non-crystalline silicon as the semiconductor material
BIPV	Building-Integrated Photovoltaics: Solar PV modules integrated into building elements such as façades or roofs.
BoS	Balance of System: All components of a PV system other than the modules, including inverters, wiring, and mounting structures.
CBAM	Carbon Border Adjustment Mechanism: EU policy tool to prevent carbon leakage by imposing a carbon price on imports.
CdTe	Cadmium Telluride: A thin-film PV technology using cadmium and tellurium as semiconductor materials.
CIGS	Copper Indium Gallium Selenide: A thin-film PV technology based on these elements.
CRM	Critical Raw Material: Materials identified as having high supply risk and economic importance.
c-Si	Crystalline Silicon: The dominant PV technology, including mono- and multicrystalline silicon.
DSSC	Dye-Sensitised Solar Cell: A PV technology using dye molecules to absorb light.
EoL	End-of-Life: The stage when PV modules reach the end of their operational lifetime and require disposal or recycling.
EPEAT	Electronic Product Environmental Assessment Tool: A global ecolabel for sustainable electronics, including PV modules.
EPBT	Energy Payback Time
EPR	Extended Producer Responsibility: Policy requiring manufacturers to manage products at end-of-life.
EU REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals: EU regulation governing chemical safety.
FTO	Fluorine-Doped Tin Oxide: A transparent conducting oxide used in PV devices.
GWp	Gigawatt-peak: A unit of PV capacity under standard test conditions.
HJT	Heterojunction Technology: A high-efficiency silicon PV cell architecture.
IBC	Interdigitated Back Contact: A silicon PV cell design with all contacts on the rear side.
IEA	International Energy Agency: Global energy policy and analysis organisation.
IEA PVPS	IEA Photovoltaic Power Systems Programme: An international collaboration on PV research and deployment.
ITO	Indium Tin Oxide: A transparent conducting oxide used in PV devices.
KPI	Key Performance Indicator: Metrics used to measure progress toward objectives.
LCA	Life Cycle Assessment: A method for evaluating environmental impacts across a product's lifecycle.

LCOE	Levelised Cost of Electricity: The average cost per unit of electricity generated over a system's lifetime.
LMICs	Low- and Middle-Income Countries: Nations classified by income level according to World Bank criteria.
Mono-Si	Monocrystalline Silicon: A high-efficiency form of crystalline silicon PV.
OPV	Organic Photovoltaics: PV technology using organic semiconductors.
ODA	Official Development Assistance: Government aid promoting economic development and welfare in developing countries.
PCE	Power Conversion Efficiency: The percentage of sunlight converted into electricity by a PV device.
PSC	Perovskite Solar Cell: A next-generation PV technology based on perovskite materials.
PV	Photovoltaics: Technology that converts sunlight directly into electricity.
REN21	Renewable Energy Policy Network for the 21st Century: Global renewable energy policy network.
R2R	Roll-to-Roll: A manufacturing process for flexible PV devices using continuous printing.
TEA@SUNRISE	Transforming Energy Access at SUNRISE: UK Aid-funded programme accelerating clean energy access.
TCO	Transparent Conducting Oxide: A material that conducts electricity while allowing light to pass through, used in PV devices.
TW	Terawatt: A unit of power equal to one trillion watts.
WEEE	Waste Electrical and Electronic Equipment Directive: EU legislation governing recycling of electrical products.

Glossary of Terms

Circular Economy	An economic system aimed at eliminating waste and continually using resources through reuse, recycling, and design for disassembly.
Energy Payback Time (EPBT)	The time required for a PV system to generate the amount of energy used in its production.
Carbon Payback Time	The time required for a PV system to offset the greenhouse gas emissions generated during its manufacturing.
Critical Raw Materials (CRMs)	Materials essential for technology but with high supply risk due to scarcity or geopolitical concentration.
End-of-Life (EoL) Management	Processes for handling PV modules after their operational lifetime, including recycling and disposal.
Extended Producer Responsibility (EPR)	A policy approach making manufacturers responsible for the entire lifecycle of their products, including disposal.
Levelised Cost of Electricity (LCOE)	A metric that calculates the average cost per unit of electricity over a system's lifetime, including installation, operation, and disposal.
Life Cycle Assessment (LCA)	A systematic analysis of environmental impacts associated with all stages of a product's life.
Photovoltaics (PV)	Technology that converts sunlight directly into electricity using semiconductor materials.
Power Conversion Efficiency (PCE)	The ratio of electrical power output to solar power input for a PV device.
Roll-to-Roll (R2R) Manufacturing	A continuous process for producing flexible PV devices using printing techniques.
Transparent Conducting Oxide (TCO)	A material that combines electrical conductivity with optical transparency, used in PV cells.

1. Introduction

As the global energy system shifts toward greater electrification, renewable energy technologies such as solar and wind are rapidly becoming the dominant sources of power generation. Among them, solar photovoltaics (PV) have demonstrated exceptional progress, now representing the lowest-cost form of electricity generation in many regions due to consistent advances along the technology learning curve.

To meet both decarbonisation targets and universal energy access goals, the installed capacity of solar PV will need to expand dramatically in the coming decades. While the solar resource is virtually unlimited and the carbon footprint of PV is significantly lower than that of fossil fuels, concerns are emerging about the broader sustainability of how these technologies are manufactured, deployed, and managed over their full lifecycle.

This report evaluates these concerns across three interconnected pillars of sustainability: environmental, economic, and social. These dimensions are particularly salient for solar PV, where low-cost modules have often relied on coal-based manufacturing and labour practices that lack transparency or violate human rights.

Our analysis considers both incumbent technologies, including crystalline silicon (c-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), and emerging technologies, with a particular focus on perovskite solar cells (PSCs). These PSCs offer new opportunities for low-impact, decentralised, and flexible manufacturing. By assessing each technology platform against sustainability criteria, this report aims to identify critical risks, emerging opportunities, and areas where policy and investment can support a just, resilient, and environmentally responsible energy transition.

2. Overview of PV technologies

Photovoltaic technologies are commonly grouped into three broad categories or generations. The first generation consists primarily of crystalline silicon (c-Si) technologies, including both monocrystalline and multicrystalline silicon. These account for over 90% of the global market due to their relatively high efficiency, long-term stability, and well-established supply chains. They are widely deployed in residential, commercial, and utility-scale installations.

Second-generation technologies include thin-film systems such as cadmium telluride and copper indium gallium selenide. These offer advantages in terms of reduced material usage and flexibility but currently occupy only a small share of the market. Their adoption is limited by factors such as toxicity concerns, resource scarcity, and cost.

Third-generation, next-generation or emerging photovoltaic technologies include perovskite solar cells, organic photovoltaics, dye-sensitised solar cells and quantum dot-based devices. These aim to deliver high performance while reducing manufacturing complexity and energy input. PSCs and organic PV (OPV) technologies are currently the front runners amongst next-generation PV technologies, boasting high performance at relatively low cost and simple fabrication. While these emerging technologies promise high efficiency and design flexibility, they also introduce new material and sustainability considerations that are explored in detail in the following sections.

Emerging Technologies

The emerging market, or next-generation PV, comprises a range of new materials and designs including perovskite solar cells (PSCs), organic PV (OPV), and dye sensitised solar cells (DSSCs). These emerging platforms are being developed with the goals of reducing manufacturing costs, increasing efficiencies, utilising earth-abundant materials, and improving end-of-life prospects that are more conducive to a circular economy. In contrast to incumbent technologies that rely on high-energy processes and globalised supply chains, emerging technologies offer the potential for regionalised, lower-capex production models. This holds the promise of shortening supply chains, building energy resilience, reducing trade deficits and creating jobs.

Perovskite solar cells are the most widely researched among these, offering laboratory-scale power conversion efficiencies exceeding 26% and strong potential for tandem integration with silicon, potentially enabling commercial devices that surpass the Shockley-Queisser limit for single-junction cells. Silicon-perovskite tandem architectures are currently being developed by several leading manufacturers for rooftop and utility-scale applications where land area or module footprint is limited, and high efficiency is commercially valuable. However, tandems also introduce additional manufacturing complexity, cost, and technical barriers that currently limit their manufacturing readiness for decentralised energy access. In contrast, single-junction perovskite devices offer significant potential for scalable, low-temperature, low-cost manufacturing using abundant materials. Due to these factors, these devices may also better support distributed production in low- and middle-income countries, especially if solvent and material systems are further optimised for environmental and human safety. From a local manufacturing perspective, the lower capex, simpler process control, and reduced infrastructure requirements of single-junction perovskites make them potentially more appropriate for distributed manufacturing and skills transfer in LMIC contexts than tandem architectures, which remain capital-intensive and centrally scaled. As the market for PV modules grows, so does the opportunity for sector-specific module types, and we can expect to see perovskite modules deployed alongside silicon modules in the foreseeable future.

Organic photovoltaics (OPV) have also made important strides, with recent laboratory devices exceeding 19% efficiency. Companies such as Heliatek have achieved IEC 61215 and UL certification for commercial OPV modules. These devices use lightweight, flexible substrates and organic semiconductors, enabling applications in curved surfaces, buildings, and transport. OPV's compatibility with non-toxic solvent systems and low-temperature printing methods makes it attractive for niche, aesthetic or space-constrained applications where silicon is impractical.

Dye-sensitised solar cells (DSSCs) continue to show competitive performance under low-light indoor conditions, often outperforming other technologies in these settings. Their visual customisability and sensitivity to diffused light make them attractive for consumer electronics, indoor sensors, and IoT devices, although their scalability for outdoor energy applications remains limited.

Next-generation PV technologies provide an important opportunity to reshape solar supply chains, localise production, build resilience, and embed circular economy principles by design. Their differentiated characteristics offer unique advantages across application domains, even as their development trajectories continue to mature.

3. PV Deployment and Market Trends

Global cumulative installed photovoltaic capacity is reported to have exceeded 1.4 TWp by the end of 2023, with 1.58 – 1.64 TWp cited by some sources (Figure 1)[1]. In the same year, annual installations reached a record 420–460 GWp, marking one of the fastest years of growth in history[2]. This growth trajectory aligns with IEA forecasts anticipating over 5 TW by 2030 under current policy pathways[3].

