EngineeringX

High-level review of the end of life of photovoltaic infrastructure in low- and middle-income countries

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Royal Academy of Engineering

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High-level review of the end of life of photovoltaic infrastructure in low- and middle-income countries

Complete with executive summary and case studies

June 2026


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Contents

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Executive Summary

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Solar photovoltaic (PV) technologies are central to global decarbonisation and electricity-access strategies, particularly in Low- and Middle-Income Countries (LMICs), where grid expansion remains slow and decentralised renewable-energy systems play a critical role. However, the rapid scaling of PV deployment is causing a future safety, environmental and governance challenge that remains poorly understood in LMIC contexts: the safe and sustainable management of PV infrastructure at end of life (EoL).

This report presents a high-level review of PV EoL systems in LMICs. It synthesises findings from a structured literature review and in-depth case studies from Malawi, Rwanda, Kenya, India, and Nepal, selected to represent a range of PV market maturities, deployment models and institutional arrangements. The specific examples referenced throughout this Executive Summary draw directly from insights generated through these five country case studies and are intended to illustrate broader cross-cutting patterns rather than provide exhaustive national assessments. The aim is to characterise how PV EoL systems currently function in LMICs, identify key risks and gaps, and highlight opportunities for safer, more circular and context-appropriate approaches.

Scale and nature of the emerging challenge

Global PV deployment has expanded rapidly, with over 2.26 terrawatts installed worldwide by 2025 and projections of 15.5 terrawatts by 2050 [1]. Figure 1 shows global yearly PV installation, module PV production and module production capacity expanding rapidly over the last 10 years. While the majority of installed capacity to date is in higher-income countries, PV markets in LMICs are growing quickly across utility-scale, commercial and industrial (C&I), and off-grid segments. In Africa and South Asia in particular, decentralised and off-grid solar systems such as solar home systems (SHS), pico-solar products (such as solar lanterns) and mini-grids have been instrumental in extending electricity access to hundreds of millions of people.

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These deployment pathways have direct implications for EoL management. Off-grid and small-scale PV systems are geographically dispersed, often short-lived and characterised by fragmented ownership and limited asset tracking. Batteries and electronic components frequently fail well before PV modules, generating early and hazardous waste streams. At the same time, a large but mostly unplanned future wave of PV module waste is emerging from C&I and utility-scale systems installed since the mid-2010s.

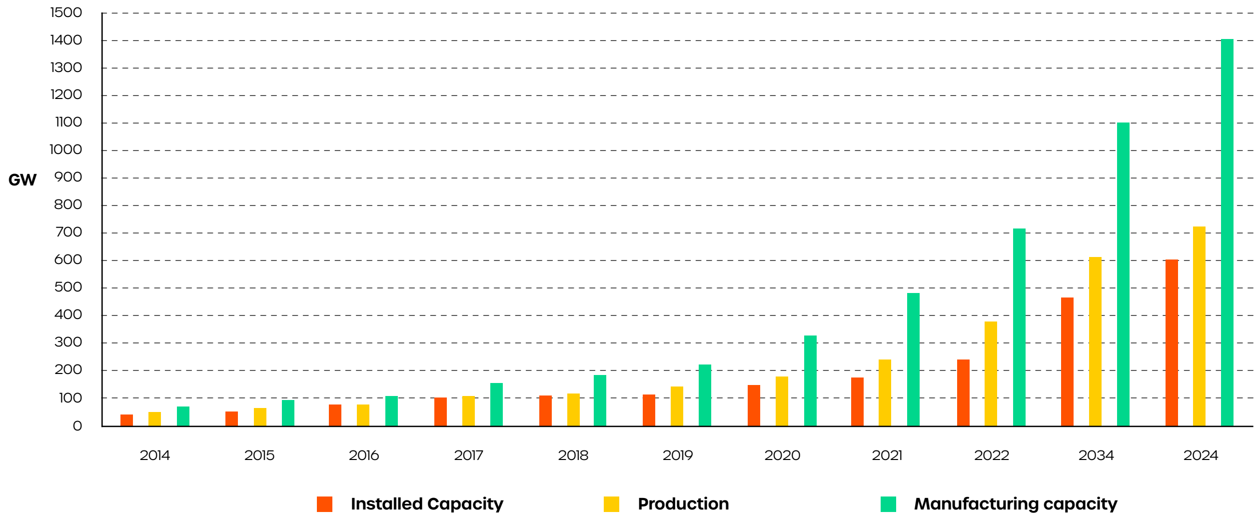
Global assessments by International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) estimate that cumulative PV waste could reach between 60 and 78 million tonnes by 2050 under more conservative or lower-deployment scenarios, and up to 210 million tonnes under a 1.5°C-aligned high-deployment pathway [18]. While these studies provide a robust global baseline, they rely predominantly on data from higher-income countries with formal waste-management systems and regulatory enforcement. Their applicability to LMIC contexts where informal repair, reuse, storage, and disposal pathways dominate is limited.

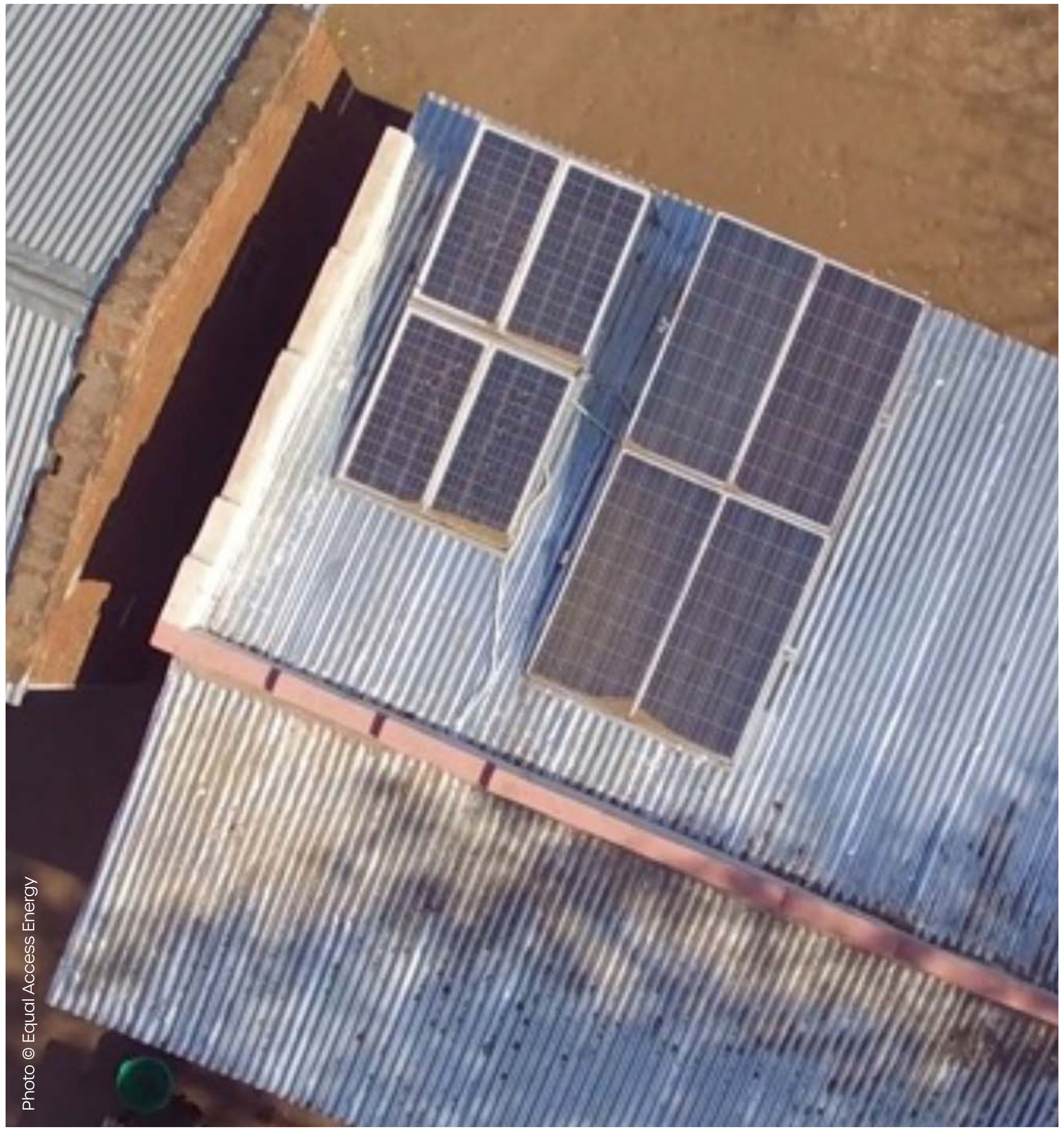
PV end-of-life systems in LMICs

Across the literature and case studies, PV EoL systems in LMICs are found to be fragmented and largely reliant on the informal sector, particularly for collection and material recovery. In most contexts, failed PV components are not immediately discarded but are instead stored in households, institutions, warehouses, or repair centres ('hibernation') delaying, but not preventing, eventual disposal or reuse. When disposal occurs, components often enter general waste streams or informal recycling networks, where valuable materials such as copper and aluminium are recovered, but hazardous residues are unmanaged.

Evidence suggests that occupational safety and environmental controls in these informal pathways are typically limited. Manual dismantling is commonly undertaken without personal protective equipment, appropriate ventilation or safe handling procedures, increasing risks of cuts, exposure to lead (from solder), cadmium (in certain thin-film modules) and battery electrolytes. Open burning of cables to recover copper and crude acid leaching practices have been documented in some e-waste contexts, contributing to localised air pollution and soil and water contamination. In addition, damaged modules and battery components disposed of in uncontrolled landfill conditions may lead to leaching of heavy metals and electrolyte materials over time. While the scale of these risks remains context-specific and often under quantified, the convergence of weak regulatory oversight, limited formal treatment capacity and informal recovery

Figure 1: Global yearly PV installation, module PV production and module production capacity 2014-2024 (GW) [1]





Solar minigrid generation hub (top) and Rooftop Solar Home System (© Equal Access Energy)

Decentralised renewable energy (DRE) solutions

Decentralised renewable energy solutions are small scale, locally distributed energy systems that generate power from renewable sources like solar, wind, biomass, or small hydro. They are deployed close to the point of use, rather than relying on large, centralised power plants and can enhance energy access, improve resilience, reduce transmission losses, and support community level control of energy resources. In the context of solar PV, DRE solutions include Solar Home Systems (SHS) and solar battery mini-grids.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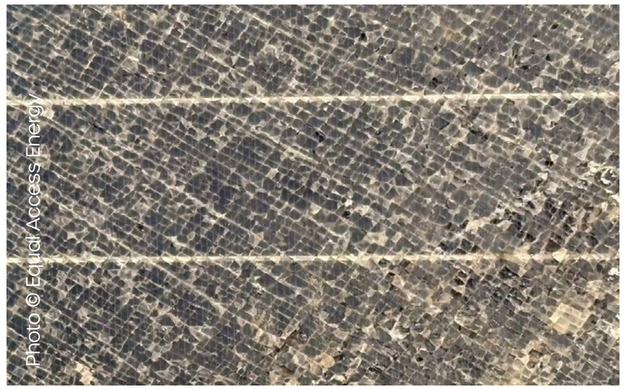
practices creates identifiable occupational health and environmental vulnerabilities.

Formal PV-specific collection, treatment and recycling infrastructure remains limited across most LMIC contexts. While some countries have begun integrating solar technologies into broader e-waste frameworks, often supported by donor engagement or development-bank conditionality, dedicated PV EoL systems are generally underdeveloped. Across the case study contexts, common features include fragmented institutional mandates, weak enforcement capacity, limited data on installed stock and waste volumes, and reliance on informal repair, reuse or disposal pathways. Even in higher-volume markets where industrial recycling capacity is emerging, regulatory frameworks for solar modules are often incomplete or lack enforceable extended producer responsibility (EPR) mechanisms.

Taken together, the case studies illustrate a spectrum of readiness rather than a binary presence or absence of systems. The comparative analysis highlights differences in regulatory maturity, market scale, donor influence, and domestic recycling capacity, while also revealing shared structural challenges. Across all cases, batteries (particularly lead-acid and increasingly lithium-ion (Li-ion)) dominate near-term risk profiles due to early failure, toxicity and informal handling. PV modules, while longer lived, present a growing medium- to long-term challenge because of their bulk, low material value by mass and high logistics costs for collection and export.

The informal sector is the backbone of PV EoL systems in LMICs, providing essential collection, repair and material recovery services where formal infrastructure is limited. These actors are socially embedded, trusted and economically indispensable, though their work often relies on unsafe, unregulated practices and they face constraints such as limited tools, training and formal recognition. Despite being difficult to regulate and placing potential barriers to implementation of formal EoL systems, their deep community networks, gender diverse participation and role in extending product lifespans make them critical to any realistic circular economy pathway.

Key risks and impacts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Unmanaged or poorly managed PV EoL systems create multiple, interlinked risks:

- **Environmental and health risks**, including soil, water and air contamination from heavy metals, acids and open burning of plastics, disproportionately affect informal workers and communities near dumpsites.
- **Resource risks**, undermine circular-economy potential and increase dependence on virgin raw material extraction.
- **Safety risks** for workers and communities arise from informal dismantling, residual electrical charge and lack of protective equipment.
- **Equity and justice concerns**, as the environmental burdens of solar deployment are transferred to vulnerable populations, potentially eroding trust in renewable-energy transitions.
- **Systemic risks** to energy-access programmes, where premature system failure and unmanaged waste undermine long-term sustainability and value for money.

Cross-cutting system gaps


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The review identifies a consistent set of system-level gaps across LMIC contexts, spanning policy, institutional, economic and technical dimensions:

- **Limited operationalisation of PV-specific EoL policy**, even where broader e-waste or renewable energy frameworks exist. Policies are often declarative rather than accompanied by implementing regulations, standards or enforcement mechanisms.
- **Fragmented institutional mandates**, with unclear allocation of responsibility across ministries of energy, environment, trade, standards authorities, and local government, leading to coordination failures and weak accountability.
- **Weak reverse-logistics and aggregation systems**, particularly for rural and off-grid markets. There are few structured pathways linking dispersed users to safe collection, preprocessing, and downstream recycling or refurbishment.
- **Insufficient data and traceability**, including limited visibility of installed PV stock, system lifetimes, component failure rates, and projected waste volumes. This constrains forecasting, investment planning and policy design.

- **Technical capacity gaps**, including limited access to safe dismantling equipment, module delamination technologies, battery diagnostics and handling capability, materials separation processes, and laboratory facilities capable of assessing material purity and environmental compliance. Skills shortages in electrical safety, materials engineering and environmental management further constrain safe EoL implementation.
- **Unfavourable recycling economics**, driven by high transport costs, dispersed waste generation, low recoverable material value (especially for crystalline silicon modules), and the absence of incentives, obligations or market signals to internalise EoL costs.
- **Heavy reliance on informal repair and recovery systems**, which persist because they are accessible, low cost and embedded within local livelihoods. Informal actors often provide valuable repair, refurbishment and material recovery services, contributing to job creation and circularity. However, in the absence of safety standards, environmental controls and formal integration, these systems can expose workers and communities to occupational and environmental risks. The challenge is therefore not elimination of informal systems, but structured integration, upgrading and support.


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Batteries are the primary early risk

Batteries are the primary early risk in a solar PV system – both in terms of e-waste generation and operational vulnerability – for several interconnected reasons related to their chemistry, lifecycle and role in the system. In the solar PV system, they fail first due to:

a. Cycle aging – repeated charging/discharging wears them out

b. Calendar aging - degradation over time, even idle

c. Temperature sensitivity – heat accelerates degradation

d. Depth of discharge (DoD) – deeper discharges shorten lifespan.

They fail first and pose the greatest environmental and safety risk if not managed, such as:

a. Toxicity – batteries contain hazardous materials (such as lead, lithium, cobalt)

b. Fire risk – damaged or improperly recycled lithium-ion batteries can cause fire

c. Leaching risk – heavy metals can contaminate soil and groundwater in landfills.

Since the batteries fail first, they represent the first major wave of hazardous e-waste from solar PV systems. Thus, batteries are the primary early risk due to:

a. Timing – the first major component to require replacement

b. Volume – with more solar plus storage systems, the total number of failing batteries will be enormous

c. Hazard – greater immediate environmental and safety risks than other components.

How hazardous are EoL Solar PV panels?

Literature reports inconsistent findings regarding the toxicity and hazardous classification of end-of-life (EoL) solar photovoltaic (PV) modules. Some studies classify certain EoL PV panels as hazardous waste, while others do not. Waste classification of PV panels is determined by measuring hazardous substance concentrations in leachate obtained from fragmented modules under standardised test conditions. However, regulatory threshold values for substances such as lead and cadmium vary significantly across jurisdictions (e.g., the US, Japan and Germany), while reported leaching results for crystalline silicon (c-Si) and cadmium telluride (CdTe) panels span from non-detectable levels to values exceeding some of these limits. Thus, in different jurisdictions, CdTe and c-Si panels could be considered either non-hazardous or hazardous waste on the basis of these test results. [43]

The main toxicity concerns stem from the use of heavy metal compounds of lead, cadmium and selenium in the manufacture of solar panels. However, solar panels use encapsulants to protect the cells from moisture, UV radiation and extreme temperatures. The high bond strength of the encapsulant shields solar cells from damage and also restricts potentially hazardous substances from leaching out into the environment [100]. An International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) study shows that disposing of solar panels in landfills is unlikely to have an adverse impact on human health. Even under the worst-case conditions, the study suggests that the risk from the panels was not significant enough to warrant a more detailed health risk assessment. However, the research was limited to the primary pollutant in each of the three biggest classes of solar panels today: c-Si, CdTe and copper indium gallium selenide (CIGS). The pollutants studied were lead, cadmium and selenium, respectively. [43]

1. Limited Real-World Environmental Data on EoL disposal and recycling of Solar PV Panels

- Most toxicity studies on (EoL) solar PV panels have been conducted under controlled laboratory conditions.
- There is a significant lack of field-based data, particularly from Low- and Middle-Income Countries (LMICs), on the actual environmental impacts of EoL PV panels.
- Test data are needed to assess the potential for damaged modules in real-world conditions to cause soil or groundwater contamination.
- There is an absence of large-scale, field-based environmental impact assessments of EoL PV modules, especially in LMIC contexts.