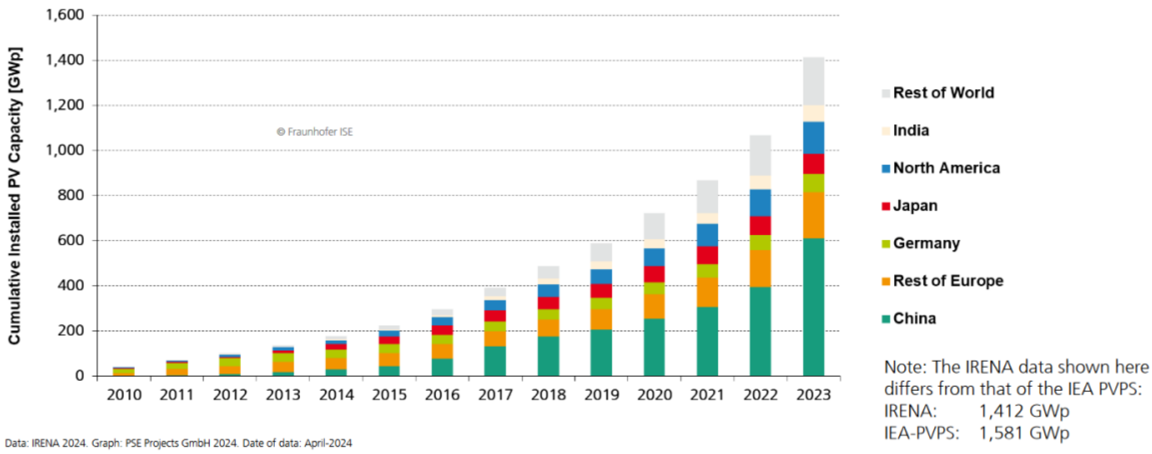

Figure 1 Global cumulative PV installation by region (source: Fraunhofer ISE[1]

Approximately 97% of PV modules shipped in 2023 were produced using crystalline silicon (c-Si). Monocrystalline silicon accounted for around 96%, while multi-crystalline silicon made up roughly 1%.[1] Thin-film technologies comprised the remaining ~3 %, with cadmium telluride (CdTe) as the only significant segment, while amorphous silicon (a-Si) and copper indium gallium diselenide (CIGS) have largely vanished from commercial production (

Table 1). In recent years monocrystalline Si wafer PV (mono-Si) has become the dominant technology while multi-crystalline Si wafer (multi-Si) technology is being phased out due to ongoing cost reduction of producing monocrystalline wafers via the Czochralski (Cz) process for more efficient PV modules (Figure 2). First Solar, a U.S. company, remains the dominant CdTe producer globally due to its early innovation in sub-$1/W module pricing and commitment to high-throughput manufacturing.[4] Figure 2 and Figure 4 illustrate the continued dominance of mono-Si and the marginal role of thin-film technologies over the past decades.

Table 1 PV Technology Market Shares in 2023 (Data from Fraunhofer ISE, 2024)

PV Technology	Installed Capacity (GWp)	Market share
Si wafer (total)	**489**	**97.4%**
Multicrystalline Si	4	0.80%
Monocrystalline Si	485	96.6%
Thin film (total)	**13**	**2.6%**
CIGS	0.57	0.11%
CdTe	12.38	2.47%
a-Si	0.12	0.02%
Total	502	100.0%

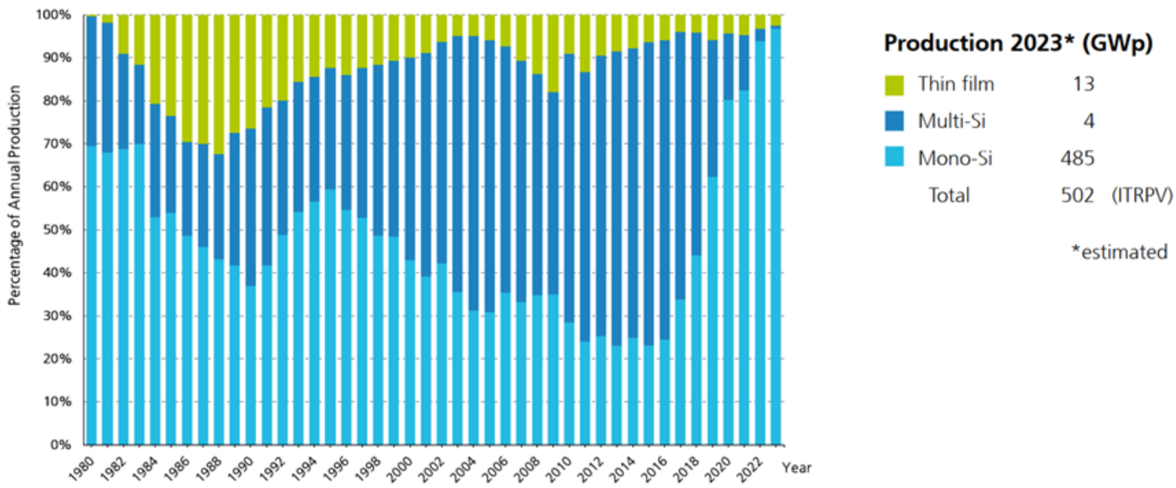

Figure 2 Global market share of PV technologies (source: Fraunhofer ISE[1])

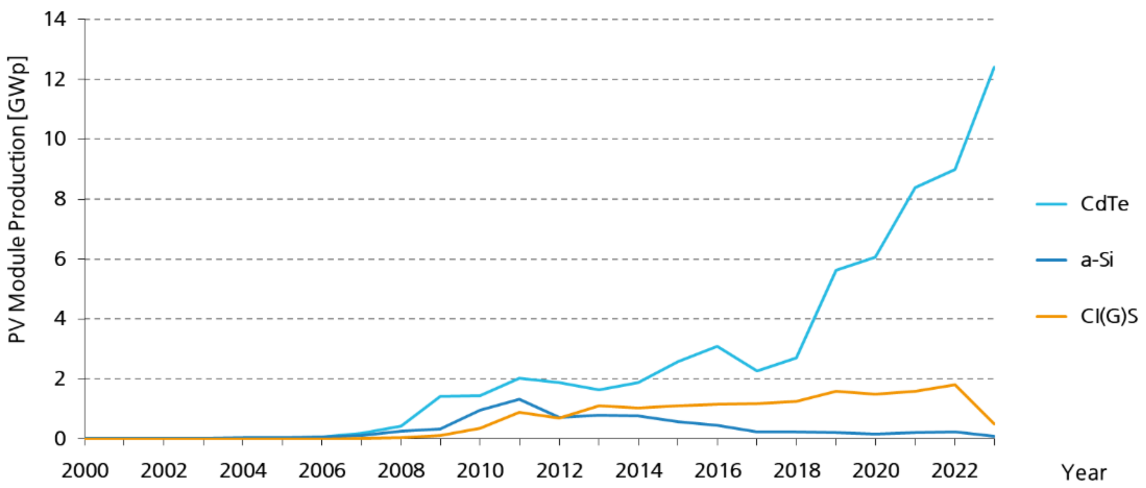

Figure 3 Annual Global PV Module Production for Thin-Film Technologies (2000–2022). CdTe production has increased significantly, while a-Si and CIGS have declined (source: Fraunhofer ISE[1]).

Approximately 99.6% of total PV capacity is grid-connected[5]. Off-grid systems, while increasing in absolute terms from ~500 MW in 2010 to ~6 GW in 2023, have declined in proportion from under 1% to ~0.4% globally[5]. In contrast, off-grid systems account for 7–8% of PV capacity installed in Africa, reflecting slower grid expansion and continued demand for standalone solutions (Figure 4)[6].

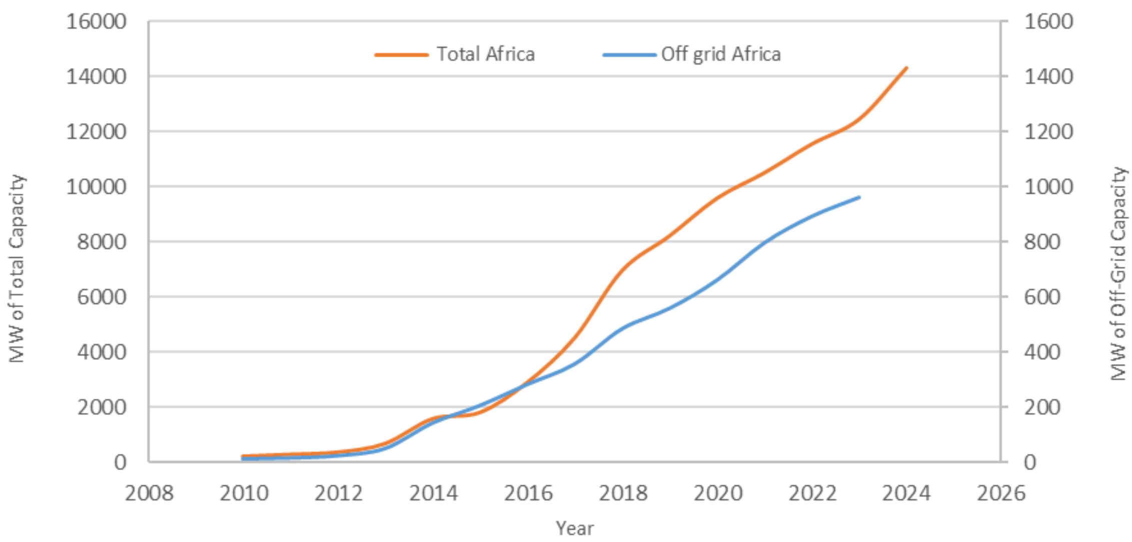

Figure 4 Grid and off-grid PV capacity in Africa (2008–2025). Data shown include both total installed capacity and the portion accounted for by off-grid systems[6].

Asia accounted for 94% of total PV module production in 2023, with mainland China leading with an 86% share. Europe, USA and Canada each contributed 2%, as shown in Figure 5. While these figures reflect manufacturing location, it is important to note that Chinese firms are also involved in module production operations outside China, including in Europe and North America, through direct ownership, joint ventures or outsourced production arrangements. For example, Chinese manufacturers such as LONGi and JinkoSolar have invested in production facilities in Vietnam, Malaysia, and the United States, and Chinese-owned companies have acquired or partnered with firms across Europe and North America to access markets and navigate trade barriers. According to the IEA and multiple industry reports, the share of Chinese firms in global module production, including overseas operations, exceeds 80%, highlighting their vertical integration and control over upstream and downstream segments of the PV value chain.[7] This complicates regional attribution and highlights China's strategic role across the entire global PV value chain.

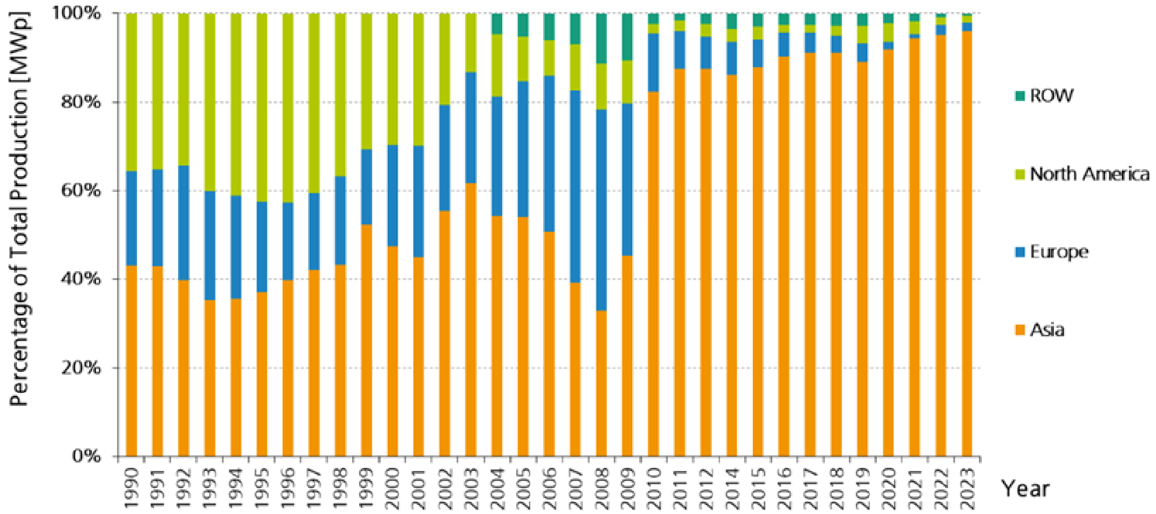

Figure 5 PV Module Production by Region (1990–2023). Percentage share of total MWp produced by region. Source: Fraunhofer ISE[1]

The dominance of monocrystalline silicon introduces several sustainability challenges, including the high embedded energy and greenhouse gas emissions associated with coal-intensive silicon processing, the significant geographic concentration of supply chains, especially in China, and a lack of diversification in manufacturing pathways that could improve resilience, transparency and circularity[8]. Meanwhile, the limited growth of off-grid PV undercuts global progress on energy access and inclusive development. These themes are explored in greater detail in subsequent sections assessing environmental, economic and social sustainability across both incumbent and emerging solar technologies.

4. Materials

The choice of materials in PV modules has significant impact on the overall sustainability of the technology. The following paragraphs outline the material composition of incumbent and emerging PV technologies, highlighting resource intensity and associated sustainability concerns.

Material selection affects not only upstream factors such as extraction, refining, and processing, but also downstream aspects including embedded energy, energy payback time, end-of-life recyclability, and circular economy potential. The materials used in incumbent technologies vary according to the device architecture. c-Si modules rely on high-purity silicon wafers, silver for electrical contacts, aluminium for frames, solar-grade glass substrates, and polymer encapsulants such as ethylene vinyl acetate. The production of silicon wafers is energy intensive and relies on international supply chains, including regions with known ethical and environmental risks. Thin-film modules based on cadmium telluride and copper indium gallium selenide require elements such as cadmium, tellurium, indium, and gallium, which are relatively scarce and geopolitically concentrated. These factors raise concerns about long-term availability, price volatility, and environmental sustainability. Understanding the material demands of current PV technologies is essential for developing circular economy strategies, mitigating supply chain risks, and ensuring responsible and ethical deployment at scale.

Third-generation technologies make use of a broader and more diverse set of materials, many of which are still being intensively researched. Perovskite solar cells typically employ metal halide perovskites based on lead or tin, combined with organic cations and halide anions such as iodide or bromide. These materials can be deposited using low-temperature, solution-based processes, making them attractive for low-cost and flexible applications. However, concerns remain around the toxicity of lead, the stability of the active layers, and the sustainability of solvents used during fabrication.

Table 2 summarises the material composition of key PV technologies, c-Si, CdTe and CIGS, and their associated costs and recycling yields per GW of module capacity. This comparison highlights the wide variation in materials used and their recoverability, with recycling yields ranging from 0 – 100%. For example, valuable and energy-intensive materials such as silver and indium appear in differing quantities across technologies, significantly influencing both cost and supply risk.

Table 2 Representative materials intensity per GWp of photovoltaic modules (STC)[8–12]

Technology	Category	Material	t/GWp
Si: mono PERC (glass-backsheet)	Glass	Front glass (≈3.2 mm)	37,990
	Active	c-Si wafer (≈130 μm)	1,449
	Metals	Cu ribbons and busbars	402
		Ag (metallization)	9.0
		Al frame	6,900
	Dopants	B, P (ppm level)	<<1
	Encapsulants and backsheet	EVA + PVF/TPT	5,123
Si — TOPCon (glass-backsheet)	Glass	Front glass (≈3.2 mm)	36,091
	Active	c-Si wafer (≈130 μm)	1,377
	Metals	Cu ribbons and busbars	382
		Ag (metallization)	9.0
		Al frame	6,555
	Dopants	B, P (ppm level)	<<1
	Encapsulants and backsheet	EVA + PVF/TPT	5,123
CdTe (glass-glass)	Glass	2 x 3.2 mm	86,304
	Active	Te	15.2
		Cd	13.39
	Metals	TCO (SnO_2)	456
		Ni	132
		Al	900
		Cu	2,987
Perovskite — Carbon electrode PSC	Glass	Cover glass	86,304
	Conductors	Carbon electrode	143,733
	TCO	FTO	10,036
	ETL	SnO_2 or TiO_2	456 or 972
	Active	Pb	2,331
		I/Br	3,298 / 620
		Cs	74.8
APT – ITO/Cu	TCO	ITO	4,419
	Metals	Cu electrode	2,987
		Ag interlayers	64
	ETL	SnO_2 or TiO_2	456 or 972
	Active	Pb	2,331
		Sn	1,561
		I/Br	3,298 / 620
		Cs	74.8
Si–Perovskite Tandem (2T, SHJ bottom)	Glass	Double glass	86,304
	Interlayer	Ultra-thin ITO	384
	Metals	Ag/Cu grids	3,496 / 2,987
	Perovskite top cell	Pb	2,331
		I/Br	3,298 / 620
	ETL	SnO_2 or TiO_2	456 or 972
	HTL	Spiro-OMeTAD	1,428

STC irradiance = 1000 W/m²; module efficiencies used: Mono-PERC 20.9%, TOPCon ≈ 22%, CdTe 18.4%; Tempered solar glass (3.2 mm) areal mass: 7.94 kg/m²; Glass-backsheet c-Si module mass: 14 kg/m² to convert composition shares[10]

These values should be interpreted as indicative, order-of-magnitude estimates based on representative module architectures and reported literature data. Actual material intensities vary with module efficiency, layer thickness, and design choices. The purpose of this comparison is not to prescribe specific architectures, but to illustrate relative material pressures, recovery opportunities, and potential circularity leverage points across technologies.

Supply bottlenecks for materials

Reliable access to affordable, high-quality photovoltaic modules is a prerequisite for scaling decentralised energy systems and delivering sustained energy access outcomes. While global PV manufacturing capacity has expanded rapidly over the past decade, this growth has not translated into uniformly resilient or accessible supply chains for low- and middle-income countries. Structural concentration of manufacturing, exposure to geopolitical and trade risks, and weak domestic distribution and regulatory capacity mean that availability, cost, and delivery timelines for modules and balance-of-system components remain highly variable across TEA@SUNRISE partner contexts. Understanding these supply-side constraints is therefore essential for realistic programme design, risk management, and the identification of targeted policy and investment interventions.

Current market

Of the raw materials used in current PV technologies, silicon metal, indium, gallium, germanium and borates are all defined as Critical Raw Materials (CRMs) by the EU due to their high supply risk.[13] Copper, cadmium, selenium, silver and tellurium are currently seen as having a lower supply risk.[14]

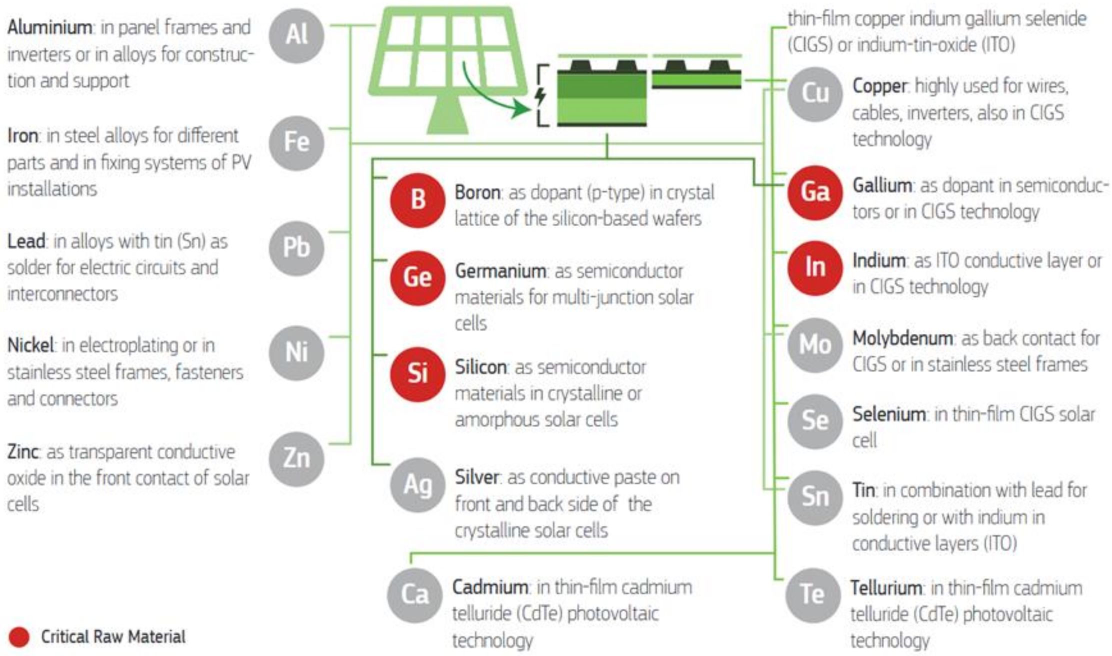

Figure 6 Raw materials used in solar PV technologies[13,15,16]