2. Limited Scope of Technology Coverage on Toxicity at EoL for Solar PV Panels

- Existing toxicity studies have primarily focused on c-Si, CdTe, and CIGS modules. As newer PV technologies emerge, there is insufficient understanding of their toxicity profiles and EoL environmental impacts. [97]
- Limited toxicity and environmental impact data for emerging and next-generation PV technologies.

3. Small Sample Sizes and Laboratory Bias

- The majority of available studies are based on small module samples tested in laboratory environments. Results may not adequately represent variability across manufacturers, production batches or field-aged modules.
- No insights are available on the hazards of informal treatment processes of solar panels for recovering materials such as silver and copper.
- Differences in sampling methods, material preparation and test protocols limit the comparability of findings.
- There is a need for larger, statistically robust datasets that account for manufacturing, geographics and ageing variability as well as the recycling/recovery process adopted.

4. Unknown Risks from Informal and Field Practices

- Unknown hazards occur from dust generated during the crushing of PV panels due to an absence of data on occupational exposure risks of recycling and handling EoL Solar PV panels (dust inhalation, toxic emissions).
- There is limited or no research on emissions resulting from uncontrolled or open burning of panels, whether for disposal or material recovery.

5. Ageing and Environmental Degradation Mechanisms

- Under various field conditions, EoL may be caused by delamination of encapsulant and backsheet layers (for example, tropical climates and desert climates), cell breakage (for example, static or dynamic wind loads), corrosion of metallization and cell interconnects (for example, moisture penetration), or massive ion migration (for example, sodium ion migration from superstrate and substrate glass sheets). [98]
- The environmental impacts associated with ageing-induced degradation specially in LMIC climatic conditions have not been studied in depth.
- The relationship between ageing mechanisms and subsequent contaminant release remains poorly understood.

6. Sheer Volume and Loss of Critical Raw Materials

- The sheer volume of solar panels reaching EoL and the valuable and critical resources locked in are an important facet to consider. Unrecovered critical raw materials mean more primary mining and the accompanying adverse environmental, social and climate impacts. These panels also occupy large amounts of space while waiting for disposal.

Case Study findings

Across the five case studies, PV markets are expanding rapidly but EoL systems are not keeping pace. Malawi and Nepal are characterised by import-dependent off-grid growth, short product lifetimes and predominantly informal disposal pathways, including household storage, abandonment and municipal dumping, with hazardous fractions often handled unsafely. Kenya presents a dual challenge: near-term accumulation of small off-grid devices (many stored in homes) alongside a future wave of bulk waste from C&I rooftop systems, yet PV modules remain largely invisible within existing e-waste implementation frameworks. India, by contrast, combines large-scale and rapidly growing deployment with an emerging domestic recycling industry and regulatory foundation, though informal de-framing and uncertain EPR implementation persist. Rwanda stands out for its comparatively formalised, centralised e-waste model, where licensed collection and dismantling – supported by donor conditionality – have embedded PV EoL considerations earlier than in peer contexts, albeit with reliance on a single operator and export routes for advanced processing. Taken together, as summarised in Table 1, the cases indicate a common set of priorities:

- Countries require stronger data and asset visibility to forecast waste volumes and plan infrastructure.
- Action should focus on practical capture mechanisms using existing municipal, service and industry networks to pilot certified collection and safe handling, while expanding repair and refurbishment to delay waste generation.
- Institutional mandates must be clarified and PV explicitly integrated into waste and energy regulation, with standards for transport, storage, testing, and reuse developed ahead of full EPR roll-out.
- Viable reverse-logistics and preprocessing models are needed to improve safety and economics, supported where appropriate by regional recycling partnerships and alignment of donor finance and procurement rules with life-cycle responsibility.

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Table 1: Summary of case study findings

Country	PV market + current EoL practices	What's working	What's missing / risk
Malawi	Donor-driven off-grid growth with short product lifetimes; widespread storage in households/institutions/warehouses, informal repair then abandonment; dumping/burning at municipal sites; limited formal dismantling/export; Li-ion often stockpiled.	Repair/refurbishment initiatives; emerging private dismantling/aggregation; industry convening platform; municipal sites could host collection.	No PV-specific framework; fragmented mandates and weak enforcement; weak product quality control; limited reverse logistics and data; economics of collection/export unfavourable.
Rwanda	Rapid off-grid/institutional deployment; EoL flows already from batteries/balance-of-system (BoS); centralised formal collection and dismantling via a licensed recycler; some battery repurposing; export for advanced processing.	PV explicitly in e-waste governance; licensed endpoint reduces dumping/burning; conditionality drives compliance; stronger traceability than peers.	Reliance on one operator and export routes; household capture weaker; compliance risks as deployment moves beyond donor programmes; long-term financial sustainability needs strengthening.
Kenya	Mature off-grid systems (OGS[AC1.1][AE1.2]) + fast-growing C&I rooftop; PV panels largely unmanaged (stored/disposed via general waste); off-grid devices frequently 'hibernated' in households; Waste Electrical and Electronic Equipment (WEEE) centres exist but are not PV-specific.	WEEE centres provide a starting point; strong service networks/technical capacity; rising awareness of an approaching C&I waste wave.	PV not operationalised within e-waste implementation; unclear mandates/coordination; limited testing/certification for reuse; weak data on installed base/age; high logistics costs.
India	Large and rapidly scaling utility + rooftop PV; waste already from damage/early replacements; informal deframing/aluminium recovery remains dominant, but formal recycling capacity is emerging; storage common because of ambiguity and logistics costs.	Regulatory foundation exists (PV in e-waste/EPR rules); industrial recyclers and some closed-loop models; strong R&D and manufacturing pull for recovered materials.	EPR targets/implementation uncertain; enforcement/auditing gaps; limited PV-specific standards (transport/reuse/recycling); high capex and logistics; limited offtake for some fractions (such as glass/silicon purity); inconsistent waste estimates.
Nepal	Import-dependent market shifting toward larger systems; EoL largely informal: storage, municipal disposal, abandonment; batteries handled by informal scrap sector (hazard risk) and some export; no formal collection/recycling.	Stakeholder willingness; installer skills base for training; informal metal/battery networks could be formalised; donor leverage to integrate circularity.	No PV-specific regulation/EPR; unclear institutional mandates; very limited data/inventory; substandard imports shorten lifetimes; low volumes + high logistics weaken business case; high exposure risks for informal workers/communities.

Opportunities and priority directions

Despite these structural gaps, the review identifies multiple cross-cutting, 'no-regrets' opportunities that align with phased, engineering-led intervention.

- **Extending product lifetimes as a first-order priority** through quality enforcement, maintenance and repair ecosystems, refurbishment centres, and life-extension hubs. This reduces waste volumes while creating local technical employment.
- **Piloting modular collection and pre-processing systems** building on existing infrastructure such as municipal transfer stations, WEEE centres, installer networks and solar service hubs. Early-stage aggregation and safe dismantling can be prioritised before full recycling infrastructure is developed.
- **Strengthening data and system visibility** by linking PV import data, installation licensing, standards certification, and asset registries to EoL planning and forecasting tools. Foundational data systems are a prerequisite for later regulatory enforcement or EPR implementation.
- **Phasing EPR proportionately** beginning with reporting, registration and collection obligations, and gradually increasing material recovery requirements as technical and institutional capacity matures.
- **Embedding EoL planning into deployment programmes** leveraging donor and development-bank conditionality to require asset tracking, safe storage and EoL budgeting at the point of installation.
- **Developing regional or shared treatment pathways**, where domestic recycling is not economically viable, to achieve economies of scale while maintaining environmental safeguards and social protections.

Recommendations

Together, these priority directions reinforce the report's broader recommendation logic, as summarised in Table 2: establish foundational data and design principles; pilot pragmatic delivery pathways and progressively shift toward more systemic, technically capable and economically viable circular PV systems that are safe, sustainable and inclusive.

Engineering relevance

PV EoL management is not solely a waste or policy issue; it is a systems engineering challenge spanning product design, reverse logistics, materials recovery, data systems, infrastructure, regulation, and human behaviour. Effective EoL systems require advances in module disassembly and delamination techniques; safe battery handling and diagnostics; materials separation processes capable of achieving sufficient purity for reuse; and low-cost testing methods to determine repair, refurbishment or second-life potential. In LMIC contexts, these technical requirements must be delivered through robust, and adaptable, solutions to constrained infrastructure environments.

Addressing these challenges safely and sustainably will require targeted skills development across the value chain: electrical and materials engineering expertise for safe dismantling and recovery; environmental engineering capacity for waste treatment and emissions control; logistics and systems design capability for distributed collection networks; and data and asset-tracking competencies to improve visibility of installed stock and waste flows. Building this multidisciplinary capability base is central to enabling circular PV systems.

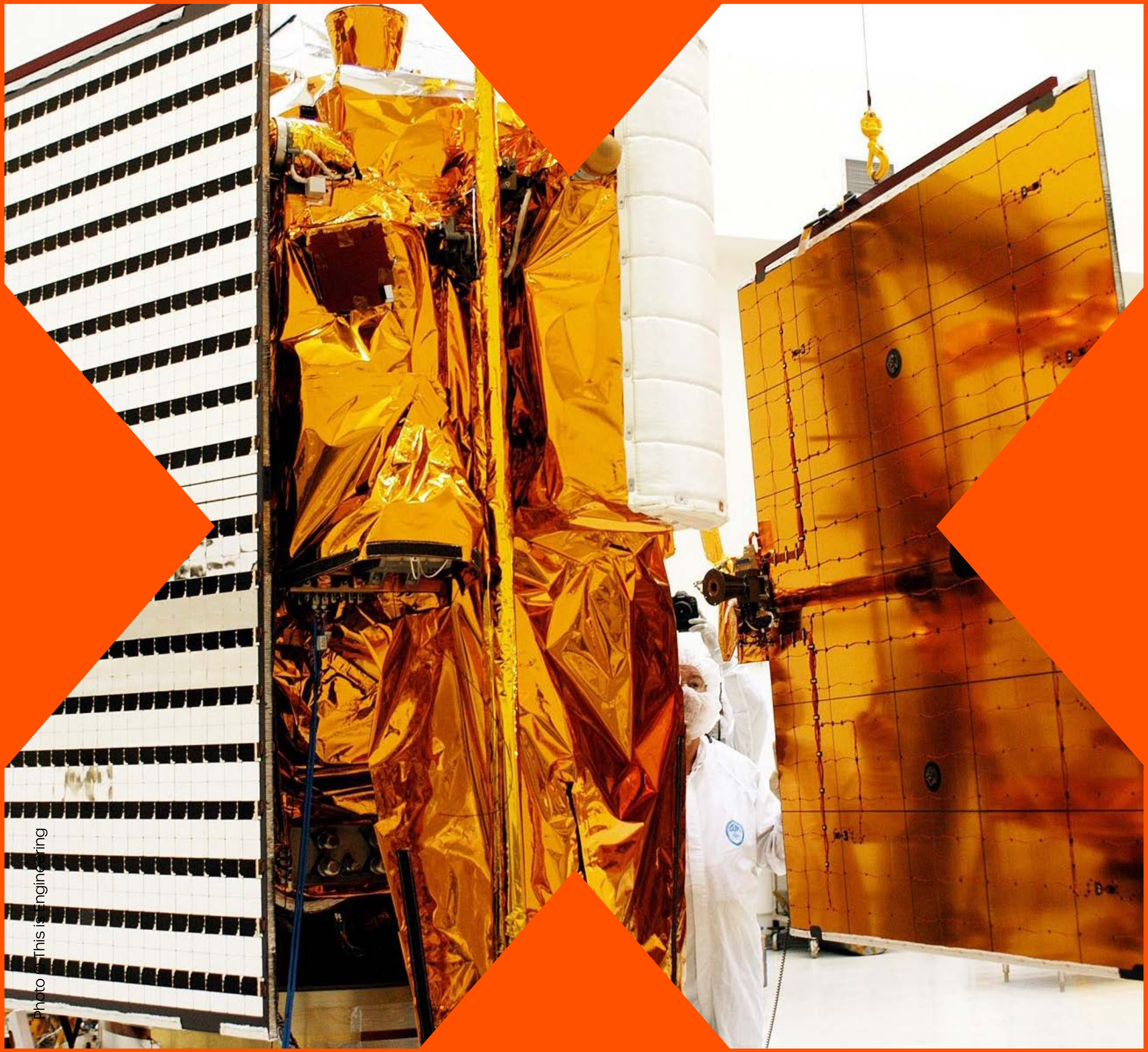
Table 2: Summary of recommendations

Recommendation	Lead	Level	Horizon	Indicative scale
Foundations				
Establish LMIC-appropriate PV EoL system design principles	Convenors + technical bodies	Cross-country	Near	Low
Build precompetitive PV EoL data and system visibility	Shared (public + private)	Country + cross-country	Near	Low–Moderate
Prioritise batteries and BoS components as the entry point	Governments + industry	Country	Near	Low
Delivery Pathways				
Professionalise and scale safe repair and refurbishment ecosystems	Solar industry + training institutions	Country	Near–Medium	Moderate
Leverage existing infrastructure for collection and aggregation	Industry + municipalities	Country	Near	Low–Moderate
Use donor and DFI conditionality to embed EoL requirements early	Donors + DFIs	Programme / country	Near	Moderate
System Shifts				
Derisk multi-actor pilots and system experimentation	Convenors + implementation partners	Country / regional	Medium	Moderate–High
Enable longer-term system shifts (regionalisation, circular design, second-life pathways)	Governments + industry	Regional / cross-country	Long	High

This report provides an evidence base to support governments, industry, funders, and engineers in designing PV systems that are not only clean at deployment, but safe, sustainable, circular, and inclusive at the end of their engineered life, and appropriately adapted to the contexts in which they operate.

List of Acronyms

AEPC	Alternative Energy Promotion Centre
ADB	Asian Development Bank
AfDB	African Development Bank
ASEAN	Association of Southeast Asian Nations
BIS	Bureau of Indian Standards
BoS	Balance of system
C&I	Commercial and industrial
CdTe	Cadmium telluride
CEE	Circular economy
CEEW	Council on Energy, Environment and Water
CIGS	Copper indium gallium selenide
CRS	Compulsory Registration Scheme (India)
c-Si	Crystalline Silicon
DFI	Development-finance institution
DKTI	GiZ's Promotion of Solar Energy in Rural and Semiurban Regions of Nepal
DoD	Depth of discharge
DP	Development Partner
DRE	Decentralised renewable energy
ECOWAS	Economic Community of West African States
EIA	Environmental Impact Assessment
EoL	End of life
EPRA	Energy and Petroleum Regulatory Authority
EPR	Extended producer responsibility
EVA	Ethylene vinyl acetate
EWIK	E-waste Initiative Kenya
FCDO	Foreign, Commonwealth & Development Office
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GOGLA	Global Off-Grid Lighting Association
GW	Gigawatt
IOE	Nepalese Institute of Engineering
IEA	International Energy Agency
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
IFC	International Finance Corporation
IREDA	Indian Renewable Energy Development Agency
IRENA	International Renewable Energy Agency
ISA	International Solar Alliance
JNNSM	Jawaharlal Nehru National Solar Mission
KU	Kathmandu University
KCIC	Kenya Climate Innovation Centre
KEBS	Kenya Bureau of Standards
KEREA	Kenya Renewable Energy Association
LMICs	Low- and Middle-Income Countries
LCA	Life-cycle assessment
MACRA	Malawi Communications Regulatory Authority
MEPA	Malawi Environmental Protection Authority
MERA	Malawi Energy Regulatory Authority
MININFRA	Rwanda Ministry of Infrastructure
MNRE	Ministry of New and Renewable Energy
MoFE	Nepalese Ministry of Forests and Environment
MV	Medium voltage
NAST	Nepal Academy of Science and Technology
NBSM	Nepal Bureau of Standards & Metrology
NEA	Nepal Electricity Authority
NEMA	National Environment Management Authority
NGO	Non-governmental organisation
NREP	Nepal Renewable Energy Programme
O&M	Operation and maintenance
PAYG	Pay-as-you-go
PCB	Printed circuit board
POSTED	Promotion of Solar Technologies for Economic Development
PPE	Personal protective equipment
PV	Photovoltaic
REIMA	Renewable Energy Industry Association of Malawi
RE-RTD	Renewable Energy Research and Technology Development
R&D	Research and development
RETS	Renewable Energy Test Station
RURA	Rwanda Utilities Regulatory Authority
SECI	Solar Energy Corporation of India
SDG	Sustainable Development Goal
SEMAN	Solar Electric Manufacturers Association Nepal
SHS	Solar home system
SIDA	Swedish International Development Cooperation Agency
TERI	The Energy and Resources Institute
TW	Terawatt
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
UNITAR	United Nations Institute for Training and Research
WEEE	Waste Electrical and Electronic Equipment
WRI	World Resources Institute



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1. Introduction

1. Introduction

Solar photovoltaic (PV) technology is now a cornerstone of global decarbonisation and electrification strategies, particularly in Low- and Middle-Income Countries (LMICs), where it plays a critical role in expanding electricity access through both grid-connected and decentralised renewable energy (DRE) systems. However, the rapid scaling of PV deployment also embeds a future waste and safety challenge. As installed PV capacity grows, increasing volumes of PV modules and associated components will reach the end of their useful life, raising questions about how these assets will be safely decommissioned, managed, reused, or recycled.

While PV end-of-life (EoL) management has received growing attention in higher-income countries [2], [3] where regulatory frameworks and recycling infrastructure are beginning to emerge, far less is known about how PV EoL systems currently operate in LMIC contexts. These contexts are characterised by rapidly expanding PV markets, a high prevalence of off-grid and small-scale systems, limited formal waste-management infrastructure, and a significant role for informal repair, reuse and recycling activities. Together, these factors create distinct risks and opportunities that are not well captured in existing global analyses.

In recognition of this gap, Engineering X, a growing collaboration between the Royal Academy of Engineering and Lloyd's Register Foundation, commissioned a high-level review of solar PV EoL infrastructure in LMICs. This report sets out the research undertaken and the key insights derived, drawing on a structured review of the existing literature alongside targeted country case studies. The aim is to improve understanding of how PV EoL systems currently function in LMICs, identify critical gaps and safety challenges, and highlight opportunities for more sustainable, circular and context-appropriate approaches to PV EoL management.