However, many forward-looking studies anticipate potential constraints across a broader range of elements. Elshkaki and Graedel point out that all current PV technologies are limited by a particular metal:[17,18] Silver used in bus bars for silicon-based technologies, tellurium for CdTe technology, indium for CIGS, and germanium for amorphous silicon. Valero *et al.* concluded that tellurium is the most critical, with cumulative demand from 2016 to 2050 projected to exceed known global resources.[19] Other high-risk materials include cadmium, copper, gallium, manganese, nickel, tin, and zinc. Silver availability is widely considered the most pressing materials challenge for the solar sector.[18] Elshkaki and Graedel recommended urgent efforts to identify alternatives to silver and other constrained elements. Substitution research includes development of conductive carbon materials, such as graphene, as lower-cost, more sustainable replacements. In 2024, cell production still required ~8.6 kt of silver (~28% of global supply) however industry pursues pathways to reduce silver consumption outlined in The International Technology Roadmap for Photovoltaics (ITRPV) which introduces a target for PV manufacturing to reduce silver consumption by 30-50% by 2030.[20] Key strategies include:

- Busbar-less designs (0BB) in high-efficiency cell architectures such as HJT and TOPCon, which significantly cut silver usage while maintaining performance.
- Copper plating and alternative metallization to replace silver in contacts, reducing reliance on CRMs.
- Process optimization to improve silver utilization efficiency and minimize waste during screen printing.

The supply of polysilicon also poses challenges, with price volatility and high geographic concentration raising concerns about supply security and resilience. Approximately 70% of global polysilicon production currently occurs in China, and although some diversification is underway, the global supply chain remains vulnerable to geopolitical risks and policy shifts.

Emerging technologies

Emerging technologies such as PSCs face their own material bottlenecks. Critical elements potentially affecting the scalability of perovskite PV include indium, tin, gold, silver, lithium, magnesium, niobium, caesium,[10] and fluorine-doped tin oxide (FTO), a widely used transparent conducting material. Importantly, flexibility in perovskite device architectures allows for the use of alternative materials and design choices, which may help reduce exposure to material criticality risks. A schematic overview of common PSC architectures and their respective material requirements is shown in Figure 7.

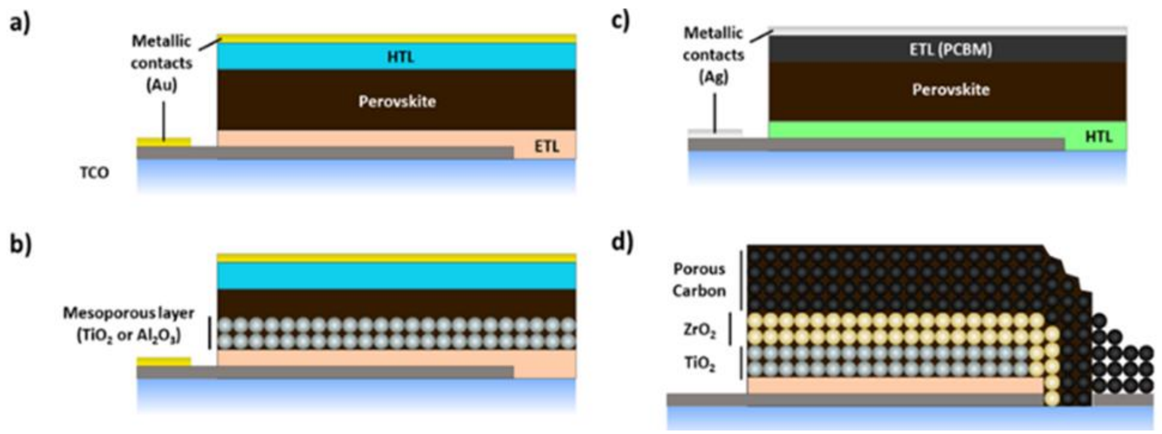

Figure 7 Perovskite solar cell configurations. Some of the most common materials employed are depicted. a) N-I-P planar configuration; b) N-I-P mesoporous configuration; c) P-I-N inverted configuration; and d) triple stack configuration (source: Charles et al.[21])

Indium is one of the most critical elements for the PV industry and has been classified as a CRM by the EU. Indium is used in CIGS panels and as ITO (indium tin oxide) in CdTe panels and some types of next-generation solar as a transparent conducting electrode. There are several motivations to find a substitute for indium. Production is concentrated in China (48%) which has high domestic demand and a history of imposing export restrictions. Recovery of indium from end-of-life products is almost unheard of. And finally, ITO is also subject to registration under EU REACH and conflict minerals regulations.[21] While alternatives such as fluorine-doped tin oxide (FTO) are used in rigid devices and may ease future tin demand, ITO remains the standard for flexible perovskite devices due to its superior electrical performance and compatibility with low-temperature processing. Substitution and material recovery remain active areas of research.

Tin may also be constrained, with cumulative demand from PV alone projected to surpass known reserves by 2050.[19] Global tin production is concentrated in China (35%), Indonesia (27%), and Myanmar (10%). While some tin is used in perovskite absorbers, the primary contribution to PV-related tin demand is expected to arise from TCO materials such as FTO. Gold, used for contact electrodes in high-efficiency perovskite cells, has limited reserves and is subject to conflict mineral regulations. Known reserves for gold could be fully depleted by 2035.[22] Silver, used as a substitute for gold in many PSCs, is itself a constrained material with reserves potentially depleted by 2037 under clean energy demand projections.[21] Caesium is also flagged as a potential constraint for TW-scale perovskite deployment due to its low abundance and limited recycling infrastructure, particularly in device designs that rely on Cs-containing absorbers or interlayers.[10]

Encouragingly, many of these materials can be substituted or recovered. For example, carbon electrodes have successfully replaced evaporated gold contacts in PSCs without significant loss in performance. Beynon *et al*. demonstrated a fully solution-processed, roll-to-roll printed PSC with flexible carbon electrodes achieving a certified power conversion efficiency (PCE) of 10.9%, compared to a reference gold-contact device with a PCE of 12.1%.[23] This relatively small performance gap highlights the promise of scalable, lower-impact architectures for commercialisation. While further efficiency improvements are needed, these can be achieved through continued advances in material interfaces, formulation, and device design.

Architectural innovation also offers pathways to reduce critical material reliance. For example, Power Roll's printed solar films eliminate the need for indium and gold by using a micro-grooved capacitor structure in place of traditional transparent electrodes, potentially enabling low-cost roll-to-roll manufacturing of lightweight, flexible solar modules. Such designs open new application spaces while reducing supply chain vulnerabilities. Furthermore, circular strategies such as device refurbishment, component reuse, and materials-focused recycling have demonstrated pathways to recover high-value materials and reduce environmental impact, potentially making PSCs the most sustainable PV technology to date.[10,21]

Hazardous materials in panels

Current market

Materials found in market dominant silicon technology are largely non-hazardous, except for lead in the conductive ribbons used to connect cells. These ribbons are typically copper coated with an alloy of silver and lead. A 60 cell module contains about 12g of lead (~ 20 mg/W).[24] However, electrically conductive adhesives are finding their way into PV modules, such as lead-free Heterojunction (HJT) and Interdigitated Back Contact (IBC) cells.

Approximately 2.5% of modules use cadmium, most notably those produced by First Solar. But in contrast to the silicon PV industry, CdTe modules have long been designed for recycling. "Early on in the game, they (First Solar) decided to implement full-scale recycling, so they really understand the process end-to-end," Ben Kroposki, NREL Director of the Power Systems Engineering Center, said. "Only *now* are the crystalline manufacturers realizing they have to get into this recycling game and start to think about that."[25] This attention to recycling infrastructure and process means leaching of cadmium from modules to the environment is negligible.

Emerging technologies

Several studies have addressed the possible environmental consequences of lead release from PSCs and have found that the risk to environmental and human health is low but still non-negligible.[26] PSC waste is classified as hazardous because of the solubility of the lead contained within it. There are understandable concerns about risks for workers during manufacturing and recycling, and the possible detriments on human health if modules are damaged or exposed to rain resulting in lead accumulating in the environment. However, life cycle assessments (LCAs) of PSCs have found that the potential impact of lead is not severe enough to necessitate its exclusion, with toxicity of grid energy far outweighing any potential impact from lead emissions.[21]

If modules are incorrectly managed, the most significant potential impacts from lead will occur at end-of-life (EOL). But LCA has shown that proper EOL infrastructure and handling will mean lead is only a minor constituent of all life-cycle impacts.[21,27] Tin can be used to replace lead, but its ecotoxicity is far worse than for lead. Other possible alternatives include indium, gallium, bismuth, and antimony. However, these metals are all designated as critical raw materials (CRMs), with long-term supply concerns that could hinder deployment to the scale needed to achieve climate goals.[21]

An alternative strategy to substitution of Pb to mitigate potential impacts in PV lifecycles is sequestration. Numerous strategies have been proven to prevent lead leakage from modules, such as using chelating agent additives;[28,29] interface modifiers with hydrophilic groups,[30,31] and including lead-absorbing materials within encapsulation materials.[32–35] Brief comparisons of these approaches are given in Table 3.