1.1. Background context of PV in LMICs

1.1.1. Electricity access

According to the SDG 7 Progress Report 2025, approximately 92% of the world's population had access to electricity by 2024 [4]. Despite this progress, major regional disparities remain. Sub-Saharan Africa continues to experience the largest access gap, with about 50–55% of the population electrified, leaving approximately 600 million people without access, representing nearly 85% of the global unserved population. By contrast, developing Asia has reached near-universal coverage, at approximately 97%, helping to offset lower access rates elsewhere and raise the global average [5].

DRE solutions have been central to recent gains in electricity access, particularly in regions where grid extension remains slow or economically challenging. Solar home systems (SHS) and solar mini-grids are estimated to have delivered electricity services to approximately 561 million people globally by 2023. In sub-Saharan Africa, DRE accounted for an estimated 55% of new electricity connections between 2020 and 2022, underscoring its critical role in reaching remote, rural and low-income populations.[5]

These electrification pathways have important implications for the future management of energy infrastructure. DRE systems are typically deployed at large scale through highly distributed, small-capacity installations, often owned or managed by households, communities or private operators rather than central utilities. While this model has proven effective in accelerating access, it also presents challenges for asset tracking, maintenance and EoL management. As millions of decentralised solar systems age and are replaced or upgraded they will contribute to a growing stock of PV equipment approaching EoL, much of it located in settings with limited formal waste-management infrastructure.

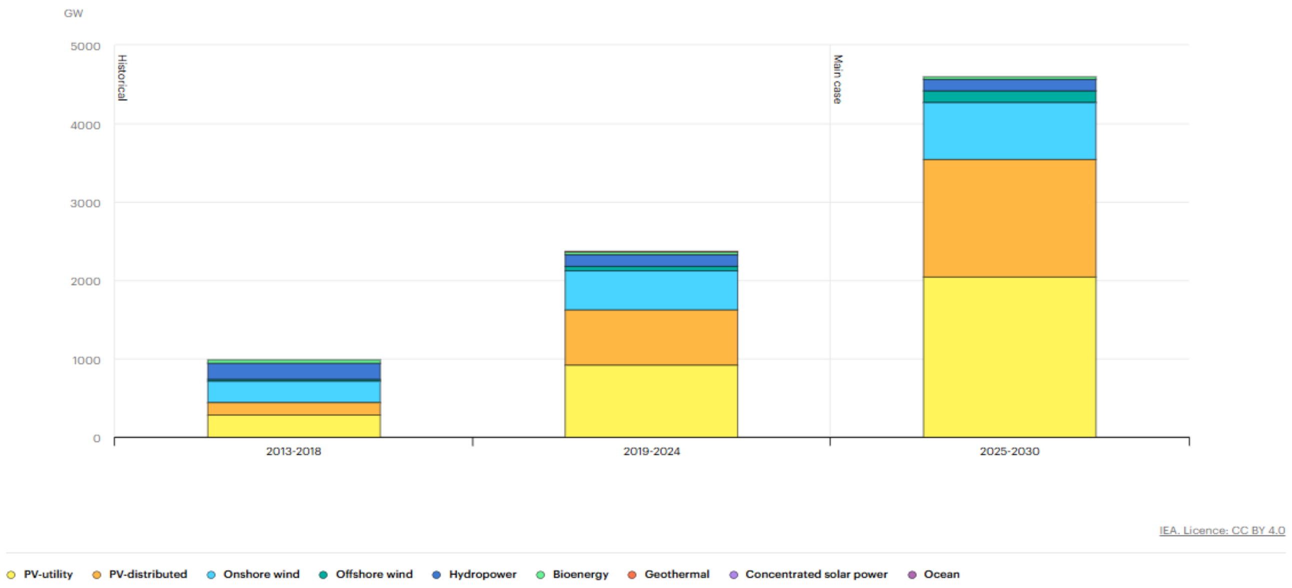
As a result, the very technologies enabling progress towards universal electricity access in LMICs are also shaping the nature and complexity of future PV EoL systems. Understanding these access pathways is therefore essential to assessing the scale, distribution and risk profile of PV EoL challenges in LMIC contexts.

1.1.2. Global PV market

The global solar PV market has expanded rapidly over the past decade and continues to accelerate. The International Energy Agency's (IEA) most recent assessment (2025) [6] estimates that approximately 2.26 terrawatts of PV capacity, including both grid-connected and off-grid systems above 40 watts, has been installed worldwide. Notably, more than 47% of this capacity has been deployed within the past three years, reflecting both declining technology costs and strong policy support for solar as a central component of energy-transition strategies.

Looking ahead, the scale of deployment is expected to increase substantially. Between 2025 and 2030, the IEA predict an extra 3.5 terrawatts of utility and distributed solar will be deployed (Figure 2) [11]. Under the IEA's Net Zero Emissions by 2050 scenario [7] global installed PV capacity is projected to reach approximately 15.5 terrawatts by 2050, implying a several-fold expansion of today's installed base. This growth trajectory indicates that the majority of PV systems currently in operation globally are relatively new, while a much larger cohort of systems will reach EoL in the coming decades.

Figure 2 Renewable Electricity capacity growth by technology segment, main case, 2013–2030 [11]



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As cumulative installed capacity continues to rise, the volume of PV modules and associated components approaching EoL will increase correspondingly. Although the timing and geographic distribution of this waste will vary, the global scale of PV deployment establishes the baseline conditions under which both formal and informal EoL management systems will need to operate. Understanding the global PV market is therefore essential for contextualising emerging PV EoL risks and opportunities in LMICs.

1.1.3. PV market in LMICs

PV deployment in LMICs has expanded rapidly over the past decade, driven by falling technology costs, increasing energy demand and national commitments to decarbonisation and energy access. However, the scale, structure and maturity of PV markets vary significantly across regions, shaping both current deployment patterns and future EoL challenges.

Across Africa, cumulative installed solar PV capacity was estimated at approximately 19.2 gigawatts by the end of 2024 [8] encompassing utility-scale projects, commercial and industrial (C&I) systems, mini-grids, and household SHS. Market forecasts for the period 2025–2028 indicate continued growth, with a medium-growth scenario projecting about 23 gigawatts of new capacity [9]. While large utility-scale installations are expected to dominate capacity additions, decentralised systems including C&I installations, residential rooftop systems and solar mini-grids remain critical for expanding access to electricity, particularly in rural and peri-urban areas.

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In South Asia, PV markets are more mature but equally diverse. India alone reported 132.85 gigawatts of cumulative installed solar capacity [10] comprising approximately 100.80 gigawatts of utility-scale ground-mounted projects, 23.16 gigawatts of grid-connected rooftop systems across commercial, industrial and residential sectors, 3.34 gigawatts of hybrid project components, and 5.55 gigawatts of off-grid solar systems, including mini-grids and household installations. These numbers highlight the coexistence of large-scale, grid-integrated PV infrastructure alongside a substantial and growing base of decentralised systems. Figure 2 shows global PV capacity growth 2013–2030 alongside other renewables.

Southeast Asia has also experienced steady growth in solar PV deployment, with installed capacity across the Association of Southeast Asian Nations (ASEAN) countries estimated at approximately 20 gigawatts by 2024 [12]. As in Africa and South Asia, PV deployment in the region spans utility-scale projects and smaller distributed systems, reflecting differing national energy strategies, grid capacities and electrification needs.

As PV markets in LMICs continue to expand, the diversity and dispersion of installed systems will strongly influence how and where PV equipment reaches EoL. Understanding the structure of these markets is therefore essential for anticipating future EoL volumes, identifying points of intervention and designing context-appropriate systems for safe, sustainable and circular management of PV assets.

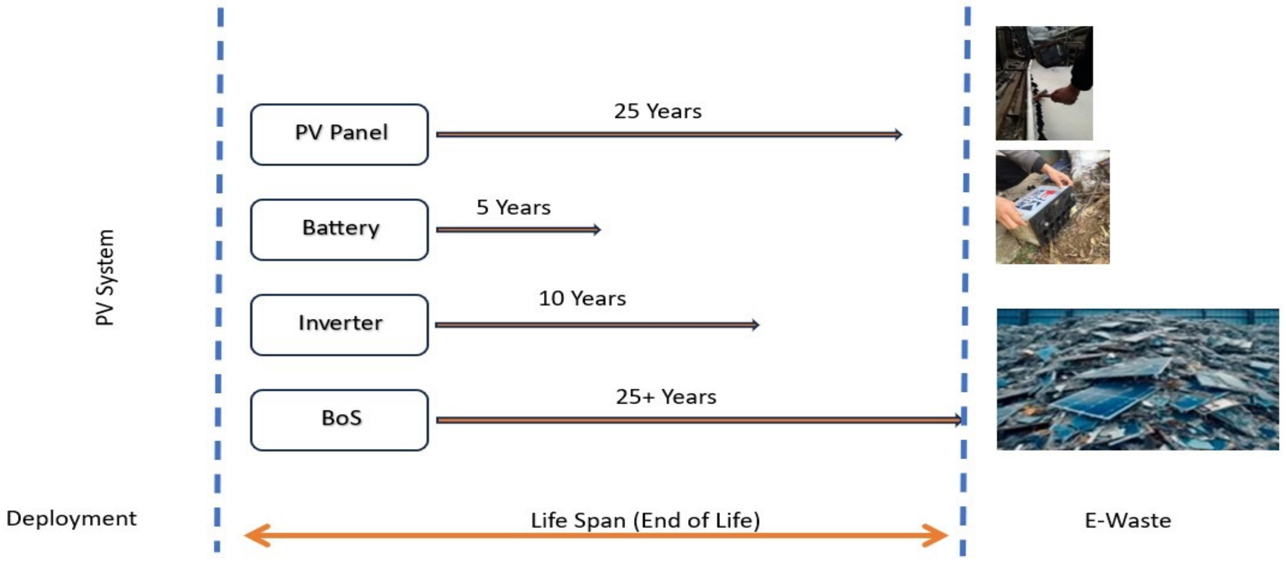
1.1.4. Off-grid solar

Since the early 2000s, the off-grid solar sector has expanded rapidly as a distinct delivery model within global PV markets, particularly in LMICs. Over this period, an estimated 375 million solar energy kits including SHS, lanterns and other pico-solar products have been sold and distributed worldwide. In Africa alone, more than 50 million off-grid solar products were sold over the past two years, reflecting continued growth in household- and community-scale PV deployment.[13]

Off-grid solar systems differ from utility-scale and grid-connected PV in ways that have direct implications for EoL management. These systems are typically smaller, geographically dispersed and deployed through a wide range of commercial, donor-supported and informal channels. Ownership is often fragmented across households, communities and private operators, with limited centralised oversight once systems are installed. While repair, refurbishment and component reuse are common in practice, they are rarely captured in formal data systems. Off-grid PV systems are also composed of multiple components with markedly different technical lifetimes, creating staggered and uneven waste flows. As illustrated in Figure 3, while PV modules may last 25 years or more, batteries often fail within approximately 5 years, inverters at about 10 years, and balance-of-system (BoS) components vary widely. This mismatch means that EoL is not a single event but a rolling process of component replacement, with batteries typically driving early and more hazardous waste streams long before modules reach their engineered life.

Looking ahead, the scale of off-grid PV deployment is expected to increase further. The IEA estimates that Africa will require approximately 60–70 gigawatts of installed solar PV capacity by 2030 to align with the Nairobi Declaration and the COP28 pledge to triple renewable-energy capacity.[14] While grid-connected utility-scale and C&I projects are expected to account for the majority of this capacity, off-grid systems are projected to deliver about 15–20% of total installed capacity, equivalent to approximately 8–12 gigawatts. This expansion is expected to involve tens of millions of extra solar products, including an estimated 70 million SHS and up to 300 million portable solar devices.

Figure 3: Lifetimes of off-grid PV system components

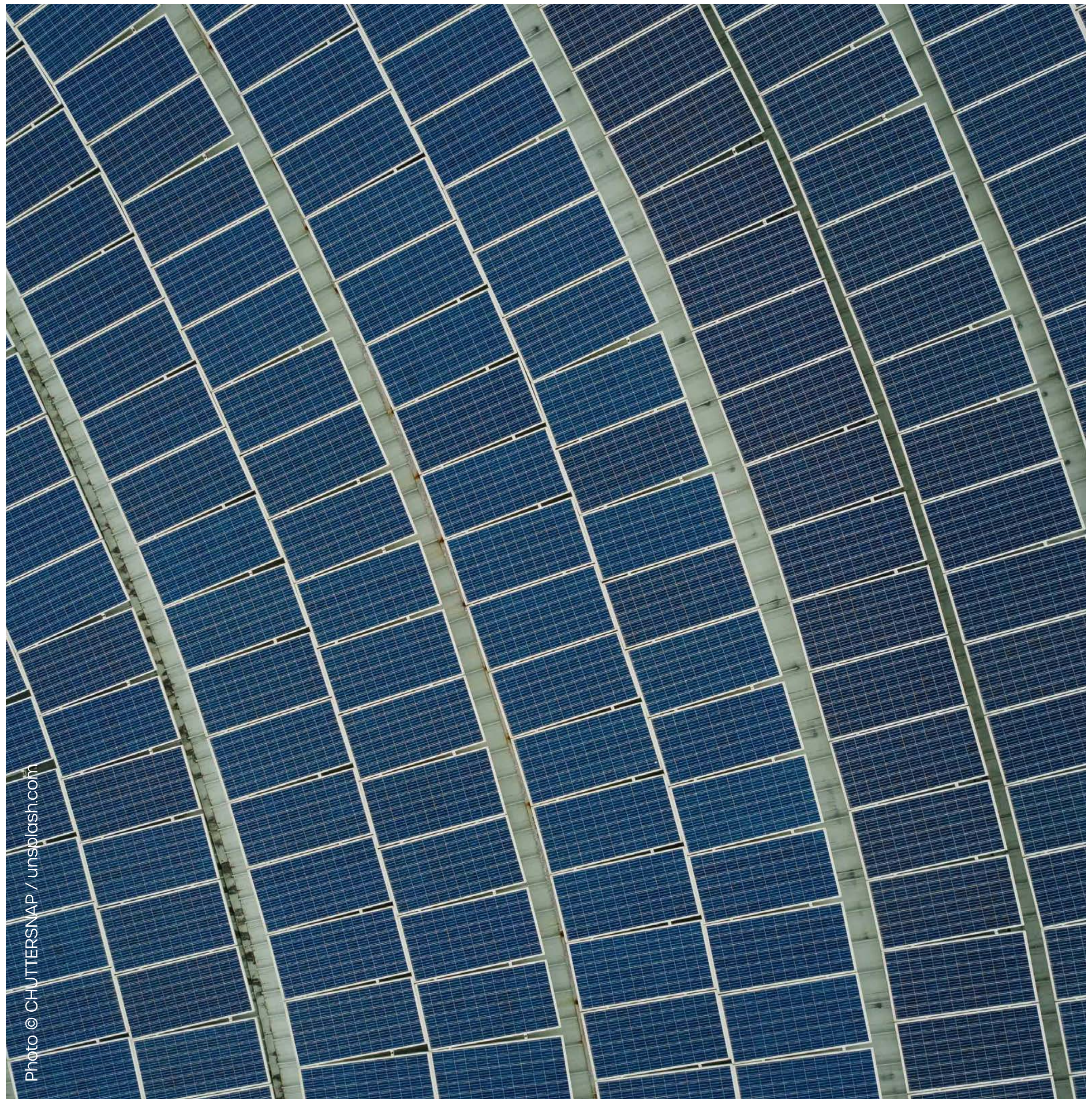


The cumulative effect of this deployment is the creation of a large, distributed and heterogeneous stock of PV assets that will gradually reach EoL. In the absence of dedicated collection, tracking and recycling systems, off-grid solar technologies risk contributing to unmanaged waste streams, informal dismantling and loss of valuable materials.

1.1.5. PV end of life

The issue of solar PV EoL management has gained increasing attention over the past decade as global PV deployment has accelerated. A foundational assessment of the scale and implications of PV waste was published jointly by the International Renewable Energy Agency (IRENA) and the IEA in 2016, drawing primarily on data from G20 countries and participants in the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) Task 12 programme.[6] That analysis estimated that global PV panel waste would grow from approximately 43,500 tonnes in 2016 to between 60 and 78 million tonnes by 2050, with significant waste volumes beginning to emerge from about 2030 onwards.

The 2016 report highlighted that, as early PV installations reach the end of their operational life, annual waste flows could reach 4–14% of installed panels by 2030, rising to 80–89% by 2050. Importantly, it also identified PV modules as a potentially valuable secondary resource. By 2030, recoverable materials from end-of-life panels were estimated to be worth up to $450 million, sufficient to manufacture approximately 60 million new PV panels (approximately 18 gigawatts of capacity). At the time, the European Union was identified



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EPR and the WEEE directive

EPR (Extended Producer Responsibility) is a policy principle that aims to shift waste management responsibilities onto producers rather than governments or consumers. It makes producers responsible for the entire life cycle of their product, including disposal.

The Waste Electrical and Electronic Equipment (WEEE) Directive is a law applying EPR to electronics in the European Union. It aims to address the environmental impacts of e-waste through prevention, improved resource efficiency, and mandated recycling, recovery and reuse. In practice, it mandates producers of e-waste to register with approved compliance schemes and to finance the collection, treatment, recovery, and environmentally sound disposal of waste.

as the only region with PV-specific waste regulation, implemented through the Waste Electrical and Electronic Equipment (WEEE) Directive based on extended producer responsibility (EPR).[15][16] In contrast, most other major PV markets including the US, China, India, and Japan classified PV panels as general or industrial waste, with limited PV-specific regulatory oversight.

Subsequent updates to this baseline by IRENA (2023) [17] and the IEA (2025) [18] reflect both the continued acceleration of PV deployment and improved modelling of system lifetimes. Under a 1.5°C global warming scenario, IRENA now estimates cumulative global PV waste could reach approximately 210 million tonnes by 2050, with the majority of this volume originating from G20 countries, reflecting their dominant share of installed capacity. Both organisations emphasise that while recycling technologies for PV modules exist, current recycling economics remain weak because of relatively low waste volumes, immature markets and limited incentives for high-value material recovery.