Table 3 Strategies for Lead (Pb) Capture in Perovskite Solar Modules

Strategy	Mechanism	Effectiveness	Notable Advantages
Chelating additives	Capture Pb^{2+} at buried interface	Passivates defect sites; enhances stability and PCE	Integrated chemically, improves performance and durability
Interface modifiers	Lewis-base binding at interfaces	Reduces Pb leakage and defect density	Dual function: Pb capture + defect healing, effective under humidity/heat stress
Encapsulation absorbers	Scavenge Pb on module surfaces	>90–99% lead capture	Simple add-on layers, compatible with existing encapsulation processes

Many parallels can be seen between First Solar's manufacture of CdTe modules and what a perovskite solar supply chain might look like. First Solar uses cadmium and tellurium sourced as byproducts of zinc and copper refining, not requiring additional mining. Modules are designed for ease of integration, supporting lower system costs beyond simply module cost, and >90% of both semiconductor material and glass can be recycled[36]. Whilst cadmium is hazardous, its use in First Solar's modules has been well managed through a combination of module design and the business model of deployment and takeback at end of life to ensures appropriate waste management which recovers cadmium preventing environmental emissions.

5. Supply bottlenecks for modules

The deployment of decentralised renewable energy systems under TEA@SUNRISE is shaped not only by demand and financing conditions, but by persistent supply-side bottlenecks across global, regional, and local value chains.[13] These bottlenecks affect the availability, cost, and timing of key system components, with direct implications for delivery risk, affordability, and market development.

A primary constraint arises from the structure of global manufacturing. Production of core decentralised energy technologies, PV modules and associated power electronics, remains highly concentrated geographically and organisationally. While this concentration has enabled substantial cost reductions through economies of scale and learning effects, it has also increased exposure to external shocks, including trade policy changes, geopolitical tensions, and disruptions to international transport and logistics. For TEA@SUNRISE partner countries, which generally lack domestic manufacturing capacity for these components, this results in a structural dependence on imported equipment and limited influence over supply allocation during periods of high global demand.

International logistics and trade processes introduce additional bottlenecks. High and volatile freight costs, port congestion, customs clearance delays, and inconsistent application of tariffs or non-tariff barriers can materially affect delivery timelines and final system prices. These challenges are particularly acute for landlocked countries, fragile contexts, and remote regions, where infrastructure constraints compound logistical risks. Smaller developers and off-grid service providers are often least able to absorb such shocks, given limited working capital and weaker bargaining power with suppliers.

At the domestic level, distribution and market structure further shape effective supply availability. In many TEA@SUNRISE countries, component distribution networks are fragmented, with variable product quality and inconsistent access to certified equipment. Limited testing capacity, weak enforcement of standards, and slow or opaque regulatory approval processes can act as de facto supply bottlenecks even where physical stock is available in-country. These constraints increase project uncertainty, raise transaction costs, and undermine confidence among investors, implementers, and end-users.

Taken together, these factors indicate that supply bottlenecks are not temporary disruptions but a structural feature of decentralised energy markets in low- and middle-income countries. For TEA@SUNRISE, this necessitates explicit recognition of supply-side risks in programme design, realistic delivery timelines, and proportionate mitigation measures to preserve value for money.

Mitigation considerations

Consistent with FCDO's risk-based and proportionate approach to programme delivery, the impacts of supply bottlenecks can be managed through targeted design and implementation measures, even where underlying drivers lie beyond direct programme control.

Key mitigation options include:

- **Diversification of suppliers and procurement routes**, reducing exposure to disruptions associated with single manufacturers, markets, or logistics corridors.
- **Flexible and phased implementation planning**, allowing timelines and system specifications to adapt to evolving supply conditions without undermining overall objectives.
- **Support for local distribution, standards, and quality-assurance capacity**, reducing delays linked to certification, customs clearance, and sub-standard equipment.
- **Risk-adjusted budgeting and contingencies**, particularly for shipping, storage, and working capital requirements, to maintain affordability and value for money under volatile market conditions.

While these measures do not eliminate global supply risks, they can materially reduce their impact on delivery reliability, market participation, and long-term sustainability.

6. Environmental impacts of production

Decentralised renewable energy systems supported under TEA@SUNRISE deliver substantial environmental benefits over their operational lifetimes, primarily through the displacement of fossil-based energy sources. However, these benefits are accompanied by upstream environmental impacts associated with the extraction of materials and the manufacturing of system components. Transparent and proportionate assessment of these impacts is important for policy coherence, environmental integrity, and alignment with FCDO Environmental Sustainability and Climate Change commitments.

Current market

The production of photovoltaic modules and associated components is energy-intensive, with life cycle greenhouse gas (GHG) emissions dominated by manufacturing processes rather than system operation. Emissions arise primarily from material processing, high-temperature manufacturing stages, and electricity consumption within industrial facilities. For crystalline silicon (c-Si) systems, wafer production and module assembly account for most embedded emissions. Panel manufacturing alone contributes over half of total lifecycle emissions, typically exceeding 30 gCO_2-eq/kWh, with upstream module production representing approximately 60–80% of total lifecycle emissions. Balance-of-system components typically contribute 10–20%, while inverters, installation, and operational activities each contribute less than 10%.[37,38,41]

In addition to energy demand, crystalline silicon PV manufacturing involves extensive use of hazardous chemicals and high-purity process water across purification, wafering, texturing, cleaning, and doping steps. Processes such as polysilicon refinement, wet chemical etching, surface passivation, and metallisation rely on acids and bases including hydrofluoric acid, nitric acid, hydrochloric acid, potassium hydroxide, and a range of dopant and carrier gases. These operations generate chemically contaminated wastewater, spent etchants, and sludge streams that require complex treatment and strict regulatory oversight. While mature manufacturing regions typically operate robust chemical management and effluent control systems, the environmental footprint, water intensity, and occupational health requirements of silicon manufacturing remain significant contributors to lifecycle impacts and present non-trivial barriers to localisation of upstream manufacturing in emerging economies.

Thin-film technologies generally exhibit lower embodied carbon due to lower material intensity and reduced processing temperatures. Life cycle assessment studies indicate that monocrystalline silicon systems emit approximately 38 gCO_2-eq/kWh, multi-crystalline silicon around 40 gCO_2-eq/kWh, copper indium gallium selenide (CIGS) approximately 33 gCO_2-eq/kWh, and cadmium telluride

(CdTe) as low as 20 gCO_2-eq/kWh, assuming 30-year lifetimes and typical European installation conditions.[8,39,40] These differences reflect both manufacturing energy intensity and materials usage.

The carbon intensity of PV manufacturing depends strongly on the energy mix of the producing region. Modules manufactured in coal-dominated regions, including parts of China, carry substantially higher embedded emissions. When deployed in low-carbon grids, this can lead to CO_2 payback times approaching 8–10 years, whereas manufacturing in regions with cleaner electricity and deployment in higher-carbon grids can reduce payback times to less than one year. This disparity highlights the importance of manufacturing location and electricity decarbonisation in achieving system-level emissions reductions.

Beyond carbon emissions, material extraction and processing introduce additional environmental pressures. PV systems, batteries, and power electronics rely on minerals and metals including silicon, aluminium, copper, lithium, nickel, and cobalt. Mining and refining activities can be associated with land disturbance, water use, pollution, and governance challenges, particularly where regulatory oversight is weak. Although these impacts are often geographically remote from TEA@SUNRISE programme areas, they remain part of the global environmental footprint of decentralised energy value chains.

End-of-life management is an emerging environmental consideration as decentralised energy markets expand and increasing volumes of modules, batteries, and electronic components reach the end of their service lives. In many TEA@SUNRISE countries, formal recycling and waste management systems remain limited. Without proactive consideration of durability, repairability, and disposal pathways, environmental burdens may be transferred to local contexts, partially offsetting operational environmental benefits.

Overall, while the environmental impacts of production are non-negligible, they do not undermine the strong net environmental benefits of decentralised renewable energy relative to fossil fuel alternatives. Instead, they highlight the importance of lifecycle-informed planning, responsible procurement, and proportionate mitigation aligned with FCDO climate and sustainability objectives.

Mitigation considerations

In line with FCDO Environmental Sustainability and Climate Change requirements, environmental impacts associated with technology production are best addressed through a lifecycle-aware and proportionate mitigation approach.

Relevant mitigation measures include:

- **Lifecycle-informed technology selection,** favouring components with longer operational lifetimes, improved efficiency, and lower embodied emissions where feasible.
- **Responsible procurement practices,** including engagement with suppliers that demonstrate compliance with recognised environmental standards and increasing use of low-carbon electricity in manufacturing.
- **Design for durability, repair, and maintenance**, reducing premature failure and replacement rates, particularly for batteries and power electronics.
- **Early consideration of end-of-life pathways,** including modular designs and partnerships that enable recycling or safe disposal as domestic systems develop.

While TEA@SUNRISE cannot directly control upstream manufacturing impacts, integrating these considerations strengthens environmental credibility, aligns deployment with net-zero objectives, and supports sustainable, climate-resilient development outcomes.

Emerging market

It is important to note that currently most life cycle assessments (LCAs) of PSC technologies are based on laboratory-scale devices and do not fully capture the impacts of large-scale production. As the technology moves towards commercialisation, it is essential to develop LCAs grounded in primary data from industrial-scale processes to provide more accurate evaluations of energy use, emissions, and circularity potential. The leading contributions to production costs and embodied carbon of lab-scale perovskite solar cells were recently found by Tian and Stranks to include:[27]

- Transparent conductive oxide (TCO) substrates used as electrodes
- Gold contacts
- Energy-intensive annealing process required to deposit charge-transfer semiconductor materials films and thermal deposition processes.

TCO substrates account for 40-60% of the total cost of a perovskite solar cell. The high-temperature annealing method usually needed to deposit semiconductor oxide films onto the TCO can use up to 74% of the energy consumed in manufacturing some devices. Therefore, finding efficient means of recovering the TCO and the semiconductor films would have a substantial impact on the cost and embodied energy of the devices.[26] Certain architectures of next-generation solar, such as that developed by UK company Power Roll, do not use a transparent conducting electrode.