Across these global assessments, there is broad consensus that PV waste volumes will scale rapidly over the coming decades as deployment accelerates and early-generation systems are decommissioned. Although positioned as a global baseline, the direct applicability of these assessments to LMICs is not clear. Much of the underlying data originates from higher-income countries with established waste-management systems, formal recycling infrastructure and regulatory enforcement mechanisms. In LMIC contexts, PV markets are more fragmented, off-grid and small-scale systems are more prevalent, and informal repair, reuse and recycling activities play a significant role. As a result, PV EoL management in LMICs is likely to follow markedly different pathways, with distinct risks related to environmental contamination, occupational health and safety, and loss of valuable materials, alongside opportunities for local value creation through repair, refurbishment and secondary markets.

1.2. Approach and report structure

Against this background, this report undertakes a high-level review of PV EoL Infrastructure in LMICs, seeking to answer these guiding questions.

- What does the PV EoL system look like in LMICs?
    - What makes up the system?
    - Who are the key players, programmes and initiatives?
    - What is the funding landscape around this?
- With respect to safe and sustainable EoL practices, what are the relevant technical, economic, social, political, environmental, supply chain, legal/ethical, and data/knowledge factors?
- What are the key issues or gaps that require action?
    - What impact are they having on people, environment, safety and so on?
    - Who are they affecting?
    - How do they affect people in LMICs in particular?
    - What are the engineering-related issues?

To answer these questions, the authors undertook a rapid, structured literature review and key stakeholder consultation for five case study countries – India, Nepal, Malawi, Rwanda and Kenya. The literature review was guided by a data extraction framework, including the key questions listed above and a range of other linked data points identified as of interest to Engineering X. The method and findings of the literature review are described in Section 2. The case studies were conducted by parallel teams, following an interview protocol designed to extract qualitative information aligning with the data extraction framework used in the literature review. The case studies are presented in Section 3. Section 4 sets out the key insights and recommendations derived from the research.

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2. Review of current knowledge and practice

2. Review of current knowledge and practice

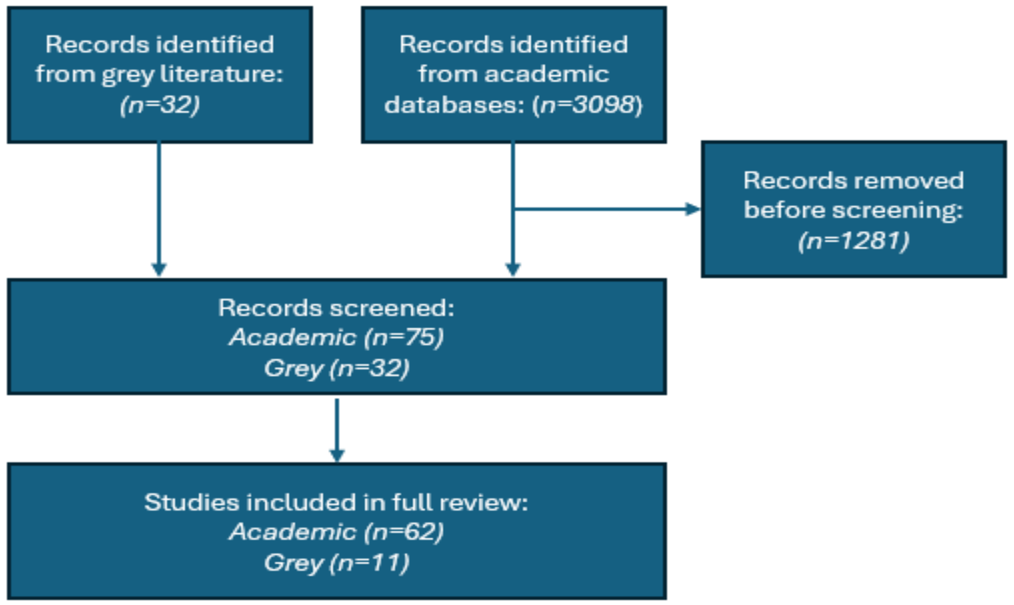
2.1. Approach and overview of the reviewed literature

Understanding the current treatment of LMIC PV EoL systems in the literature was deemed essential to the high-level review; however, a detailed, systematic review was not possible in the timescales. A rapid search and selection strategy was implemented, with a top 100 papers identified for initial review by the team of six research consultants. Following an initial validity test, each paper was reviewed against a data extraction framework designed around the research questions (see Appendix 5.1). The reviewers thus used the framework to capture key findings from each document.

Literature was identified through a mixture of structured and snowball sampling and covered academic and nonacademic ('grey') literature sources. This process is shown in Figure 4 and described in the paragraphs below.

The structured academic review was conducted using SCOPUS and Web of Science searches, using a combination of keywords to form a search string based on the themes of solar waste and circular economies in LMICs. The full search string can be found in Appendix 5.1. This search generated n = 1,892 results on SCOPUS and n = 1,204 results from Web of Science. Key information (including title, abstract, author, publication year and citation count) from these n = 3,098 results was exported and filtered for duplicates, leaving n = 1,817 unique results.

Figure 4: Literature review process



These results were then further filtered to the top 100 academic articles based on relevance to the objectives of the original proposal, namely: to review the EoL of PV infrastructure, focused on the drivers of social and environmental harm in LMICs, and to build an evidence base on challenges and opportunities for safer, more sustainable PV EoL management in LMICs. Preference was given to more recent articles (post-2020). These top n = 75 papers were allocated across the review team for initial screening, then detailed review and data extraction.

A structured grey literature search was conducted to complement the academic review and capture practitioner, policy and industry perspectives, recognising that much relevant evidence on PV EoL systems in LMICs is published in reports, toolkits and programme evaluations rather than peer-reviewed journals. The approach combined targeted searches of key sector organisations active in off-grid solar, e-waste and circular economy (CEE), review of donor programme documentation, snowballing from references within academic and organisational reports, and identification of relevant outputs through the consortium's professional networks. This process identified n = 32 relevant grey literature documents, which were catalogued and screened using the same inclusion criteria as the academic review: relevance to PV EoL, focus on LMIC contexts and substantive insight into social, environmental, governance, or market drivers of harm and/or opportunity.

The resulting n = 107 papers underwent eligibility screening, with n = 34 being excluded due to lacking an LMIC focus, lacking EoL focus or being overly technical research and development reports (for example researching new PV technologies). This left n = 73 papers included in the full review.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Of the n = 73 reviewed documents, 77% consisted of academic sources and the rest were grey literature. The grey literature largely consisted of literature reviews supplemented by primary data collection through interviews or case studies. However, as is often the case with such publications, the methodologies were not documented and were thus unclear. The academic papers consisted of modelling studies (n = 27), literature reviews (n = 14), empirical research (n = 11) and other types of studies (n = 4), most of which were laboratory-based experiments. The modelling studies were dominated by life cycle assessments (LCAs) (n = 10), whereas the empirical studies mostly consisted of case studies or summaries of interviews with high-level stakeholders. Notably, only six of the academic articles incorporated the voices of end-users or people working in the waste sector. The most prominent research funder was the National Natural Science Foundation of China, which was involved in eight of the studies. Of these, three had an international focus and the remaining five were about China.

Figure 5 shows the geographical focus of the literature. About a third of studies (n = 28, 38%) covered multiple countries. Of these, eight focused on Africa, five on Asia and one on Latin America. The remainder either had global coverage (n = 11) or were concerned solely with LMICs (n = 3). In terms of the single-country papers, there were concentrations on China (n = 12 papers) and India (n = 10), primarily driven by the countries' boom in solar manufacturing and installation and the recent sustainability-focused policies and directives. These are followed by a range of other countries with a maximum of three papers each.

2.2. PV EoL Challenges in LMIC Contexts

2.2.1. Geographies facing significant PV waste issue

The reviewed literature indicates that the scale and timing of PV waste emergence varies substantially across regions, but several geographies already illustrate the magnitude of the future challenge. Modelling from China demonstrates the scale and urgency of the PV waste issue, projecting that national PV waste by 2050 will exceed 70,000 square kilometres or 7.8 million tonnes, which is nearly equivalent to the global in-use PV stock in 2020. This waste area is about 4.8 times the size of Beijing (approximately 16,410.54 square kilometres).[62] Similarly, one of the first detailed PV waste forecasts for Malaysia projects between 229,009 tonnes and 481,137 tonnes of waste by 2050, emphasising the need for early action even though these volumes remain relatively small compared to national greenhouse gas (GHG) emissions. The study identifies the optimal window to launch a crystalline silicon (c-Si) recycling facility between 2029 and 2039, based on a consistent annual waste input of roughly 7,200 tonnes per year to ensure economic viability.[57] Beyond single-country projections, the global PV recycling market is valued at $2.1 billion in 2024 and is projected to grow to $9.4 billion by 2033.[54][75] Meanwhile, regional analyses highlight West Africa as another critical hotspot, where cumulative PV waste generation by 2050 is estimated between 2.3 and 7.8 million tons under different scenarios, with off-grid systems contributing about 70% of this volume. The recoverable secondary materials from this waste range from 213 to 704 kilotons, representing a potential economic value of $143–475 million, which is enough material to produce a further 6–19 gigawatts of solar PV capacity.[59]

Figure 5 Geographical focus of literature review

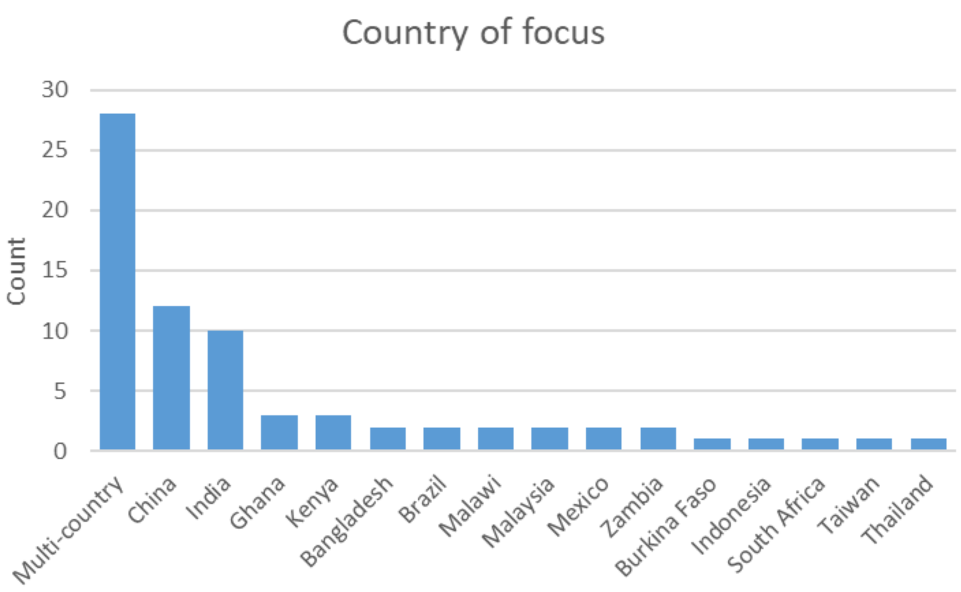

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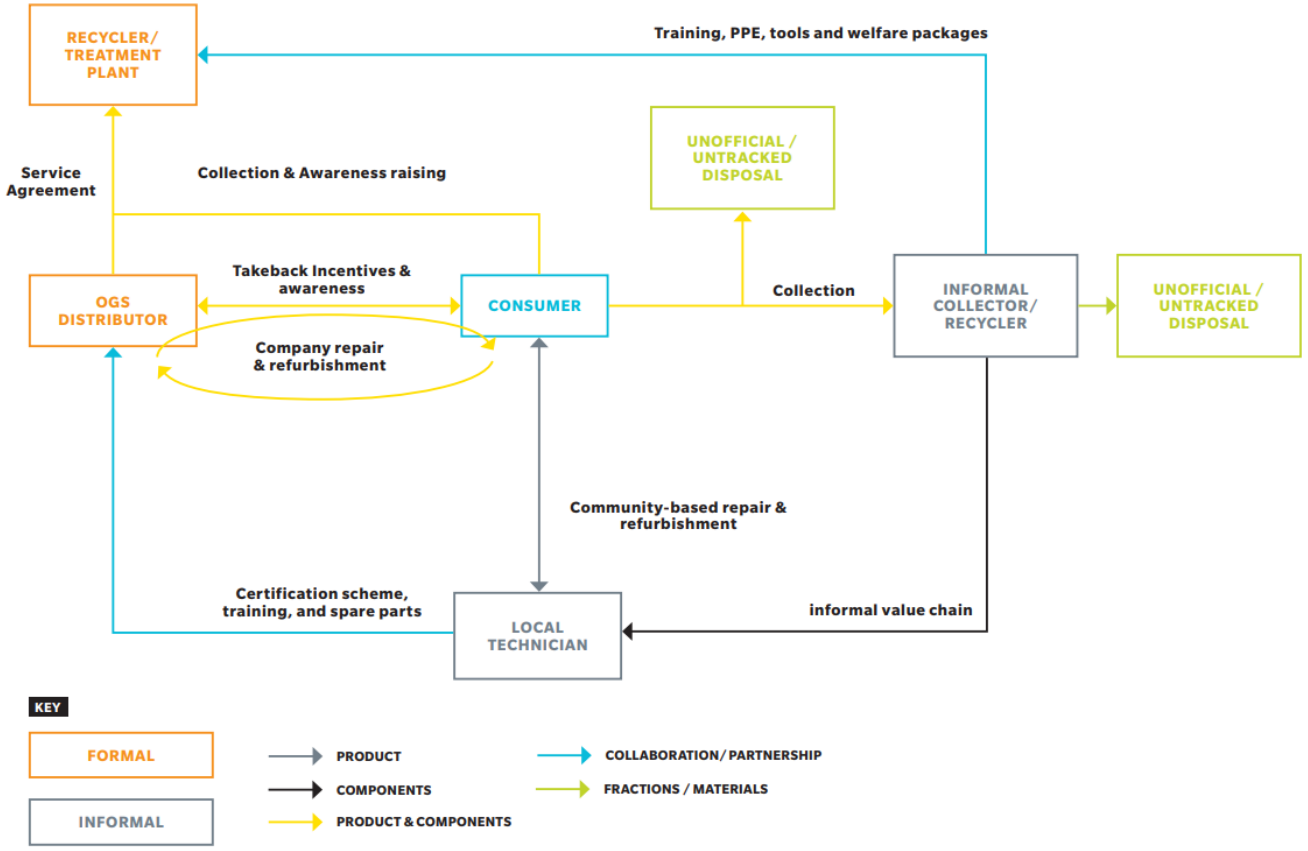
Figure 6 Off-grid solar EoL as experienced by projects funded under CLASP and Efficiency for Access's PV-focused Global LEAP challenge [19]



2.2.2. Characterising the PV EoL system

PV EoL systems in LMICs are highly fragmented, characterised by informal collection and processing with limited formal sector intervention. The system's structure is defined by the initial challenge of collection and the subsequent divergence of waste into formal and informal pathways, each with distinct processes, economic drivers and environmental consequences. Figure 6 depicts the off-grid solar EoL as experienced by projects funded under CLASP and Efficiency for Access's PV-focused Global LEAP challenge [19].

The foundational challenge for any EoL system is acquiring waste products. Consumer behaviour significantly affects this as decisions are based on an unstructured assessment of functionality. This leads to product hoarding.[20–23] Researchers in Kenya found that 65% of solar products remain in the home after they stop functioning,[24] while research on electronic waste in Mexico found that 40% is stored in homes or warehouses without further processing.[25] Research from the Global Platform for Action shows this also holds true in displacement settings.[26]

Collection of products that enter the waste stream tends to be irregular. Products under warranty may have contractual take-back arrangements with producers, although articles pointed out that such schemes tend to only exist as isolated pilot programmes with minimal coverage, e.g. Bboxx in Rwanda, Mobisol in East Africa.[23][27] It is more common for consumer initiatives to require customers to return the products to dedicated collection points (such as the WEEE Centre network in Kenya).[28] However, primary procurement channels usually rely on unregulated mechanisms, such as door-to-door scavenging by waste pickers or sales to repair shops and scrap dealers.[22][28][29] Once collected, products enter one of two streams (informal versus formal), largely determined by their origin and material value, which are detailed below.

Formal sector processes: Limited capacities and export dependence

Formal recycling is mostly focused on large-scale industrial PV waste (for example large-scale solar plants) rather than off-grid solar.[29] Because of a lack of specialised infrastructure in most LMICs, processing often involves disassembly and sorting followed by exporting components to facilities abroad.[28][30] The Global LEAP scoping report describes how emerging recycling companies (For example WEEE Centre, Enviroserve, Phenix Recycling, BESIC, EWIK, Recykla International) process solar e-waste: metals and plastics may be treated locally, while panels and lithium batteries are exported to Europe; the quality and safety of lead-acid battery recycling varies.[19] Key recycling processes for recycling panels include delamination, material separation and material extraction,[31] and final disposal is performed by licensed treatment facilities.[32]

Informal sector processes: Manual recovery and environmental hazards

Across sub-Saharan Africa (for example in Zambia, Kenya, Ghana, DRC and Malawi), EoL activities are usually performed informally by collectors or repair shop workers using rudimentary methods and tools.[22][23][27][28][33] Spare parts that could be used to repair other units are locally salvaged, and valuable fractions (such as ferrous and nonferrous metals and lead-acid batteries) are separated from the remaining material and sold on.[4][19][21][23][28] A study in India described how units are disassembled in clandestine workshops operated by local scrap dealers: firstly, the aluminium frame is separated from the panel and cut into small pieces; the glass front of the panel is then burned off in a furnace; the cells are then recovered and the silver extracted.[34] Studies from Kenya, Malawi and Burkina Faso described open-air burning to recover copper from the cables and informal lead smelting of batteries with minimal pollution control or protective equipment.[22][27–29]

Recovered materials and components are reused, often being stored for extended periods before entering second-life.[9]
The nonvaluable remains (or even whole products) tend to be dumped via landfilling or uncontrolled burning.[21–23][27–29][35–39][40]

Reconciling with the informal sector: Barriers and opportunities

The dominance of the informal sector presents a complex mix of systemic barriers and potential opportunities for effective EoL management.