Gold dominates the environmental impact of PSCs due to its high production impacts, energy intensity associated with its deposition via evaporation, and low deposition efficiency of this process. The same is true when platinum is used in its place. Silver and carbon both have lower embodied impacts than gold, but silver still contributes considerably to overall production impacts due to energy consumption in its deposition. However, carbon may represent a lower impact electrode option with R2R solution deposition recently demonstrated[21,23]

Solvent selection represents an additional and often underappreciated contributor to the environmental and health impacts of emerging PV manufacturing.[21,37] Many high-performance perovskite and organic semiconductor formulations rely on polar aprotic or halogenated solvents with high toxicity, volatility, and regulatory burden, increasing occupational health risks, solvent recovery costs, and lifecycle environmental impacts. Solvent losses during coating, drying, and cleaning can dominate VOC emissions and contribute significantly to cumulative energy demand when abatement and recovery systems are required. Transitioning toward low-toxicity, bio-derived, or easily recoverable solvent systems, alongside closed-loop solvent recycling and formulation optimisation for high solids loading, offers a major opportunity to reduce embodied impacts while improving manufacturability and regulatory compliance. Embedding green solvent selection early in scale-up pathways is critical to ensure sustainability advantages of emerging PV technologies translate from laboratory demonstrations into industrial reality.[37,38]

Despite these advances, the environmental performance of PSCs at commercial scale remains an open question. Continued improvement in device stability, yield, and processing efficiency must be coupled with rigorous LCA studies using real-world data from manufacturing lines. This is particularly important for understanding trade-offs between different architectures, processing choices, and end-of-life recovery routes. As the field progresses, these insights will be essential for validating the sustainability advantages of PSCs relative to incumbent PV technologies.

OPV manufacturing typically relies on ambient or low-temperature solution processing, avoiding energy-intensive steps such as vacuum deposition or high-temperature annealing. This inherently reduces the embedded energy of OPV modules compared to conventional and even some emerging PV technologies[39,40]. However, the environmental profile of OPVs is strongly dependent on material choices, particularly the nature of the active layer and interfacial materials, as well as solvent use during processing. Some high-performance donor or acceptor molecules are synthesised through multistep processes involving toxic reagents, which can offset benefits gained through low-energy processing. In addition, halogenated solvents, commonly used for achieving optimal film morphology, are associated with health and environmental hazards[41]. Progress is being made toward greener solvent systems and scalable green chemistry approaches, but widespread industrial adoption remains limited.

The lightweight nature of both flexible PSCs and OPV can potentially reduce transport-related emissions and may offer advantages in embodied carbon for certain applications such as building-integrated PV (BIPV) or consumer electronics. End-of-life management for OPV is still in its infancy. Although many of the materials used in OPVs are inherently more environmentally benign, the diversity of organic compounds and encapsulation materials may pose challenges for recycling. Designing for disassembly and the use of recyclable or biodegradable needs to be advanced to maximise the sustainability of OPV technology.

7. Ethical impacts of production

Current market

The solar value chain is typically divided into four main parts: upstream, midstream, downstream, and auxiliary/ancillary or supporting. Upstream activities of silicon PV manufacture are the most concentrated geographically, have the highest barriers to entry and are those most strongly linked to the practice of forced labour. Activities encompass extraction of raw materials such as quartzite (silicon), silver, aluminium and coal, as well as the production of metallurgical grade silicon, solar-grade polysilicon and silicon ingots. The processing steps within these upstream activities all require large amounts of energy to enable the high temperatures and are the reason for the coal extraction which is often used in captive power plants to drive these co-located processes.

Two regions within China have become focal points for this activity: Xinjiang in the Northwest of China and Jiangsu in the Northeast. Of the two, Xinjiang has greater coal reserves and has produced the greatest growth in upstream PV production due to the development of the Zhundong Coal Power Base and the associated low energy prices. Within the Xinjiang Uyghur Autonomous Region (XUAR) there are credible first-hand reports of forced labour, coercive recruitment, intimidation, restrictions on movement, surveillance, and political indoctrination. Several recent reports have highlighted evidence of forced labour in XUAR by the government of the People's Republic of China.[42–45] Solar supply chains are especially susceptible because the XUAR produces approximately 25% of the world's polysilicon. Crawford and Murphy found 11 companies engaged in forced labour transfers, four additional companies located within industrial parks that have accepted labour transfers, and 90 Chinese and international companies whose supply chains are affected.[42] Recent years have witnessed a decline in the percentage of polysilicon produced in the XUAR amid international efforts, but most globally-manufactured solar modules retain some exposure to the XUAR through the upstream activities. PV manufacturers have introduced module traceability to comply with international regulations but further progress on transparency in supply chains is still needed.

Quite simply, our industry's work to power the energy transition and enable the fight against climate change does not serve as credits to offset its social and human rights obligations.

First Solar CEO Mark Widmar

Recent audits show that ethical risks are not confined to silicon supply chains. In 2023, First Solar disclosed that subcontractors at its Malaysian CdTe module manufacturing site engaged in practices such as charging recruitment fees, retaining passports, and withholding wages. The company has since reimbursed affected workers, returned passports, capped working hours at 60 per week, and committed to ongoing audits and remediation.[46]

This case illustrates that even firms with strong environmental credentials can face social compliance challenges, underscoring the need for robust due diligence and continuous monitoring across all PV technologies. Policy frameworks should therefore mandate transparent labour practices and independent audits across all PV supply chains, including thin-film technologies, to ensure that sustainability encompasses both environmental and social dimensions.

> ***What First Solar has done is the critical due diligence that all companies need to do around the world to ensure they are identifying and remediating forced labor in their supply chains. It does happen, and companies have to be on the lookout for it.***
>
> *Laura T. Murphy, professor of human rights and contemporary slavery at Sheffield Hallam University*

The international community is beginning to take note of China's forced labour issues. The US introduced the Uyghur Forced Labour Prevention Act in 2021, and the EU is considering similar policies. Failing to shift away from suppliers with any connection to the XUAR could therefore impede the industry's development.[43] Despite the focus on China's dominance in polysilicon production it's interesting to note that existing polysilicon production outside of China amounts to approximately 80 GW of annual production, more than either the EU or the USA installed in 2024, and 100 times greater than that installed in Africa in 2023. With a further 60 GW soon to be commissioned in Oman and India many markets will be able to source polysilicon free from XUAR inputs but must develop ingot, wafer and cell manufacturing to do so.

Global polysilicon production from the XUAR has steadily declined—from about 45% in 2020 to 35% by 2022, reaching below 25% as of around 2024.[42] This declining share of production from XUAR signals progress toward reducing exposure to forced-labour risks in solar supply chains. This trend strengthens the feasibility of compliance with emerging regulations such as the U.S. Uyghur Forced Labor Prevention Act and anticipated EU due diligence laws, which require traceable, ethically sourced inputs. However, diversification alone is not sufficient; governments and industry must pair supply chain shifts with mandatory transparency standards, independent audits, and procurement policies that reward verified low-risk sources. These measures will ensure that ethical improvements keep pace with rapid PV capacity growth and avoid reputational or trade risks for manufacturers and developers.

The manufacture of cells, module assembly and production of ancillary system components such as cables and inverters constitutes the **midstream** part of the solar value chain. Some of this remains linked to the XUAR but in general this sector is more geographically diffuse and is characterised by lower entry barriers and high competition, resulting in lower profit margins.

Even with separation from the XUAR, ethical concerns remain that threaten the sustainability of solar development and hinder the realisation of a just energy transition. Employment for local communities is often limited, and they may be adversely impacted by localised environmental and social effects. Furthermore, the energy generated may not reach the local community, failing to address their energy access needs and revenues from the electricity generated flow to investors rather than the local citizens.

Installation, operation, maintenance, dismantling and disposal constitute the **downstream** parts of the solar value chain. Given the ubiquity of solar PV this sector is yet more geographically diffuse, with high competition. Margins can be very low, with companies at times depending on subsidy programmes. The downstream activities are those most closely linked to the end-user.

Solar electronic waste holds economic value, thus the implementation of robust recycling processes for end-of-life panels is important. However, labourers in the solar waste chain can experience unequal treatment depending on whether they work in formal recycling systems or informal and often hazardous dismantling and disposal sectors.[47] Disparities shaped by social hierarchies and weak regulatory enforcement result in marginalised communities overrepresented in the informal sector and thus facing health and economic risks. This raises concerns about safety, justice, regulation, and inclusion in this part of the solar value chain.[47] These structural weaknesses in incumbent supply chains underline the strategic opportunity for next-generation PV to embed ethical sourcing, transparency, and distributed manufacturing models from the outset rather than retrofitting compliance later

Emerging market

If next-generation solar is to address the principal ethical concerns of silicon PV, it is by avoiding the extraction and processing of materials in the XUAR. Next-generation solar materials are distributed widely, but to avoid a first-mover advantage, such as that seen within the XUAR, routes to commercialisation must be demonstrated in multiple locations. Research conducted to date suggests that next-generation solar plants do not need to match the size of semiconductor factories to be competitive, potentially leading to distributed local manufacture, perhaps serving local markets with the creation of rewarding jobs.

Any ethical concerns associated with the midstream and downstream parts of the solar value chain may remain without careful planning. An example would be disposal of perovskite modules containing water soluble lead; if this were to happen it would pose a significant environmental threat and could severely jeopardise the sustainability of perovskite modules. Considering end-of-life in the choice of materials, module design and delivery business model can address this risk, turning it into an advantage by reusing the valuable materials in future modules.

As a final comment, the combination of silicon with perovskites as tandem modules holds a great deal of promise for higher efficiency, lower cost modules. If these are to be delivered for a just energy transition it is imperative that the ethical sustainability of silicon PV is addressed as we also develop new, ethical methods of manufacturing next-generation solar.

8. Waste and end-of-life issues

Current market

Most photovoltaic modules reaching end-of-life (EOL) today are landfilled rather than recycled. Establishing material circularity for crystalline silicon (c-Si) PV remains challenging due to "linear lock-in", where manufacturing is optimised for performance and longevity, but not for disassembly or material recovery. Current recycling efforts focus mainly on high-value, easily recoverable components such as aluminium frames and copper wiring. However, glass is often downcycled and photoactive layers remain difficult to access due to encapsulants and laminates that resist separation.

Two main recycling pathways exist: direct reuse of functional components such as silicon wafers, or complete separation and repurification of materials for re-manufacture. Recovered silicon offers substantially lower environmental impacts than virgin material, with life-cycle emissions of around 2.85 kg CO_2-eq kg^{-1} compared to 9.02–9.32 kg CO_2-eq kg^{-1} for virgin silicon from quartz. However, wafer fragility, high damage rates during delamination, contamination, and legacy designs that resist disassembly limit recovery yields and often necessitate energy-intensive post-processing, reducing economic viability.

Environmental performance varies with the recycling method. Mechanical processes can save approximately 680 kg CO_2-eq per tonne of modules processed, nitric acid-based chemical recycling up to 1460 kg CO_2-eq t^{-1}, and green solvents such as dimethyl isosorbide around 978 kg CO_2-eq t^{-1}. High-purity processes, such as the ROSI method, can achieve around 1 t CO_2-eq savings per tonne. Despite these benefits, cost remains a critical barrier: recycling c-Si PV has been estimated to cost 9.28 USD m^{-2} (including externalities), while recovered materials are worth about 13.60 USD m^{-2}. The economics depend strongly on recovery yields and purity, and in the absence of regulatory drivers, landfill remains the dominant EOL route.

The mismatch between mass and value further complicates recovery economics. Glass and steel account for most of the mass, but critical materials such as silver and copper are present only in small quantities, although their extraction from ore is resource-intensive. This "sustainability value" supports the case for advanced recovery processes, but low concentrations and declining use of certain metals (for example, silver use in PV has fallen by ~80 % since 2010) make separation economically challenging without design-for-recycling standards and policy incentives.

Emerging market

Perovskite solar cells (PSCs) and other next-generation PV technologies offer opportunities to embed circularity from the outset[21]. Recovering high-value components such as lead, transparent conductive oxide (TCO) substrates, and charge-transport layers could reduce manufacturing costs and waste generation while lowering environmental impacts[26]. Life-cycle modelling suggests that recycling materials in PSCs could reduce primary energy consumption and life-cycle greenhouse gas emissions by over 70 %, improving energy payback times significantly. In optimised architectures, recycled PSC modules could achieve an energy payback time as low as 0.09 years and a greenhouse gas emission factor of 13.4 g CO_2-eq kWh^{-1}, outperforming even market-leading c-Si modules (1.3–2.4 years, 22.1–38.1 g CO_2-eq kWh^{-1})[27].

These estimates are based largely on laboratory-scale devices and should be validated with primary industrial data as the technology approaches commercialisation. Valadez-Villalobos *et al.* (2024) emphasise that optimising device configurations, considering real-world degradation pathways, and integrating recovery methods into manufacturing are essential to achieving both economic and environmental viability. Designs that avoid scarce materials, such as architectures not requiring indium-based TCOs or noble-metal electrodes, could further enhance circularity. For example, UK-developed printed perovskite modules with carbon electrodes eliminate the need for evaporated gold, enabling low-cost roll-to-roll processing compatible with large-scale recycling[21].

Resource use intensity

Resource use intensity is a defining characteristic of photovoltaic systems and the electricity they generate, reflecting both the scale of material inputs and the specificity of the resources required. PV technologies require large quantities of bulk materials such as glass, aluminium, and steel, alongside smaller but critical quantities of high-value and scarce elements including silver, indium, and tellurium. While the mass of these critical materials is small relative to the total module weight, their extraction often involves high embodied energy, significant environmental impact, and in some cases supply chain risks due to geographic concentration of production. For example, producing 1 MW of monocrystalline silicon PV may require 25–30 kg of silver and over 3 tonnes of aluminium, while CIGS and CdTe systems have lower silver demand but higher reliance on indium, gallium, or tellurium. These material intensities translate into a clear “resource footprint” for PV electricity, which is typically lower in operational phase impacts than fossil generation but is front-loaded during manufacturing. Consequently, strategies to improve material efficiency, reduce reliance on critical raw materials, and enhance recovery rates at end-of-life are central to lowering the overall resource intensity of PV electricity and ensuring its long-term sustainability.

9. Legislation and Regulation

Current market

Legislative and regulatory frameworks governing photovoltaic (PV) manufacturing, deployment, and end-of-life (EOL) management vary widely across jurisdictions, with significant gaps in coverage, particularly in many Official Development Assistance (ODA)-eligible countries. In established PV markets, extended producer responsibility (EPR) schemes and environmental performance standards are the primary policy levers for improving sustainability. Within the European Union (EU), the Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU) mandates that PV modules placed on the market after 2012 must be collected and recycled at EOL, with producers financing these activities. The EU Circular Economy Action Plan and revisions to the Ecodesign Directive are introducing requirements for design for disassembly, modularity, and reparability, aligned with broader "right-to-repair" legislation. These provisions are directly relevant to addressing the end-of-life challenges discussed earlier in this report, particularly the difficulty of recovering high-value materials from modules optimised for durability rather than disassembly[48,49].

Outside the EU, several countries have implemented targeted PV EPR frameworks. Japan requires PV manufacturers to fund collection and recycling under its Home Appliance Recycling Law, while Australia's Solar Panel Product Stewardship Scheme is transitioning from a voluntary to a mandatory recycling target regime. In the United States, regulation is state-led: Washington requires manufacturers to submit approved PV recycling plans, and California regulates PV modules under hazardous waste provisions. However, major manufacturing and deployment centres such as China and much of Southeast Asia currently lack binding EPR requirements for PV, instead prioritising energy efficiency and production expansion[50].

In ODA-eligible countries, policy frameworks for PV generally focus on deployment incentives such as feed-in tariffs, auctions, or net metering, with limited provisions addressing supply chain sustainability or EOL management. This creates a risk of "future waste lock-in" as growing volumes of PV are deployed without corresponding investment in recycling or circular economy infrastructure. Certification schemes such as the Electronic Product Environmental Assessment Tool (EPEAT), which cover PV modules meeting sustainability and recyclability criteria, have limited uptake in ODA markets due to low awareness, certification costs, and lack of regulatory drivers[50].

Emerging market

For next-generation PV technologies, no jurisdiction currently enforces PV-specific EPR or circularity regulations. However, emerging policy trends from the silicon sector are likely to influence their governance. This includes design-for-disassembly standards, hazardous substance restrictions (e.g. under EU REACH), eco-labelling schemes such as EPEAT, and potentially minimum recycled content requirements.

As noted in the materials criticality section of this report, perovskite PV may face additional scrutiny due to its use of lead and other potentially scarce or hazardous elements. Anticipated regulatory measures could include mandatory encapsulation standards to prevent environmental release, safe handling requirements during manufacturing and recycling, and producer-funded take-back schemes. The EU's Critical Raw Materials Act may also influence next-generation PV deployment, particularly regarding indium, tin, and gold supply security.

By adopting regulatory measures early in commercialisation, next-generation PV can avoid the "linear lock-in" that has hindered silicon PV recycling, as highlighted in the end-of-life section. Mandating modular designs, separable functional layers, and recyclability from the outset would reduce long-term waste management costs and environmental impacts. This could be complemented by "right-to-repair" provisions and integration into circular economy legislation, ensuring these technologies align with global sustainability targets[21,27].

The policy and regulatory landscape for PV is evolving rapidly, with implications for both incumbent silicon technologies and emerging solar such as perovskite and OPV. In high-income markets, frameworks such as the EU Circular Economy Action Plan, Eco-design Directive, and Right to Repair legislation are setting clear expectations for design-for-disassembly, recyclability, and extended producer responsibility. In ODA countries, however, the absence of robust PV-specific regulations leaves end-of-life management largely unaddressed, risking increased waste volumes, informal recycling, and material leakage. Leveraging international standards such as EPEAT for PV modules, harmonising producer responsibility schemes, and embedding circularity criteria into procurement could accelerate adoption of best practice. Crucially, integrating these policy tools early into the commercialisation of next-generation PV technologies offers the opportunity to avoid the linear lock-in seen in silicon supply chains, reduce future recycling costs, and build resilient, sustainable markets that align with both climate and development goals

10. Economics

Current market

The costs of materials and production for photovoltaic (PV) technologies broadly mirror their environmental impacts, with energy-intensive materials and processes contributing both to higher embodied carbon and higher manufacturing costs. For crystalline silicon (c-Si) PV, wafer production and module assembly dominate both cost and carbon footprint, while balance-of-system (BoS) components increasingly influence total installed system cost at scale. Thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) benefit from lower material intensity and lower processing temperatures but remain limited in market share due to scale, supply-chain concentration, and material availability constraints.

Levelised cost of electricity (LCOE) remains the primary metric for economic competitiveness in mature electricity markets, integrating capital expenditure, operational expenditure, and, where accounted for, end-of-life (EOL) costs. Recent analysis from Fraunhofer ISE (2024) indicates that in Germany, LCOEs for PV range from approximately €0.045–€0.12/kWh depending on system scale and storage integration.[1] Rooftop PV with battery storage lies at the upper end of this range, while large-scale utility PV without storage competes at the lower end with onshore wind. By contrast, fossil fuel-based generation remains significantly more expensive, with gas and coal typically exceeding €0.12/kWh and nuclear approaching €0.45/kWh. These figures reflect mature market conditions, low financing costs, and highly optimised global supply chains.

End-of-life management increasingly influences long-term system economics and regulatory compliance in mature markets. Technologies aligned with circular design principles, high Environmental Performance Assessment Tool (EPEAT) scores, and extended producer responsibility (EPR) frameworks are better positioned to capture residual value through material recovery and reuse. Conversely, poor EOL performance increases compliance costs and decommissioning liabilities, ultimately raising the effective cost of electricity. European circular economy policy, including design-for-disassembly and right-to-repair directives, is expected to progressively reduce EOL costs by improving recovery yields and stimulating secondary materials markets.