Characterisation of the informal sector: The informal sector possesses strong community networks, business acumen, deep material knowledge, and is often male dominated.[41] Generally, the collectors who gather waste from households are different to aggregators and industrial disposers. Working in the informal e-waste sector is a precarious business that carries social stigma. For instance, informal scrap dealers in Uganda noted that a lack of verifiable ownership data made them prone to hassle from the police and accusation of product theft.[41]

Barriers: The prevalence of the informal sector is often seen as a barrier to developing the EoL market due to the difficulties of effectively regulating it.[34][36][38] Informal operators often outcompete formal recyclers by operating at the fringes of legality and externalising environmental and health costs.[21] By 'cherry-picking' the most valuable fractions (for example PCBs and cables), they deprive formal facilities of the critical volumes and revenue needed to achieve sustainability.[19]

Opportunities: Conversely, the sector's embeddedness can be viewed as offering unique leverage points for systemic improvement. The Global LEAP challenge highlights opportunities to collaborate with the informal sector, thereby building trust within communities and boosting local value chains and jobs. Informal repairers and refuse collectors are also a valuable source of knowledge about local e-waste ecosystems.[41]

2.2.3. Social, economic and environmental impacts of the current PV waste system

Workers in the sector

Workers involved in PV waste handling are routinely exposed to hazardous materials [19][21–23][27–29][32-33][36][38][47] such as lead, mercury, dioxins, silver, and glass dust.[19][27][28][31][34] These risks are especially acute for informal workers, who often work with crude tools, lack appropriate protective equipment and possess limited awareness of occupational hazards.[19][22][23][27][29][30][34][38][40][41] Dangerous practices documented across multiple countries increase the risks of injury, fires and electrocution.[22][34][40][41] The informal workforce is predominantly made up of young, low-educated and socially marginalised individuals who depend on low and precarious incomes.[22][23][29] This incentivises hasty and clandestine work, further exacerbating health and safety risks.[34]

However, the shift to a more regulated EoL sector risks introducing further inequities.[38] For example, the proposed EPR principles in Kenya could disproportionately burden local repairers with extra fees, reporting obligations and penalties for noncompliance. Guidelines requiring all waste from the informal repairers to go through licensed collection centres or treatment facilities could further marginalise this sector [24][51].

For the formal sector, unmanaged e-waste poses significant reputational risks to both individual solar companies and the off-grid systems (OGS) industry as a whole.[41] International investors and donors are increasingly attentive to these risks and wary of being associated with the negative social and environmental impacts of growing amounts of solar e-waste[19][27][48]. Some now require e-waste policies as a condition for grants and result-based financings (RBFs) [48]. This is particularly relevant given the financial precarity of the off-grid solar sector; as one study notes, investors agree that solar companies are not yet positioned to manage e-waste alone, as most rely on subsidies and are yet to reach financial sustainability [48].

Local communities

Communities near disposal sites suffer from pollution caused by the open burning or dumping of PV and e-waste, which leads to exposure to toxic substances.[19][20][22][28][29][33][36][38] Informal recycling of lead-acid batteries is especially harmful and is considered a leading global source of toxic pollution affecting human health.[19][27][29] Toxic hotspots such as Agbogbloshie in Ghana create unsafe living conditions, pollute local ecosystems, and reduce agricultural productivity.[27] While life-cycle assessments (LCAs) consistently show that EoL recycling reduces community health impacts, most of the empirical evidence on this comes from high-income contexts; a literature review in sub-Saharan Africa, for example, notes very few studies have measured health impacts in affected communities.[27]

Despite these harms, the literature also highlights opportunities for positive local impact through job creation,[19][26][28][31][32][36][38][46] upskilling and entrepreneurship in formal recycling and EoL interventions.[18] However, local communities also experience energy injustices that exacerbate waste accumulation. In South Africa, load-shedding drives the uptake of off-grid solar systems,[38] while in Zambia, the market dominance of unregulated, low-quality products forces consumers into repeated purchases, generating excess waste.[23] In Malawi, informal lead-acid battery recycling is pervasive. Lead emissions estimated at 100 times the lethal dose per battery and cause severe environmental and health damage.[22][73]

International communities

Although the Basel Convention has been widely adopted in LMICs, compliance remains weak and porous borders allow e-waste to move between countries.[22][27][29][41] Several studies warned of 'near-to-die' PV products being dumped in LMICs, thus absolving High-Income Countries of disposal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responsibilities.[53] While such exports may extend product life, they may ultimately transfer the waste burden to recipient countries.[53][58] This worsens global inequities by externalising environmental and health harms to poorer communities while allowing global consumers to benefit from 'clean' technologies.[33] Thus, international demand and regulations affect waste flows in other geographies.[31][22]

Waste flows are also driven by the lack of domestic recycling infrastructure [67]. Li-ion batteries from Africa are exported to Europe for recycling because of a lack of local facilities.[19] While this ensures safer processing, it perpetuates resource dependency and misses opportunities for local value creation.[27] Additionally, improper disposal results in the loss of valuable materials [22][28][68][70][77] which in turn drives demand for raw materials and harmful extraction processes.[33] International trade patterns further shape this dynamic,[66] with PV panel production concentrated in China, Hong Kong, South Korea, Canada, and the US, while most developing countries remain technology consumers [31] .

The environment

Improper disposal of PV waste leads to the leaching of hazardous materials, including lead, plastics, lithium, tin, and cadmium into soil and water systems,[21][22][31][34] causing global warming, acidification, eutrophication, biodiversity loss, and agricultural productivity loss.[27][35] LCAs consistently demonstrate that recycling has significantly lower environmental impacts than landfilling or incineration, with reductions ranging from 25% to 83% [46] across various countries, including India,[35] China,[66][68] Mexico,[46] Malawi,[22] and Thailand.[51] In Malawi, an LCA revealed lead-acid batteries as the most environmentally damaging component of SHSs, accounting for 54%–99% of impacts across each category considered.[73] The study found that battery life must exceed three years for SHSs to offer global warming benefits over diesel gensets.[73] In most cases, however, lead-acid batteries often degrade within about two years.[27]

2.2.4. The PV EoL ecosystem: System challenges and enabling factors

Economic factors: Financial viability and conflicting incentives

An analysis of different e-waste streams found PV panel waste generates the lowest profits and is economically less viable than other product types (such as mobile phones, computers, TVs, wind turbines).[25] Indeed, the literature consistently reported the financial unviability of recycling as the biggest single barrier to the solar PV EoL system.[21][27][28][37][39][47-51] Subsidies are likely required to incentivise EoL processes. [39][41][49][50][52].

Component-level analyses provide a more nuanced perspective. In sub-Saharan Africa, lead-acid batteries and copper cables can have positive recycling values, making them attractive to both formal and informal recyclers.[26-28] Meanwhile, the costs of recycling the PV modules themselves far outweigh the potential revenues. Glass is a particularly labour-intensive and environmentally destructive panel material, comprising over 75% of the total panel weight and being effectively worthless. [34] There are also valuable materials in the panels, but they are expensive to extract and the volumes are small.[47] These factors lead to varying costs of recycling for different product types. Data from eight PV waste pilots funded under the Global LEAP challenge found that an entry-level solar lantern has a negative value (therefore, a cost) of $1.36/unit at EoL, while an SHS with a lead-acid battery has a positive value of $1.01/unit.[41]

The lack of recycling facilities is also a key barrier, partially because high waste volumes are needed to approach financial viability[19][39][49] and there is a limited ability to gather waste to provide sufficient throughput. This can be attributed to the lack of collection points for customers to relinquish their waste, the absence of take-back schemes and customer propensity to hold onto their broken products.[41]

Financial viability is further compounded by the transportation costs of aggregating waste,[19][38][39] which can be substantial: an analysis of a proposed e-waste plant from India found that collection and transportation costs accounted for a quarter of the total plant treatment costs.[43] Collection is also affected by economies of scale and a study from Kenya found that off-grid solar volumes are too small at present to support cost-effective collection systems.[20] Enabling shifts to economic viability includes creating cost-sharing mechanisms between all parties involved in the EoL process,[539] future rises in material prices,[54], and strengthening secondary markets for recovered glass, silicon and metals[25][50].

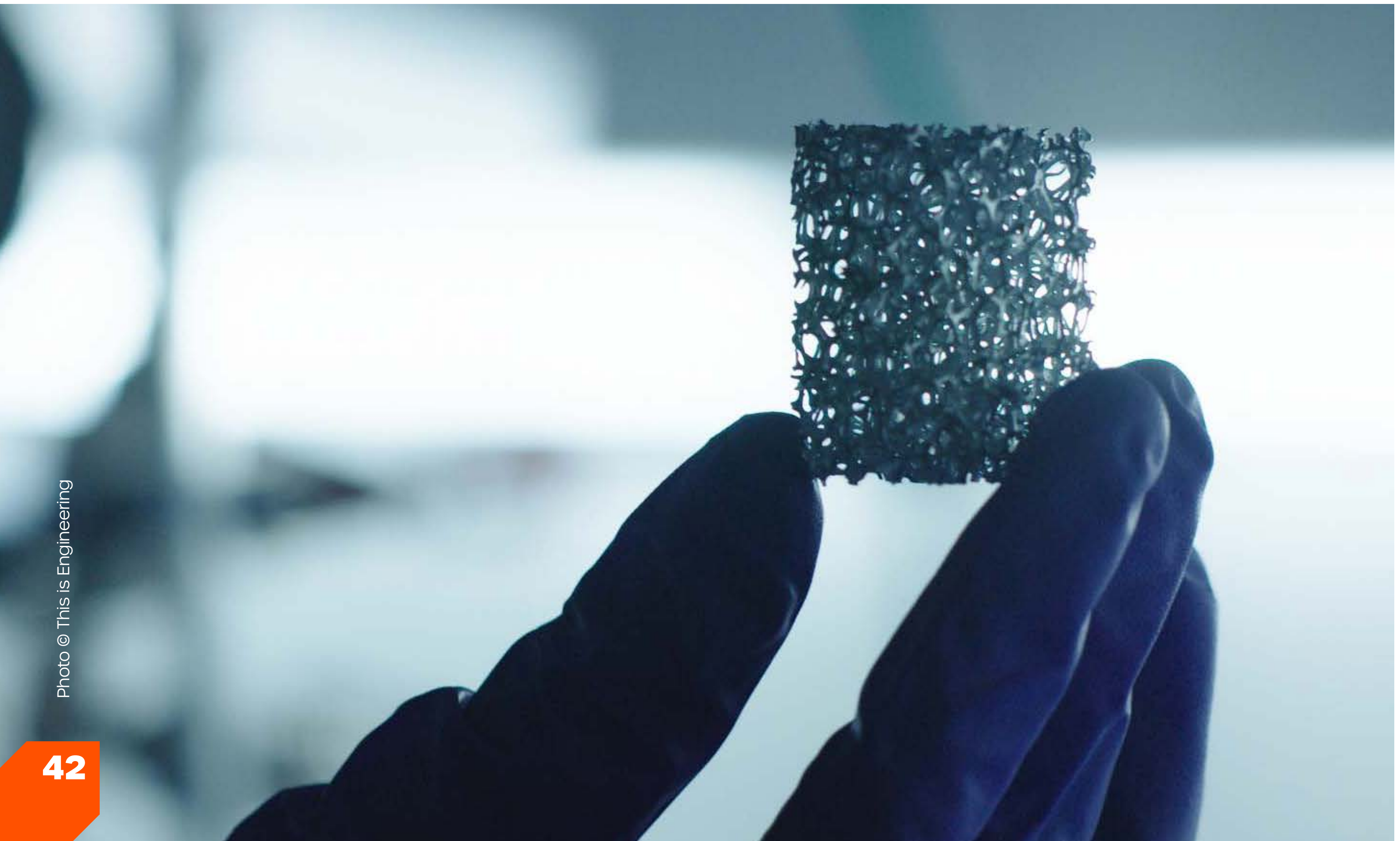
The systemic lack of financial viability for recycling creates a foundational barrier that directly influences household behaviour, as the absence of profitable recovery channels means consumers are rarely incentivised to return their waste. Several studies observed the need for incentives to reclaim products from consumers.[21] [55] [46] [48] [41] [46] [40] Suggestions included cash, airtime, discounts to reclaim products, and free products. Research from off-grid solar customers found that incentive preferences were

Photo © Andreas Gücklhorn / unsplash.com dominated by free or discounted products.[20][41] However, the incentive level needs to be appropriately set with long redemption periods so that customers do not give up products prematurely.[41]

Furthermore, the fear that embedding recycling costs will raise product prices presents an ethical dilemma that potentially compromises energy-access goals.[32] This tension highlights the unresolved question of how the financial burden of EoL management should be distributed among governments, taxpayers, users, and producers.[28] There is a clear need for harmonisation between energy-access and waste-management policies, as raising product costs to internalise recycling expenses could negatively impact product costs and energy access.[32] This risk is acute for rural consumers and communities, who often have limited financial means to improve on current practices.[30]

This dynamic can also push consumers towards lower-quality products with shorter lifespans that are harder to recycle, thus exacerbating the e-waste problem.[22][23] Therefore, willingness to pay for responsible EoL processes can act as a system enabler.[46]

EoL initiatives are often perceived as high-risk because of uncertain costs, untested business models and nascent legislation.[41] The lack of successful e-waste recycling systems examples makes it challenging for investors to assess returns and subsequently understand how to allocate resources.[44] There is a clear need for more grant funding to support innovations and scaling in the EoL space;[19][41] results-based financing, which is currently common in the energy-access sector, could particularly incentivise early adopters of e-waste management practices and fund innovative business models.[41]



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Governance and policy factors: The need for coherent regulation and political will

The literature widely acknowledges the need for coherent policies and regulations for solar PV waste management.[25][29][31][32][34][35][37][38][44][49][52-55] These would ensure that all associated waste streams are managed responsibly and safely, that products incorporate CEE considerations, that products are of a sufficient quality, and that there is transparency across the supply chain.[23][31][60] EPR models such as the European Union's Waste from Electrical and Electronic Equipment (WEEE) directive were frequently cited as aspirational frameworks for achieving this as they oblige producers to finance the collection, treatment, recovery, and environmentally sound disposal of waste from private households.[31][32][37][39][43][48][52][47[[61]

The lack of PV-specific regulations and standards was found to hinder the development of PV EoL processes in Brazil,[61] Mexico,[46] Malawi,[22] and China,[62] and the absence of policies to be a bottleneck in Malawi,[22] Malaysia,[57] Ghana,[30][63] Zambia,[23][40] and China.[39] However, positive examples from LMICs are emerging. The Basel Convention is a global treaty that controls the transboundary movements of hazardous and other wastes, aiming to reduce their transfer from high-income countries to LMICs. Most countries in sub-Saharan Africa have ratified the Convention including key off-grid solar hotspots such as Kenya, Rwanda, Tanzania, Uganda, and Mozambique. This provides a foundation for e-waste regulation, although enforcement is generally weak.[27] Kenya and Rwanda have e-waste frameworks based on EPR principles, and Ghana has an eco-levy on solar imports that relieves suppliers of operational responsibility for disposal.[27][32]

However, the prevalence of the informal sector in LMICs makes implementing these policies and regulations exceptionally challenging.[28][36] EPR and eco-levy schemes only apply to regulated products, while 72% of off-grid solar sales are unregulated.[27] This, coupled with weak enforcement capacity, makes EPR policies extremely difficult to implement even when they do exist.[22][23][27][28][30][32][38][59] Importantly, the challenge does not arise from the presence of informal actors themselves, who provide essential collection, repair and livelihood functions in many LMIC contexts, but from the absence of enabling policy, infrastructure and integration mechanisms that allow these activities to operate safely and within formalised EoL systems.

These implementation challenges are underpinned by significant political and governance hurdles. A fundamental issue is the lack of coordination and clear institutional mandates. Effective management requires cross-sector coordination between government ministries, NGOs, donors, and private firms, which is often lacking.[19][21][22][28][36][64][65]. Even where frameworks exist, governments are often hampered by unclear mandates and a lack of resources. For instance, experience from South Africa highlights challenges such as weak enforcement, the proliferation of multiple producer responsibility organisations (PROs) with limited oversight of EPR implementation and ambiguous regulatory lines that blur accountability.[38] More broadly, governments often lack the resources, technical capacity and coordinated authority to effectively provide enabling legal frameworks.[19][21]

Compounding these structural weaknesses are systemic governance gaps. Inadequate monitoring of waste flows creates a critical accountability barrier, making it impossible to track progress, enforce compliance or hold actors responsible.[66] This is exacerbated by risks of corruption and pressure from powerful global supply chains, which can overshadow nascent regulatory efforts.[33] Furthermore, the difficulty of managing transboundary waste flows requires robust regional collaboration and often exceeds current administrative capacities.[33][41][62][50]

These governance shortfalls reflect a deeper political prioritisation gap. Ambitious climate and energy-access targets drive global PV deployment, but the focus on the resulting waste problem is often inadequate.[54][67] As observed by studies in Ghana and Zambia, political attention remains fixed on increasing energy-access statistics, while the development of concomitant waste management systems is deprioritised. This creates a dangerous policy lag.[54][67]

Operational realities: Supply chain, logistics and infrastructural gaps

A foundational structural challenge is the import-dependent nature of the off-grid solar supply chain. With minimal domestic manufacturing in LMICs, most products are imported. This complicates the enforcement of quality and durability standards, as regulatory oversight is diluted across global manufacturers and distributors.

This dispersed, import-reliant model exacerbates severe logistical barriers to collecting EoL products. The high costs of collecting products from geographically dispersed customers,[19][40][48] coupled with a general lack of waste management infrastructure in rural areas,[20] stifles collection efforts. Weak reverse-logistics systems were noted across LMICs in general[53] and were specifically called out in Ghana,[36] South Africa,[38] and India.[47][52] The physical characteristics of PV panels, such as their weight, size and fragility, make transportation particularly costly and complex, a barrier explicitly identified in waste assessments from China.[39] Furthermore, a critical missing element is the lack of viable, scalable business models dedicated to waste collection, which remains a persistent obstacle to systematic recovery.[19][37]

These logistical and economic realities directly influence the feasibility of recycling infrastructure. Because of the high contribution of waste transportation to overall costs, recycling facilities should be strategically sited to minimise such costs.[68] They should have proximity to markets with multimodal transport links.[49][69] A spatio-temporal assessment of PV waste in China highlights how the uneven distribution of resources means that approximately 40% of systems are in the north/north-west of China and far from manufacturing bases in the east of China. So, the transportation costs of PV for manufacturers are huge and may discourage PV manufacturers from recycling, creating an emergent risk of landfilling/illegal disposal emerging as a result.[62]

Despite the clear need, limited PV module recycling infrastructure remains a challenge across LMICs[19][21][27][28][30][32][36][38][40][47][52][59][56][57] including in major manufacturing hubs in China that have been investing heavily in research about PV EoL.[37][54] In Africa, the inability to recycle Li-ion batteries was regarded as a more immediate bottleneck than the absence of PV cell facilities.[19][41] Paradoxically, the Global LEAP Challenge report noted that the capacity of three of its grantees who do have recycling facilities in Africa was only about 30% utilised, which is likely due to waste collection challenges.[41]

This absence of recycling capacity in sub-Saharan Africa creates the need for Li-ion batteries, solar panels and PCBs to be shipped to other continents for treatment.[28][41] While this exports environmental harms, it also conflicts with local goals of industrial development, and faces potential restrictions under the Basel Convention's controls on transboundary waste movement.[50]

Social dimensions and consumer engagement

A key social challenge is the low consumer literacy and the multiplicity of languages in many markets.[27][60] This complicates efforts to educate consumers about EoL practices and is compounded by cultural factors, such as the perception of solar products as status symbols, which encourages households to hoard nonfunctional units.[20][21][48] More broadly, the absence of a widespread culture of recycling means that even where laws and regulations exist, compliance can be low.[46]

These dynamics are linked to deeper social injustices. Research from Malawi highlights how the burdens of the current systems are disproportionately borne by the most vulnerable. Health and environmental risks are concentrated in the poorest communities forced to live near rubbish dumps, while marginalised informal workers face direct health risks due to unsafe handling practices.[22] Furthermore, product failures and a lack of accessible repair options can erode trust in solar technology itself, slowing adoption and undermining cooperation with formal take-back schemes.[27] Building engagement, therefore, depends on trust. Research from Zambia demonstrated how confidence in local repairers significantly increased the willingness to repair products, pointing to the importance of community-based relationships in shaping EoL behaviour.[23]

Data and knowledge factors: Critical gaps undermining effective management

Critical knowledge gaps exist at every level of the value chain, undermining effective management. Low awareness among solar PV users about the importance of EoL practices remains a major barrier, illustrating the need for targeted educational


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programmes to increase awareness of health risks and disposal impacts.[19][20][21][23][25][30][31][32][40][41][46] Several actors believe that such education should begin from the point of sale such as by including disposal guidance in a customers' 'welcome kit'.[41][60] It should cover usage and maintenance advice to extend product lifespans, such as best battery charging practices and cleaning procedures for panels.[22][41]

Knowledge gaps among intermediaries are equally significant. Technicians, sales agents and companies, who are typically the primary point of contact with the customer, often possess varying knowledge levels needed to guide EoL decisions. Technicians need to be equipped to make decisions about how to deal with nonfunctioning products; this, in turn, would help develop second-hand markets.[32][36][41][70]. Indeed, the LEAP Challenge found that extensive staff training was a critical success factor for the pilots they funded and recommended that the training curriculum should cover health and environmental risks, the motivation for responsible waste management, health and safety relating to handling and storage of e-waste, PPE and storage requirements, and individual project processes for collection and community engagement.[41] Effective technician training can also help mitigate premature waste generation caused by poor installation that results in product breakages, shortening the product's lifespan and thus accelerating the generation of PV waste.[22][49] Similarly, companies selling solar products require better knowledge of available recycling options and associated costs to make viable EoL decisions.[19]

At a systemic level, severe data gaps hinder planning and policy. There is a consistent lack of reliable data on installed PV stock, accurate EoL timelines, PV waste volumes, material flows, and national recycling capabilities.[19][37][52][66][67] These gaps are particularly acute for the off-grid solar sector[51][55][67] especially for unregulated products that dominate sales.[27] Furthermore, a lack of performance data on ageing modules and second-life outcomes for repaired products creates market hesitancy and limits circular pathways.[38][61] The data that does exist is often unreliable, with common underreporting of waste volumes to avoid taxes or responsibilities.[34][50] Collectively, these informational deficits create large uncertainties around the impacts of the current system, future waste volumes and optimal management strategies.[39][67] revealing the need for internationally harmonised monitoring systems to track waste.[22] [50] [52] [58] [70]

2.2.5. Stakeholder mapping of PV waste sector: Key players, programmes and initiatives

The solar PV EoL system in LMICs involves a wide range of actors operating across international, regional, national, and local levels. These include international organisations, development-finance institutions, national governments and regulators, solar companies, recyclers, research institutions, and end users. Together, these actors shape policy design, standards setting, financing, market practices, waste collection, recycling capacity, and consumer behaviour.

The literature indicates that PV EoL governance is therefore inherently multi-actor and multilevel. International bodies and donor programmes help frame agendas and incentives; national institutions establish regulatory and enforcement conditions; private-sector actors influence operational practices and market development; and recyclers, repairers and consumers ultimately determine how materials move through formal and informal EoL pathways.

Given the breadth of actors involved, a full stakeholder mapping is provided in Appendix 5.2, where the principal organisations, initiatives and stakeholder categories identified through the literature review are summarised.

2.3. Key engineering challenges and opportunities for PV EoL systems

This section highlights the technical and engineering-related challenges reported in the literature. As this review focused on LMICs, the findings are inherently biased towards research from this context. Therefore, while not exhaustive, the following list outlines the most acute and addressable barriers and opportunities for the country bloc.

2.3.1. Circular economy considerations in PV product design and repair

PV products are rarely designed with CEE principles in mind[58] [22] [25] [32] [36] [52] [37] [50] Many off-grid products are engineered for durability in harsh environments, resisting dust, rain and physical damage, but these robust designs often complicate dismantling and recycling.[41] Interestingly, unregulated SHSs typically employ simple, modular designs that enable repair and refurbishment, supporting informal repair economies and extending product lifetimes when spare parts are available.[27] In contrast, regulated products, especially pay-as-you-go (PAYG) systems, often incorporate proprietary, tamper-resistant designs that limit repairability to protect warranties and prevent unauthorised access, further constraining circularity [27] [41] [71] This tension extends to manufacturing; emerging technologies that enhance durability and performance, such as high-temperature vacuum lamination, can also complicate disassembly during EoL recycling phase[76].

The role of repair in reducing waste is substantial. A study from China estimated that the PV sector could generate up to 30 times more waste if modules fail to achieve their intended lifespan.[62] While there is limited data on repair within the formal solar sector, where warranties often focus on fixed-term guarantees of product functionality, the Global LEAP Fund highlighted need for off-grid solar companies to offer reliable repair services for out-of-warranty products.[41] Research from Ghana estimated that minimally damaged PV panels still performing with lowered efficiency have about five times the value for reuse rather than recycle.[63]

Much of the existing literature tends to focus on informal repairers, acknowledging their resourcefulness and critical role in extending product lifespans.[22][24][34][40] However, the sector faces considerable constraints. For example, the Global LEAP final report found that many informal technicians lack access to high-quality tools for repair, often breaking casings to access internal components and then reassembling them with glue, which reduces the product lifespan.[41] Sourcing high-quality parts remains challenging because of the costs and complexities of importing small volumes, and the dominance of low-quality, unregulated products limits what can be harvested from local waste streams.[41] This makes the repair and refurbishment of regulated products particularly valuable as they can serve as a source of reliable spare parts.[27][28] Other behaviours observed in some markets include customers swapping parts between broken devices, as noted by SolarAid in Zambia[23] and frequent reports of missing, lost, or stolen components among nonusers.[24]

2.3.2. Opportunities for advancing a circular solar economy

Market growth and economic potential

The rapid expansion of the solar market means that future waste volumes will grow substantially, necessitating proactive EoL system development.[28][31][48] A growing supply chain for critical materials such as silicon, germanium and lithium used in panel manufacturing further increases the incentive for EoL management.[31] Economic analysis also indicates that the total value of solar PV e-waste generated between 2020 and 2047 could reach approximately $645 trillion at current commodity prices, with up to 70% ($452 trillion) recoverability using state-of-the-art recycling techniques.[52] Another projection estimates cumulative economic value from recycling could reach $14 billion by 2050, driven by high-value materials such as silver, copper and tellurium.[72] Recycled materials can also significantly reduce pressure on raw material supply chains; a study from China highlights a 'complementary effect', in which recycled inputs could satisfy an average of 65% of annual new capacity needs.[72] Conversely, without adequate recycling systems, the accumulation of waste also represents a future financial burden for countries.[59][67] It is also important to note a current urban bias in the knowledge base, with a focus on certified companies in East Africa that may neglect generic products and informal markets elsewhere in sub-Saharan Africa.[19]

Designing for circularity

Products should be intentionally designed with CEE principles in mind. EEP Africa provides several recommendations here, including: engage with manufacturers to replace hazardous materials with environmentally-friendly alternatives; design for easy dismantling using screws and surface mounting instead of adhesives, and with clear component labelling; minimise contaminants by limiting plastic varieties; adopt modular designs to simplify fault diagnosis and on-site repair; provide spare parts and an easy-to-understand repair guide; proactively address common failure points using smart monitoring; use robust, longer-lasting components and protect fragile parts; and encourage multiple product lives through the second-hand markets by using open-source software, common parts and supporting product standardisation.[78]


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Facilitating third-party repairs

Open-source repair applications can significantly extend product lifespans.[24][52] For example, with support from the LEAP Challenge, SunnyMoney developed a free app that guides diagnostics and repair for products from major OGS companies, demonstrating potential for wider adoption with further investment.[41]

Improving product tracking

Improved product traceability could support future collection, forecasting and accountability, particularly where PAYG platforms already generate asset-level data,[28][53] opportunities for blockchain to digitalise the entire value chain and resolve tracking issues also exist.[39][79]

Innovating waste collection systems

OGS companies can leverage their existing customer relationships and distribution networks to promote product return behaviour, raise awareness about e-waste and enable reverse-logistics systems.[19-21][27][28][32][41] These established channels, alongside informal collection networks, provide practical entry points for aggregating PV waste in dispersed markets. The literature highlights the potential of collaborative take-back models and hybrid formal–informal approaches, where trusted local collectors can increase return rates while helping to reduce collection and transportation costs.[21][22][41]

Developing recycling infrastructure

There is a clear need to expand recycling facilities in LMICs.[69] Lead recycling is particularly feasible in terms of its economic viability and environmental sustainability although it requires significant capital investment.[27][69] In the interim, local dismantling followed by export for advanced recycling offers a pragmatic solution.[27] Governments can also lower the cost of e-waste removal by investing in broader waste management infrastructure.[41]

2.3.3. Synthesis: Priority engineering challenges and opportunities for PV EoL

Systems-level improvements

Enhancing the broader infrastructure for managing PV system waste is critical.

- **Improved tracking, forecasting and data systems**. There is a need for better systems to track the amount of PV stock, its whereabouts and battery health.[19] Concurrently, waste forecasting techniques such as GRA-BiLSTM and Weibull failure rate models require improved data inputs.[50][55][68]
- **Standardised decision-making protocols**. Technicians need better

support for making decisions on dealing with products. This requires innovation around nondestructive testing and standardised data collection and sharing protocols across the supply chain. [46][61] Some progress has been made here; Marinna et al. [61] developed a methodology for decision-making and reuse of PV modules as a resource extension in Brazil, but the extent to which this has been implemented or tested in other contexts is unclear.

- **Lack of testing and certification infrastructure**. Beyond the widespread absence of enforced technical standards, there is also a notable shortage of testing facilities and processes to support implementation including for the second-life recertification.[23][36][38]

Product design

Current product designs create barriers to circularity and long-term sustainability.

- **Designs that hinder EoL processing**. PV modules are rarely designed for recycling.[54] Opportunities exist to improve design for repairability, recyclability and reduced environmental impact.[19][37][54][67][69]
- **Increasing complexity and toxicity**. PV products are becoming riskier and harder to recycle. Thin-film PV technologies contain more toxic materials (for example gallium, selenium, tellurium, and indium) which require careful disposal,[70] and are also more complex to disassemble and recycle because of their thin multijunction layers.[71] These challenges point to a need for R&D in recycling technologies for new panel types.[39]
- **Battery lifespan as a system weakness**. Batteries are often the first component to fail so there is a clear opportunity for their lifetime improvement.[19][27][33] Lead-acid batteries degrade particularly quickly,[27][69] accelerated by battery misuse (for example unregulated systems often use automotive batteries not designed for continuous discharge),[22][27] lack of charge controllers,[22][27] and improper sizing relative to panels, which causes chronic undercharging.[27]
- **'Black-boxing' that prevents repair**. Regulated products, especially tamper-proof PAYG systems, often use sealed designs that prevent informal repair and therefore reduce lifespan.[67] Proprietary components can also hinder informal or local repair efforts, effectively reducing product lifespan.[27]

Recycling processes

The core recycling technology faces fundamental hurdles between cost and recovery efficiency.

- **Low material recovery rates and purity**. Under rudimentary extraction processes, low recovery rates and poor purity of extracted materials hinder economic viability.[33][39][46][47][54] While several different processing methods are employed, there is often a trade-off between cost and recovery rate. For example, mechanical crushing is low cost but has limited recovery efficiency due to incomplete separation, resulting in material losses. Thermal cutting and laser peeling methods are efficient and nondestructive but operate on a piece-by-piece basis and are energy-intensive.[72]
- **The challenge of EVA delamination**. Ethylene-vinyl acetate (EVA) is a specialised thermoplastic copolymer film that seals and bonds the solar cells within the panel structure, acting as a strong adhesive that bonds the glass, solar cells and backsheet into a laminated structure. Breaking down this adhesive bond cost-effectively remains a central technological challenge in the PV recycling process.[33][38][39][43][47][54]
- **Need for advanced and efficient methods**. Innovations in thermal and chemical recycling methods are emerging but are yet to be deployed at scale.[46][54][72] Improving the overall energy efficiency of recycling processes is a parallel pathway to enhancing financial viability.[43][62][64][71]


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3. Case Studies

3. Case Studies

3.1. Introduction

The case studies are designed to complement the cross-country literature review by providing grounded, system-level insights into how PV EoL challenges manifest in practice, how they are currently managed and where opportunities for intervention exist.

3.1.1. Case study approach and methodology

The case studies were developed using a mixed-methods approach combining targeted (country specific) desk-based review of policy, regulatory and academic literature with qualitative stakeholder engagement. For each country, the team reviewed relevant national energy and waste policies, e-waste strategies, regulatory frameworks, and available empirical studies on off-grid solar, electronic waste and CEE practices. This was supplemented by informal and semistructured interviews with stakeholders across the private sector, government, regulators, academia, civil society, and donor organisations.

Interviews focused on mapping current PV deployment pathways, EoL practices, institutional roles and responsibilities, market incentives, and perceived barriers and opportunities for improved PV EoL management. Given the exploratory and system-mapping nature of the study, interviews were primarily qualitative and interpretive rather than statistically representative. A full list of stakeholders consulted for each country is provided in Appendix 5.3.

3.1.2. Selection and justification of case study countries

Five countries were selected for detailed case study: Malawi, Kenya, Rwanda, Nepal, and India. The selection was guided by the need to capture diversity across geographies, market maturities and institutional models, while remaining feasible within the project time frame. Together, they represent contrasting but complementary system types, including donor-driven off-grid expansion (Malawi); rapidly growing private-sector and commercial solar markets (Kenya); a highly formalised and state-regulated e-waste model shaped by donor conditionality (Rwanda); and community- and entrepreneur-led renewable-energy deployment with emerging CEE initiatives (Nepal). India provides a higher-volume, more industrialised reference point, reflecting a rapidly scaling utility and rooftop PV market, an emerging domestic manufacturing base and early development of PV recycling capacity and formal regulatory foundations.

3.1.3. Role of the case studies within the report

The case studies are not intended to be exhaustive national assessments. Rather, they function as illustrative system snapshots that highlight common patterns, divergences and leverage points across LMIC PV EoL systems. Findings from the case studies are synthesised in the subsequent cross-country analysis to inform the technical, policy and engineering recommendations presented later in the report.

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3.2. Malawi

3.2.1. Country and PV market context

PV market overview

Malawi's energy sector is characterised by persistently low levels of grid electrification and a strong reliance on off-grid solar technologies to meet national and international energy-access targets. Fewer than one-third of households have access to electricity, with rural access rates below 5%, making decentralised solar systems a pillar of Malawi's electrification strategy.[80] National policy frameworks,[80][81] explicitly recognise SHS and pico-solar products as legitimate and necessary contributors to universal access. This policy orientation has been reinforced by large donor-funded programmes, most notably the World Bank-supported ASCENT programme, which aims to deliver electricity services to more than 800,000 households, schools and health facilities through a mix of grid extension and off-grid solar solutions. Off-grid solar is expected to carry a substantial share of this expansion, particularly in rural and peri-urban areas where grid extension remains economically challenging. As a result, Malawi has experienced rapid growth in the deployment of SHS, institutional PV systems and small-scale C&I rooftop installations, largely delivered through private-sector supply chains.

Stakeholders reported persistent quality challenges, including the circulation of substandard and counterfeit products, particularly in informal and lower-tier markets where price competition is intense and regulatory enforcement is weak. Short product lifetimes are a defining feature of Malawi's off-grid PV market. This emerging stream of PV-related e-waste is not yet fully recognised within energy-access planning but represents a structurally embedded risk within current electrification pathways.

Relevant policies and initiatives

Malawi currently has no policy or regulatory framework specifically addressing the EoL management of solar photovoltaic (PV) technologies. Instead, PV waste is implicitly captured within broader energy, waste and environmental governance frameworks, none of which provide clear mandates, pathways or enforcement mechanisms tailored to solar technologies.

- **National E-waste Management Policy (2024)**[82] recognises WEEE as a rapidly growing and under-managed waste stream and proposes the introduction of EPR, the establishment of take-back and collection systems, financing mechanisms for recycling infrastructure, and national awareness and capacity-building programmes. The policy does not explicitly address solar PV modules, batteries or BoS components, nor does it define PV-specific interventions. Implementation remains at an early stage, with limited operationalisation, financing or enforcement to date.
- **National Energy Policy (2018)**[81] The policy explicitly recognises SHS, pico-solar products, mini-grids, and other decentralised technologies as legitimate contributors to national electrification targets. However, the policy is silent on EoL considerations, product stewardship or waste management responsibilities associated with solar technologies.