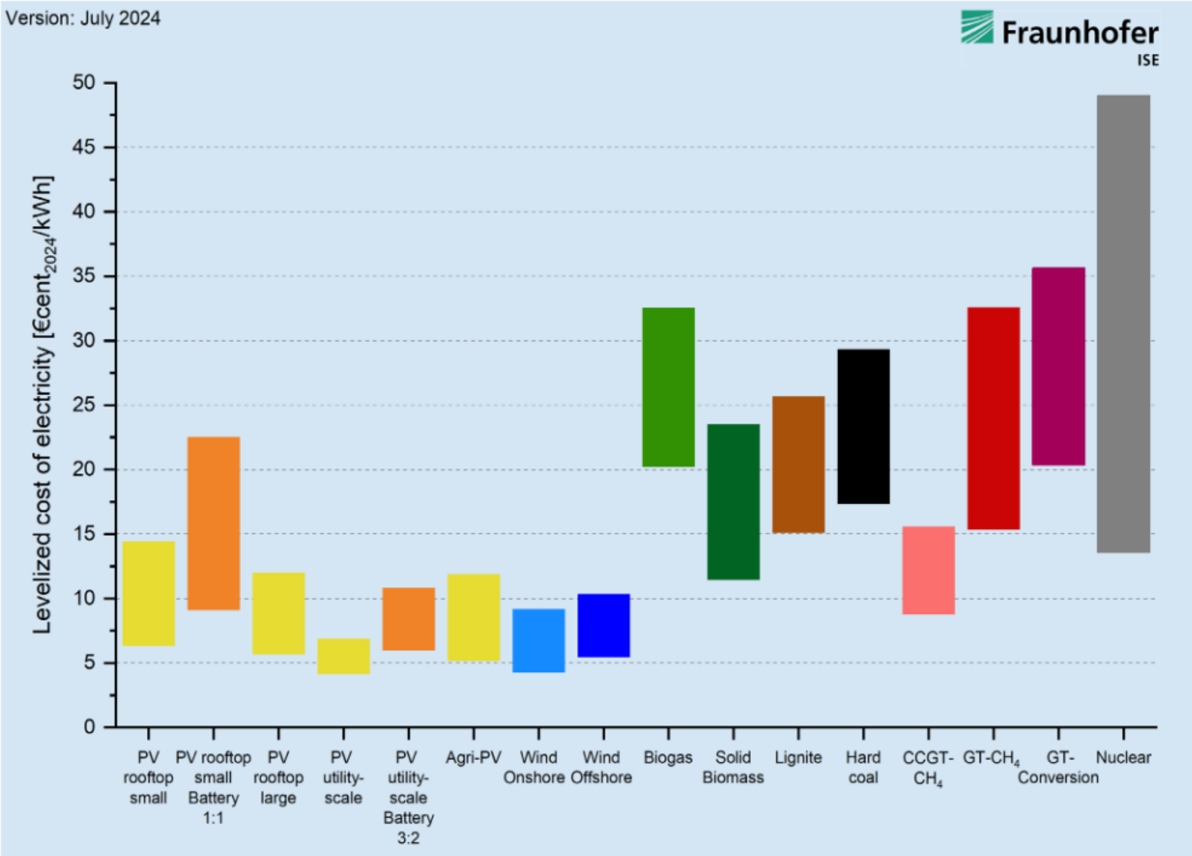

Figure 8 LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2024. Specific investments are considered using a minimum and maximum value for each technology[51]

Emerging market

Emerging photovoltaic technologies, particularly perovskite solar cells (PSCs) and organic photovoltaics (OPV), exhibit fundamentally different cost structures and risk profiles compared with incumbent technologies. While laboratory-scale demonstrations indicate strong potential for low-temperature processing, reduced energy input, and simplified manufacturing, current device architectures still rely on high-value components such as transparent conducting oxide (TCO) substrates and, in some cases, precious metal electrodes, which disproportionately influence cost and environmental performance.[26,27] Manufacturing yields, durability, certification pathways, and long-term reliability remain key economic uncertainties at this stage of technology development.

At scale, emerging PV platforms offer the potential for lower capital expenditure, modular production lines, and compatibility with existing printing and converting industries, enabling more distributed manufacturing models than silicon-based technologies. If material substitution, solvent optimisation, and circular design principles are embedded early, these platforms could deliver competitive module costs while reducing exposure to critical material constraints and end-of-life liabilities. However, these advantages remain conditional on successful scale-up, bankability demonstration, and the development of supporting supply chains for encapsulation, interconnection, and quality assurance.

In low- and middle-income countries, the economic case for emerging PV technologies is shaped not only by module cost but also by financing conditions, service models, and infrastructure availability. Although utility-scale PV LCOEs in many LMICs are already below USD 0.05/kWh, higher financing costs and limited access to concessional capital increase effective deployment costs. Decentralised systems further shift the economic emphasis from lowest LCOE toward total cost of service, durability, ease of maintenance, and local repairability. Solar–battery mini-grids and pay-as-you-go systems can outperform diesel alternatives on lifecycle cost while delivering improved health and resilience benefits.

End-of-life economics are rarely internalised in emerging markets, yet represent a growing long-term risk. Embedding design-for-disassembly, component reuse, and refurbishment pathways from the outset can reduce lifecycle costs and enable local value creation. Evidence from refurbishment programmes in Kenya and Bangladesh indicates that up to 40% of faulty solar home system components can be economically recovered when products are designed for repair and disassembly, supporting job creation and skills development alongside cost reduction.

11. Potential for local manufacture

Current market

There is meaningful scope to localise parts of today's PV value chain, but the opportunity is uneven along the chain. Module assembly and balance-of-system manufacturing are the most amenable to localisation because they are less capital intensive, have shorter lead-times, and rely on widely available industrial capabilities such as glass handling, polymer lamination, aluminium framing, junction box and cable harness production. Many countries have already localised these final steps while importing cells or wafers, often catalysed by public procurement rules, local-content incentives, or tariff policies[52,53]. By contrast, upstream steps, including polysilicon, ingot and wafering, and high-throughput cell lines, remain highly concentrated geographically, dominated by mainland China due to large economies of scale, integrated supplier networks, and low electricity prices. As of 2023, China accounted for most wafers and cells and around 80% of module manufacturing capacity, which creates a high barrier for fully integrated local supply chains in most markets.[53]

The main opportunities for local manufacture in incumbent technologies are, therefore, to establish or expand module assembly, frames, mounting structures, junction boxes and cables, inverters and transformers, and service ecosystems for O&M and testing, while gradually moving upstream as domestic markets scale and skills deepen. These activities can be paired with quality infrastructure, such as type-approval, reliability labs, and enforcement of IEC 61215 and 61730, to ensure bankability and reduce failure rates[50]. For silicon modules there may be potential for metallurgical grade silicon production in Africa using local quartz deposits, potentially feeding polysilicon producers in the EU and the USA wishing to avoid XUAR inputs (metallurgical grade silicon in China is increasingly produced in the XUAR and has poor transparency in the solar supply chain. Where thin-film CdTe or CIGS are concerned, localisation is more challenging because production is concentrated in a few firms with proprietary process know-how, though local glass, frames, and balance-of-plant can still be supplied regionally.

The principal barriers are high capex and power quality requirements upstream, limited access to specialised inputs such as solar-grade glass and EVA backsheets, certification capacity, and financing costs that raise the effective price of domestic production relative to imports. Policy volatility, trade remedies, and uncertain demand pipelines can hinder investment. Embedding extended producer responsibility and circular-design requirements can help build local end-of-life services and secondary materials markets, improving the economics of domestic manufacturing over time by raising recovery value and reducing waste liabilities, as discussed in earlier sections[48,49].

Emerging market

Next-generation PV offers a different localisation profile. Perovskite and OPV devices can be fabricated at low temperature and, in some architectures, by printing or roll-to-roll coating, which reduces energy demand and plant capex relative to conventional cell lines. This opens credible pathways for distributed, smaller-scale factories co-located with demand, especially for flexible or building-integrated products and for niche modules where weight and form factor matter[21,54]. Demonstrations of fully solution-processed perovskite devices with printed carbon electrodes, and TCO-free, micro-structured films, show that architectural choices can decouple manufacturing from some scarce inputs like indium and gold, and from vacuum equipment, which supports simpler, more modular plants[23].

The opportunities here are lower capex per unit of output, rapid line replication, the ability to leverage existing converting and printing industries, and the chance to embed design-for-disassembly and material recovery from the outset, which supports local circular value chains and jobs. In parallel, tandem perovskite-on-silicon is advancing for utility-scale markets through existing crystalline-Si factories, but those lines will remain capital intensive and centralised in the near term[10].

Key barriers for distributed manufacture of emerging tech include durability and certification at scale, secure local supply of barrier films and transparent conductors, solvent use and occupational health compliance, lead handling and take-back obligations for perovskite devices, and bankability until multi-year field data are available. For flexible perovskite and OPV, access to high-barrier encapsulation and reliable interconnect solutions is often the rate-limiting step rather than the printing itself.[21,27].

Cross-cutting policy levers that enable local manufacture

Stable demand visibility through auctions and multi-year procurement, domestic quality infrastructure and testing, incentives that reward circular design and high recyclability, and access to affordable finance are the main enablers across both incumbent and emerging technologies. Product ecolabelling and procurement standards, for example EPEAT for PV modules, can create a market premium for designs that are easier to disassemble and recycle, supporting local end-of-life industries and secondary materials markets. In combination with the EU's circular-economy measures, including design for disassembly, product passports, and EPR, these policies reduce long-run costs and raise the competitiveness of domestic manufacturing, particularly when paired with programmes that build supplier capability and skills[50,55].

Conclusion

The global solar PV sector stands at a critical juncture. While photovoltaics have become the most cost-competitive source of electricity worldwide, their long-term sustainability will depend on how supply chains, manufacturing impacts, and end-of-life outcomes are managed as deployment scales. Current deployment models are dominated by coal-intensive manufacturing, concentrated supply chains, and inadequate end-of-life strategies. They risk locking in environmental harm, resource insecurity, and social injustice. These challenges are particularly acute for low- and middle-income countries, where energy access goals intersect with systemic vulnerabilities in global markets.

Emerging technologies such as perovskite and organic photovoltaics offer a transformative opportunity to reshape this trajectory. Their potential for low-temperature, modular manufacturing, reduced material intensity, and compatibility with circular economy principles could enable distributed production, local job creation, and improved resilience. However, these benefits will only materialize if sustainability is embedded from the outset, through design-for-disassembly, ethical sourcing, and robust regulatory frameworks that anticipate future waste streams and material constraints.

Policy action is therefore urgent and must be multidimensional: decarbonising and diversifying supply chains, mandating traceability and labour standards, incentivising circular design, and accelerating innovation in next-generation PV. For LMICs, coupling technology transfer with local manufacturing and recycling infrastructure will be essential to ensure that solar deployment delivers not only clean energy but also inclusive economic development.

In short, the solar transition must evolve beyond a narrow focus on cost and capacity. By aligning environmental integrity, social justice, and economic resilience, stakeholders can secure a photovoltaic future that is not only low-carbon but truly sustainable, powering climate goals while advancing a just and equitable energy system for all. The TEA@SUNRISE network draws together individuals who share these goals and are committed to embedding them in the future phases of solar deployment. As the network continues to grow and communicate its members can take a leadership role in shaping future solar energy systems.

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