Overall, Malawi's policy landscape demonstrates growing recognition of e-waste as a national challenge but stops short of addressing the specific characteristics, risks, and scale of PV EoL flows.

3.2.2. Current PV EoL practices

Existing EoL pathways

The majority of solar PV companies operating in Malawi lack formal EoL management systems or structured take-back mechanisms. Interviews with private solar firms, regulators and local authorities indicated that responsibility for failed components typically ends once products are sold or donor projects conclude. As a result, EoL PV components are commonly stored in company warehouses, informal repair workshops, institutional storerooms, households, or left in communities once systems fail. In the absence of accessible, affordable and regulated recycling infrastructure, a substantial share of PV waste enters informal waste streams.

At the end-user level, households and institutions often retain faulty SHS components (batteries, controllers, lanterns, panels) until fully unusable. Some attempt repairs via local technicians, but repeated failures frequently lead to abandonment, and – with no official collection points – most users dispose of failed components through general household waste, consistent with wider national patterns of long-term storage and informal disposal. SolarAid and partners provide an important repair and refurbishment pathway through repair labs and training centres that extend the lifespan of GOGLA-certified products, but stakeholders reported that capacity is outpaced by failure volumes – particularly for low-cost PAYG systems and noncertified imports – leading to stockpiling of nonrepairable devices and associated secondary waste risks.

Where components cannot be repaired or reused, PV waste is routinely discarded at municipal dumpsites, where waste pickers recover higher-value materials such as copper and aluminium and low-value plastics and insulation are often burned. Malawi's only known structured pathway is operated by Omicron and its sister company SETEBOS, which provide PV waste handling and preprocessing capacity of approximately 200–5,000 small PV panels per month: selected fractions are dismantled and exported (such as PV cells to Dubai), aluminium frames are sold locally or regionally, and glass and hard plastics are typically landfilled because of limited recycling routes. Li-ion batteries are stockpiled given the absence of domestic or regional processing options, and stakeholders reported that buy-back or return schemes have seen low compliance because of transport costs, weak incentives and limited enforcement.

Policy and institutional framework

Interviews across government, regulators, municipal authorities, and industry groups highlighted fragmented and unclear institutional responsibility for PV EoL management. No agency has been formally designated to oversee PV EoL across the value chain. Malawi Environmental Protection Authority (MEPA) holds a general hazardous waste mandate but lacks PV-specific standards and enforcement tools; the Malawi Energy Regulatory Authority (MERA) regulates product standards and imports but has no disposal authority; and city councils manage municipal waste but lack mandate and capacity for specialised e-waste streams.

Malawi Communications Regulatory Authority (MACRA) has led development of national e-waste policy, but implementation has been limited. Renewable Energy Industry Association of Malawi (REIAMA) has begun convening industry discussions on PV waste, but these efforts remain voluntary. Stakeholders emphasised weak coordination across institutions, contributing to limited oversight and continued reliance on informal disposal pathways.

Market and supply chain considerations

Malawi's import-dependent PV supply chain shapes EoL outcomes. Imports from manufacturers in China span wide quality and price ranges, and weak enforcement enables substandard and counterfeit products to enter the market, accelerating failures and waste generation. Solar companies reported that, without clear disposal routes, failed products are often stored indefinitely to avoid liability or reputational risks.

Informal aggregation networks underpin material recovery: plastics are sorted and sold locally, while metals (notably copper and aluminium) are exported through regional trade routes. Stakeholders noted competition in scrap export markets and the transboundary nature of material flows. Despite these networks, Malawi lacks coordinated reverse logistics for PV waste at scale; municipal transfer stations could serve as collection hubs, but pilots and financing mechanisms are not yet in place.

Social and environmental impacts

Available evidence indicates significant risks from informal recycling and disposal, particularly for lead-acid batteries, where unsafe handling can cause severe lead and acid contamination and undermine the environmental benefits of solar electrification. Open burning of cables and plastics releases toxic emissions and dumping of panels and electronics contributes to contamination at municipal sites. Li-ion batteries represent an emerging risk as deployments increase without corresponding treatment pathways.

Impacts are concentrated among informal waste workers and communities near dumpsites, where exposure occurs without protective equipment and alongside unmanaged waste accumulation. Premature SHS failures also reduce energy service reliability, increase household financial vulnerability and erode trust in solar technologies. Stockpiles of failed PV systems at schools, clinics, NGOs, and government facilities represent a growing unmanaged hazard.

3.2.3. Market strengths and weaknesses

Areas of good practice

- Repair and refurbishment initiatives (SolarAid) are starting to demonstrate viable approaches for extending product lifetimes and delaying waste generation.
- Existing private-sector operators (Omicron) show technical capacity for PV dismantling, aggregation and export-based material recovery.
- Industry coordination through REIAMA provides an emerging platform for collective action and discussions on PV waste.
- Municipal waste infrastructure offers practical entry points for future PV collection systems.

Key challenges

- **Technical:** Malawi lacks domestic capacity to recycle PV modules or Li-ion batteries, while lead-acid battery treatment occurs largely through informal and unsafe processes. Short battery lifetimes accelerate waste accumulation and nonmetallic fractions such as glass and mixed plastics currently have no viable processing routes, resulting in landfilling or open dumping.
- **Economic:** PV components are bulky and low in recoverable value, making export-based recycling costly and often uneconomic without subsidies or cross-financing mechanisms. Recycling costs frequently exceed material value, creating limited incentives for voluntary take-back or participation by solar companies.
- **Regulatory and Institutional:** No authority has been formally assigned responsibility for PV EoL management, resulting in fragmented oversight and

weak enforcement. Limited control of product standards allows substandard equipment to enter the market and fail prematurely, while the absence of reliable national data constrains planning and investment in formal waste management systems.

- **Social:** Informal dismantling exposes workers and nearby communities to hazardous materials, while awareness of safe disposal options remains low among households and institutions. Environmental and health impacts are therefore disproportionately borne by vulnerable populations living near informal recycling and disposal sites.

3.2.4. Opportunities and priority actions

Opportunities

Immediate (0–2 years)

- Pilot PV collection points in major urban centres using existing municipal waste-transfer infrastructure.
- Expand repair and refurbishment programmes to delay entry of systems into waste streams.
- Implement coordinated national awareness campaigns on safe PV disposal and handling.

Medium term (2–5 years)

- Assign clear institutional responsibility for PV EoL management across energy and environmental agencies.
- Develop national reverse-logistics systems linking collection points with aggregators and licensed recyclers.
- Establish national PV deployment and waste-tracking systems to support future policy design and EPR implementation.

Long term (5+ years)

- Introduce phased EPR mechanisms once collection and data systems are operational.
- Develop regional recycling partnerships to achieve economies of scale for specialised material recovery.
- Integrate PV life cycle planning into future energy-access programmes and national CEE strategies.

Priority actions

- **Conduct a national PV waste-flow assessment:** Develop an evidence base on existing and projected PV waste volumes, storage practices and disposal pathways to support policy development and infrastructure planning.
- **Pilot decentralised PV collection systems:** Establish certified collection points through municipalities, solar companies and service centres in major urban areas to enable safe aggregation of EoL PV components.
- **Clarify institutional mandates for PV EoL management:** Assign clear responsibility across environmental, energy and local government institutions and establish coordination mechanisms to address regulatory fragmentation.
- **Strengthen repair and refurbishment capacity:** Expand technician training and support existing repair initiatives to extend system lifetimes and delay entry of PV components into waste streams.
- **Develop a national reverse-logistics model:** Link local collection points with aggregators and licensed processors to enable safe handling, preprocessing and preparation of materials for regional recycling.
- **Improve enforcement of solar product quality standards:** Strengthen import controls and market surveillance to reduce substandard equipment entering the market and contributing to premature system failure.
- **Integrate PV EoL requirements into electrification programmes:** Ensure future donor-funded and national energy-access initiatives include provisions for repair, collection and safe disposal throughout the project life cycle.

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3.3. Rwanda

3.3.1. Country and PV market context

PV market overview

Rwanda has experienced rapid growth in solar photovoltaic (PV) deployment over the past decade, driven by a strong national commitment to universal energy access and extensive donor-supported programmes. SHS, solar lanterns, institutional installations for schools, health centres, and telecom infrastructure as well as mini-grids form the core of Rwanda's current PV market. The majority of systems have been deployed since approximately 2015, aligned with the government's Rural Electrification Strategy, which positions off-grid and mini-grid solutions as key contributors to national access targets. Available evidence suggests that Rwanda's PV fleet remains relatively young in life cycle terms. However, early component failures and warranty-driven replacements are already generating EoL flows, particularly for batteries, lamps, charge controllers, and cabling. Studies of the off-grid sector indicate that many small solar products are sold with one- to three-year warranties, while batteries (especially in SHS) often require replacement within 1.5–3 years, meaning that PV-related waste emerges well before full system EoL.[83]. Stakeholders reported that a substantial increase in PV and BoS waste is expected in the near term, as early deployments from the mid-2010s reach replacement cycles.

Unlike many peer countries, Rwanda is increasingly recognised as a regional leader in structured e-waste governance, including solar-related waste. The country has developed a comprehensive National E-Waste Management Policy[84] and invested, with donor support, in a centralised dismantling and recycling facility operated through a public–private partnership. Solar products are explicitly included within the scope of Rwanda's e-waste framework and off-grid solar companies participating in donor-funded programmes – such as results-based financing schemes supported by the World Bank – are required to demonstrate formal arrangements for EoL management, typically through memoranda of understanding with licensed recyclers.

As a result, while Rwanda's PV market is still dominated by off-grid and institutional systems rather than large-scale grid-connected solar, EoL considerations have been embedded earlier in the deployment cycle than in most LMIC contexts.

Relevant policies and initiatives

Rwanda has established one of the most advanced and coherent policy frameworks for electronic waste management in sub-Saharan Africa, with explicit relevance for PV technologies. The National E-Waste Management Policy (2018).[84] provides a comprehensive framework covering the collection, transport, treatment, and disposal of waste electrical and electronic equipment, explicitly including solar PV. The policy embeds principles of EPR, private-sector participation, licensing of recyclers, and environmentally sound management, with a strong emphasis on minimising environmental and public-health risks associated with unmanaged e-waste.

The Energy Policy (2025) reinforces this framework by prioritising renewable-energy deployment alongside environmental sustainability and responsible infrastructure development. While the policy does not provide detailed technical guidance on PV EoL management, it explicitly recognises waste management as a cross-cutting concern within the energy transition, creating a clear policy mandate for integrating PV life cycle considerations as deployment scales.[85] In practice, Rwanda's policy framework is operationalised through a centralised, licensed e-waste management model, delivered via public–private partnerships. Stakeholder interviews confirmed that policy implementation in the solar sector is closely linked to donor and development-bank conditionality, particularly for off-grid solar programmes supported by results-based financing. Solar companies participating in these schemes are required to demonstrate formal EoL arrangements, typically through memoranda of understanding with licensed recyclers which cover the collection and treatment of PV modules, batteries and BoS components.

3.3.2. Current PV EoL practices

Existing EoL pathways

At the core Rwanda's centralised e-Waste system is Enviroserve Rwanda, the country's sole licensed formal e-waste recycler, which plays a central role in the collection, handling and treatment of PV EoL materials. PV panels, batteries, cables, lamps, and associated electronic components are collected through multiple channels, including off-grid solar companies, telecom operators, public and private institutions. Stakeholders reported that formal collection is most systematic for commercial, institutional and donor-supported solar deployments, where contractual and regulatory requirements are clearer, while household-level collection remains more limited and dependent on awareness and accessibility.

A defining feature of Rwanda's PV EoL system is the role of donor- and development-bank conditionality. Solar companies participating in off-grid programmes supported by the World Bank and other development partners through results-based financing schemes are required to demonstrate formal EoL management arrangements as a condition of funding. In practice, this has led most participating companies to sign memoranda of understanding with Enviroserve, ensuring that PV modules, batteries and BoS components are directed into licensed treatment pathways from the outset.

At Enviroserve's facility, received equipment is sorted, tested and dismantled according to material type and hazard class. Batteries are routinely tested for residual performance, and those operating at approximately 80% of original capacity or above may be repurposed for secondary applications. Components that cannot be processed locally such as PV modules and certain battery chemistries are prepared for export to international recycling facilities with more advanced treatment technologies, such as Dubai. Hazardous fractions are managed under controlled conditions, avoiding informal dismantling, open burning or uncontrolled disposal pathways that are common in less formalised systems.

Policy and institutional framework

Rwanda's PV EoL system is underpinned by relatively clear institutional arrangements, anchored in national e-waste policy, though day-to-day enforcement relies more on programme design and financing conditions than on routine inspection or penalties. Overall policy oversight for e-waste management sits with the Ministry of Environment, which is responsible for setting national direction on environmentally sound management of electronic waste, including renewable-energy technologies. Responsibility for the deployment and regulation of solar PV systems is shared with energy-sector institutions, reflecting Rwanda's integrated approach to aligning energy access, environmental protection and infrastructure development under national planning frameworks.

Stakeholders also noted that privately financed or non-donor-supported systems may be less consistently captured, as routine inspections, penalties and independent verification mechanisms remain limited. As PV deployment expands beyond donor-backed programmes, sustaining high compliance levels is likely to require stronger integration of PV EoL obligations into standard regulatory and licensing processes, rather than reliance on conditionality alone.

Market and supply chain considerations

Rwanda's PV EoL supply chain is characterised by a highly centralised model, with collection, dismantling and coordination concentrated around a single licensed recycling facility. This approach simplifies institutional coordination and compliance but also creates reliance on one operator for national PV and e-waste flows. Stakeholders noted that while this model has enabled rapid system development, it introduces potential risks related to capacity constraints and operational resilience as waste volumes increase.

In practice, collection and transport costs are typically borne by private companies, particularly off-grid solar providers and institutional system owners, while direct recycling fees are limited or absent. Local processing focuses on dismantling, sorting, testing, and preprocessing, with advanced material recovery conducted abroad because of the lack of domestic treatment technology. Enviroserve already manages cross-border e-waste flows from neighbouring countries, positioning Rwanda as a potential regional hub for solar and electronic waste management, albeit one that currently depends on international downstream processing. Stakeholders reported that existing capacity is sufficient for current PV waste volumes, but expansion is anticipated within the next two to three years as early off-grid solar systems reach replacement cycles and overall PV deployment continues to grow.

Social and environmental impacts

Centralised collection and controlled processing significantly reduce the risks associated with open dumping, burning and informal dismantling of PV components, helping to prevent soil, water and air contamination. Occupational health and safety conditions are also improved, as PV and battery handling takes place within licensed facilities operating under regulated procedures, rather than through informal waste picking or household-level disposal. By providing a recognised and licensed endpoint for PV waste, Rwanda's system largely prevents solar panels, batteries and associated electronics from entering municipal dumpsites or informal waste streams, although not completely. This reduces exposure risks for vulnerable communities living near disposal sites and supports broader national environmental and public-health objectives.

However, stakeholders identified several remaining challenges. Public awareness of PV EoL obligations remains relatively low, particularly at the household level, which can limit return rates for small solar devices. Behavioural barriers persist where incentives to return EoL equipment are weak or unclear. In addition, Rwanda's continued reliance on export for final material recovery introduces cost and carbon implications and leaves the system exposed to international market and regulatory changes, highlighting the importance of developing greater domestic processing capacity over time.

3.3.3. Market strengths and weaknesses

Areas of good practice

- Rwanda has an established national e-waste policy framework that explicitly includes solar technologies.
- A centralised licensed recycling model has reduced fragmentation and created a clearer endpoint for PV-related waste streams.

- Donor and development-finance conditionality has been effective in driving compliance among off-grid solar companies in supported programmes.
- Coordination between public institutions, private-sector actors and development partners has enabled early operationalisation of e-waste systems relative to many peer contexts.

Key challenges

- **Technical:** Domestic capacity for advanced PV module and battery recycling remains limited, requiring continued reliance on export for downstream material recovery and treatment.
- **Economic:** Long-term financial sustainability of the centralised recycling model may become challenging as PV waste volumes increase, particularly given dependence on external processing markets and associated transport costs.
- **Regulatory and institutional:** Rwanda's system currently relies heavily on donor and programme conditionality to ensure compliance and stronger integration of PV EoL requirements into routine regulatory and licensing frameworks will be required as privately financed deployment expands. Dependence on a single licensed operator introduces potential system resilience risks as waste volumes scale.
- **Social:** Household-level collection and consumer engagement mechanisms remain underdeveloped, limiting return rates for small solar devices and dispersed off-grid users.

3.3.4. Opportunities and priority actions

Opportunities

Immediate (0–2 years)

- Strengthen public awareness and practical guidance on return options for SHS and pico-solar products, targeting households, installers and local authorities.
- Improve accessibility of household-level collection pathways, including through retail/service networks and community drop-off points.

Medium term (2–5 years)

- Expand local preprocessing capacity and improve logistics models for collection and consolidation, reducing handling risks and improving traceability.
- Strengthen national data systems to track PV deployments and forecast waste streams, including through linkage to programme reporting and import records.

Long term (5+ years)

- Develop Rwanda's role as a regional hub for PV and e-waste management where appropriate, while ensuring safeguards, regional agreements and viable downstream options.
- Explore pathways to increase domestic value capture over time through targeted investment in processing technologies that match projected waste volumes and material streams.

Priority Actions

- Strengthen household collection and engagement mechanisms to reduce leakage of small solar-waste streams by improving accessibility of return pathways through retailers, service networks and community collection points.
- Build PV deployment and EoL data visibility to support forecasting, infrastructure planning and evidence-based sequencing of policy and investment decisions.
- Reduce dependence on export for downstream processing through phased expansion of domestic preprocessing and material recovery capacity where economically and technically viable.
- Transition from conditionality-led compliance toward mainstream regulatory integration, embedding PV EoL requirements within licensing, permitting and routine regulatory oversight as privately financed deployment expands.
- Expand decentralised collection and logistics systems to complement the centralised recycling model and improve capture rates for dispersed household and off-grid solar equipment.
- Strengthen long-term financial sustainability mechanisms for PV waste management, including cost-recovery models and industry participation frameworks aligned with EPR principles.
- Enhance system resilience and capacity planning by reducing reliance on a single licensed operator and supporting scalable operational arrangements as national PV waste volumes increase.

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3.4. Kenya

3.4.1. Country and PV market context

PV market overview

Kenya hosts one of the most mature and diversified PV markets in sub-Saharan Africa, characterised by long-standing deployment of off-grid solar technologies alongside rapidly growing C&I rooftop PV and an expanding utility-scale pipeline. Off-grid solar has played a central role in Kenya's energy-access strategy for over a decade, with an estimated 10 million people using off-grid solar systems by 2022, primarily through solar lanterns and SHS distributed via PAYG business models [86]. While OGS remains important for rural and peri-urban households, C&I solar has emerged as the dominant growth segment in recent years. High grid electricity tariffs, concerns over reliability and favourable daytime load profiles have made grid-tied rooftop PV financially attractive for businesses, universities, hospitals, and industrial facilities.

According to stakeholder estimates from Strathmore University, Kenya now hosts approximately 400 megawatts of captive C&I PV capacity, with installations accelerating from about 2015–2016 onwards as system costs declined and new 'energy-as-a-service' business models emerged. This rapid C&I expansion has important implications for PV EoL dynamics. Most large rooftop and institutional systems are still within their operational lifetimes, but the first significant wave of C&I PV modules is expected to approach EoL from about 2030–2035, based on installation timelines and typical 25- to 30-year module lifespans. Nevertheless, damaged modules, inverter failures and early component replacements are already appearing in small but increasing numbers, particularly where systems are exposed to poor installation practices or environmental stressors.

Alongside C&I growth, Kenya remains one of the world's largest markets for small-scale solar devices. As shown in the literature review, many off-grid solar products have short effective lifespans, often because of battery failure, product quality issues or lack of affordable repair options, leading to near-term generation of PV-related electronic waste.[86] This is especially true in Kenya, with the majority of broken solar products being 'hibernated' in households, with approximately 70–72% of failed devices stored at home, sometimes for several years, because of uncertainty over disposal options, residual perceived value or emotional attachment.[87]

As a result, Kenya's PV market is characterised by a dual EoL challenge: a near-term accumulation of small-scale PV and battery waste from OGS systems, much of it informally stored or disposed of, and a latent but potentially large future waste wave from C&I and utility-scale PV installations that has not yet been systematically planned for.

Relevant policies and initiatives

Kenya has taken comparatively early steps to address electronic waste through the adoption of the National E-Waste Management Strategy (2019)[88] which establishes a national framework for environmentally sound management of WEEE. The strategy outlines core principles including EPR, the development of licensed collection and treatment centres, public awareness programmes, and improved coordination between government, private sector and informal actors. However, the strategy is explicitly technology-agnostic and does not provide PV-specific guidance or operational mechanisms for the management of solar panels, inverters or BoS components. As a result, PV waste is implicitly grouped within broader e-waste categories, without recognition of its distinct material composition, long lifetimes, or future bulk volumes from C&I and utility-scale systems.

Kenya's Draft National Energy Policy (2025–2034) places strong emphasis on accelerating renewable-energy deployment, increasing private-sector participation and supporting decarbonisation across the economy. Solar PV – particularly C&I rooftop systems and utility-scale generation – is positioned as a key contributor to energy security and affordability. However, the draft policy does not explicitly address PV EoL management, circularity or life cycle responsibilities for solar infrastructure, reflecting a continued separation between energy planning and waste governance.[89] Stakeholders noted that recent regulatory attention has focused more heavily on battery waste, particularly in the context of electric mobility and Li-ion imports, rather than PV modules themselves.

3.4.2. Current PV EoL practices

Existing EoL pathways

At present, Kenya has no dedicated EoL management system for solar PV panels. Instead, PV modules and associated components follow a range of informal or ad-hoc pathways depending on system type and location. For commercial, industrial and institutional installations, damaged or replaced modules are typically stored on-site or retained by system owners with eventual disposal often occurring through general waste channels. There is limited evidence of structured take-back or recycling arrangements for PV panels originating from C&I systems.

Within the off-grid solar sector, studies indicate that the dominant response to failed SHS and pico-solar products is long-term household storage, commonly referred to as 'hibernation'.[87]. Nonfunctional equipment is frequently retained because of uncertainty over disposal options or perceived residual value. Smaller proportions of users return products to vendors, while others dispose of components through burning, burying or dumping. Battery collection pathways are comparatively more developed – particularly for lead-acid batteries – although these systems present their own environmental and health risks. In contrast, formal collection and treatment pathways for Li-ion batteries remain limited.

Kenya has established several WEEE collection centres, primarily located in urban areas. However, these facilities largely function as aggregation points and do not yet provide PV-specific dismantling or downstream processing. As a result, PV panels remain largely invisible within Kenya's existing waste-management system, with most waste volumes neither formally recorded nor systematically managed.

Policy and institutional framework

Several national and local institutions hold mandates that are indirectly relevant to PV EoL management. The National Environment Management Authority (NEMA) oversees environmental regulation and licensing of waste and e-waste handlers, while the Energy and Petroleum Regulatory Authority (EPRA) regulates energy installations and maintains records of grid-connected and large PV systems. The Kenya Bureau of Standards (KEBS) is responsible for product standards and quality assurance for imported solar equipment and county governments manage local waste collection and disposal services.

Despite this institutional coverage, coordination among these actors on PV-specific EoL issues remains limited. Stakeholders reported ongoing uncertainty regarding mandates, enforcement responsibilities and the classification of PV modules within existing e-waste regulations. Although Kenya has relatively strong foundations for general e-waste governance, PV EoL management remains largely unarticulated within both energy and waste policy. This creates a risk that emerging PV waste streams – particularly from C&I and utility-scale systems – will default into waste pathways that are not designed to manage the scale, materials or logistical requirements of solar infrastructure.

Market and supply chain considerations

Kenya's PV supply chain is highly import-dependent, with nearly all modules sourced internationally and no domestic manufacturing capacity. While advanced recycling technologies exist globally, exporting PV modules for treatment is logistically complex, costly and politically sensitive. Local preprocessing activities – such as frame removal, basic dismantling and performance testing – could provide a feasible intermediate step but are not yet established at scale.

Within the off-grid sector, long distances to service centres strongly influence whether products are returned, stored or discarded. For C&I installations, declining global PV prices may increasingly favour local reuse or repurposing of panels rather than importation of second-life equipment, provided appropriate testing, certification and liability frameworks are developed.

Social and environmental impacts

At present, Kenya's PV EoL impacts remain largely latent rather than acute, although risks are clearly emerging. As PV deployment expands, increasing volumes of waste panels are likely to enter general waste streams and accumulate in major dumpsites such as Dandora alongside other hazardous materials. Informal waste pickers and surrounding communities are therefore likely to face disproportionate exposure risks as PV waste becomes more prevalent.

Distributional impacts are also expected to vary spatially. Urban areas, particularly Nairobi, are likely to experience the highest concentrations of PV waste because of dense C&I deployment, while rural off-grid users face challenges related to equipment storage, limited access to return pathways and information gaps regarding safe disposal practices.

3.4.3. Market strengths and weaknesses

Areas of good practice

- Existing WEEE collection centres provide a foundation for future PV aggregation.
- Strong technical and academic capacity, notably at Strathmore University, supporting PV system design, training and policy advice.
- Active private-sector service networks (installers, PAYG agents, call centres) that could be leveraged for EoL collection and incentives.
- Growing awareness within government and industry that PV EoL will become a significant issue in the next decade.
- Donor-funded initiatives supporting waste infrastructure and CEE research.

Key challenges

- **Technical:** No local PV panel recycling facilities, no standardised testing infrastructure to assess second-life PV module suitability and limited data on installed PV capacity by age and location.
- **Economic:** High costs associated with collection, transport and export of bulky PV modules, weak economic incentives for private actors to manage PV waste proactively.
- **Regulatory and institutional:** Absence of PV-specific EoL regulations. Fragmented institutional responsibilities

across NEMA, EPRA, KEBS and counties. Policy focus skewed toward batteries rather than full PV systems.

- **Social:** Risk of future environmental injustice if PV waste enters informal waste streams and limited consumer awareness of PV disposal responsibilities.

3.4.4. Opportunities and priority actions

Opportunities

Immediate (0 to 2 years)

- Integrate PV panels explicitly into existing e-waste regulations and guidelines.
- Pilot PV collection at WEEE centres, starting in Nairobi and other urban hubs.
- Develop awareness programmes for C&I system owners on future EoL responsibilities.

Medium term (2 to 5 years)

- Establish PV module testing and certification protocols to enable safe reuse or repurposing (e.g. panels operating at ~80% capacity).
- Support local preprocessing facilities (dismantling, sorting, testing) as a first step toward circularity.
- Improve national data systems linking EPRA installation records to future EoL planning.

Long term (5+ years)

- Design a Kenya-appropriate EPR model for PV systems, phased in as waste volumes increase.
- Explore regional recycling partnerships where full domestic recycling is not viable.
- Embed PV EoL planning into broader energy-transition and CEE strategies.

Priority actions

- Clarify institutional responsibility for PV EoL management.
- Incorporate PV panels into national e-waste implementation frameworks.
- Pilot urban PV collection and aggregation schemes.
- Develop engineering-led testing and reuse standards for second-life PV.
- Strengthen PV deployment and asset-tracking data to support forecasting.
- Engage C&I system owners early to plan for future EoL obligations.
- Support capacity building for county governments and WEEE centres.

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3.5. India

3.5.1. Country and PV market context

PV market overview

India's solar photovoltaic sector has expanded rapidly over the past decade, fundamentally reshaping the country's renewable-energy landscape. Installed solar capacity stood at approximately 35 gigawatts (AC) in 2019,[90] increasing to about 64 gigawatts by March 2023[91] and reaching approximately 123 gigawatts by August 2025.[92] Projections indicate continued growth at an annual rate of approximately 7% between 2025 and 2047. Deployment is geographically concentrated in western and southern states, with Rajasthan, Gujarat, Maharashtra, Tamil Nadu, and Karnataka accounting for roughly 75 per cent of installed capacity.

India's PV market spans utility-scale, C&I, rooftop, hybrid, and off-grid systems. Ground-mounted solar plants dominate installations (100.80 gigawatts), followed by grid-connected rooftop systems (23.16 gigawatts), hybrid projects (3.34 gigawatts), and off-grid solar (5.55 gigawatts). The installed base remains relatively young, with most capacity deployed after 2010, meaning waste from full module lifetimes is expected to peak after 2040.[90]

Despite this, PV waste is already emerging from transport damage, installation losses, early failures, and operational replacements. Estimates vary widely: early projections suggest 11–34 kilotonnes by 2030,[90] while long-term projections range from approximately 4.5 million tonnes by 2050[91] to 11,221 kilotonnes of cumulative waste by 2047, based on 146 kilotonnes already generated from 97.8 gigawatts of installed capacity by 2024.[92] Approximately 92% of projected waste is expected from c-Si modules, with approximately 8% (888 kilotonnes) from thin-film technologies.

Unlike other case study countries, India also hosts a rapidly expanding domestic PV manufacturing industry, now reaching approximately 100 gigawatts of nameplate capacity under government-supported industrial policies. Stakeholders noted that manufacturing growth increases demand for critical minerals such as silver and copper while generating manufacturing waste streams estimated at 1–2% of production volumes, creating extra incentives for recycling development.

Relevant policies and initiatives

The Jawaharlal Nehru National Solar Mission (JNNSM), launched in 2010 under the National Action Plan on Climate Change, established the foundation for India's large-scale solar expansion, increasing national targets from 20 gigawatts to 100 gigawatts by 2022. Implementation has been supported by institutions including the Solar Energy Corporation of India (SECI), responsible for major procurement and Viability Gap Funding programmes, and the Indian Renewable Energy Development Agency (IREDA), which supports solar park development and financing. More recently, the Prime Minister Surya Ghar initiative has accelerated residential rooftop deployment alongside utility-scale expansion.

The Ministry of New and Renewable Energy (MNRE) guidelines for grid-connected solar projects require developers to dispose of EoL PV modules comply with E-Waste (Management and Handling) Rules, signalling regulatory recognition of PV waste challenges. Some SECI and government procurement processes now include contractual requirements for safe EoL disposal through authorised recyclers.

India's E-Waste (Management and Handling) Rules, first introduced in 2011, established EPR and were revised in 2022 to include solar panels within obligated products. Recycling targets are intended to be met through EPR credit mechanisms; however, implementation has been deferred because of limited waste volumes and emerging recycling capacity. Current regulatory guidance emphasises safe storage of panels pending infrastructure development. Stakeholders indicated ongoing discussions to establish a dedicated solar-waste framework, recognising that existing e-waste regulations were designed for short-lived electronics rather than long-lifetime PV infrastructure. Interim policy proposals include routing PV waste generated from 2029 to centralised storage facilities, enabling reuse of functional panels before recycling or disposal.[93]

Further regulatory frameworks include the Hazardous Waste Management and Transboundary Movement Rules (HWMR), which implement Basel Convention obligations for hazardous waste handling, and the Battery Waste Management Rules (BWMR), which apply EPR principles across battery chemistries and mandate increasing use of domestically recovered materials.

Complementing these measures, the Ministry of Mines' Critical Minerals Mission includes a INR 15 billion incentive scheme to strengthen domestic recovery and recycling of strategic materials from battery and e-waste streams. While not PV-specific, the programme supports improved material security for solar technologies containing critical inputs such as silver, silicon and other metals.

3.5.2. Current PV EoL practices

Existing EoL pathways

Currently, damaged and defective solar PV panels and associated components in India are mostly collected by the informal sector, primarily for aluminium recovery. Stakeholder interviews indicate that a limited number of informal recyclers, particularly in southern India, are engaged in rudimentary metal recovery from EoL PV panels. While formal recycling capacity is emerging, much of the material flow continues to be channelled through informal dismantling networks. In terms of repair, reuse, resale, storage, dumping, and recycling practices, pathways remain fragmented. Some panels are stored at project sites or warehouses because of regulatory ambiguity or limited authorised recycling capacity, while others are informally dismantled. At the same time, formal infrastructure is beginning to scale. For example, Regain operates an industrial facility spanning approximately 90,000 square feet, with an installed capacity to process 250 megawatts, or roughly 500,000 modules, annually. Since commencing operations in April 2025, the plant has reportedly recycled over 1,000 tonnes of solar PV waste. Another formal recycler, Beyond Renewables is currently able to handle 500 panels per day, and generates glass, copper, aluminium, and metallurgical grade silicon as outputs. However, the large majority of panels they receive are already deframed as the aluminium has a high value, is easily sold in the scrap market and easy to remove.

Policy and institutional framework

The government has issued guidelines for the storage of EoL PV panels, however, stakeholders indicated that these are impractical given the large amount of space that would be blocked. Also, there is little enforcement or monitoring regarding the adherence to these guidelines. Stakeholders indicated there may be some differences in the applicability of jurisdiction for handling EoL PV panels – whether they should be under the Ministry of Renewable Energy or under the Ministry of Environment, Forests and Climate Change. There are no India specific standards for recycling or guidelines for transport.

Market and supply chain considerations

The Bureau of Indian Standards (BIS) has mandated compulsory registration under the Compulsory Registration Scheme (CRS), requiring adherence to Indian Standards (IS) such as IS 14286 (C-Si) and IS 16077 (Thin-Film), alongside international IS/IEC 61730 (Parts 1 & 2) for safety, ensuring modules meet stringent performance, design and quality criteria, including minimum efficiency levels. This is to ensure that imported panels are of a high quality and do not fail early. Additionally, there is a focus on import substitution through incentives to manufacture solar panels in India. This can create both market for recycled materials, as well as access to manufacturing waste. Transport costs are an important factor in locating recycling facilities and more than one stakeholder mentioned that logistics costs are an issue in achieving unit economics because of the high access to waste costs as well given that recycler have to purchase the panels. One of the stakeholders is working on a mobile solution, to take the recycling plant to the location rather than transport the panels to a centralised facility. The value of glass is minimal but is the largest fraction by mass. However, extraction technologies and efficiency of extraction at commercial scale are not clear. With good process efficiencies, it may be possible to recycle panels with little or no EPR.

Social and environmental impacts

The main environmental risks arise from improper processing of cables and other electronic parts, as well as batteries. There are some studies on the reliability of panels in various climatic conditions which also mention degradation of panels and back sheets that may lead to adverse environmental impacts. One study mentioned that the separation of glass from plastic may expose labourers to lead, silver and glass dust. However, stakeholder interviews did not bring these up as environmental challenges. One safety aspect mentioned was to ensure that there is no residual charge in the panels that may be an issue at the time of decommissioning or handling EoL PV panels.

3.5.3. Market strengths and weaknesses

Areas of good practice

- **Policy and regulatory:** EoL solar is included under EPR-based E-waste Rules creating the necessary obligation for producers to ensure financing mechanisms for EoL collection, treatment and recycling.
- **Industry-led circular business models:** Systems such as First Solar's closed-loop system, with a manufacturing plant near Chennai, has an installed manufacturing capacity of 3.3 gigawatts and an in-house recycling capacity of approximately 9,514 tonnes per annum (TPA), enabling high-value material recovery.
- **Active research and advocacy community:** This community is engaged in policy and technology discussions, as well as government-supported initiatives such as the Renewable Energy Research and Technology Development (RE-RTD) Programme programme from the MNRE, innovation challenges with prize money for successful startups.
- **Infrastructure for PV manufacturing:** These production-linked incentive schemes, create demand for recycled materials as well as feedstock for recyclers Council on Energy, Environment and Water (CEEW) suggested that by their estimates 38% of material demand for solar industry can be met in 2047 from recycling of EoL PV panels).

Key challenges

- **Technical:** Absence of scalable and commercial recycling technologies; low maturity of recycling technologies to recover materials such as silicon. The purity of recycled fractions, and especially silicon, is of a lower metallurgical grade which does not find enough downstream options. Improving the purity is a technical challenge faced by recyclers, and recovery efficiency is challenging, particularly in the case of silver.

- **Economic:** High capex for recycling facilities (INR 135–143.8 million), with risk-perception among investors heightened by regulatory certainty, specifically, the lack of EPR targets. Waste procurement costs are also high – informal recyclers take EoL panels for the aluminium frames which fetch good value in the scrap market, and dispose of the rest of the panels. The logistics cost of moving panels is more than INR 4,050/tonne,[1] which makes collection economically unattractive for recyclers.
- **Regulatory and institutional:** India currently does not have a dedicated national standard specifically governing solar PV module reuse or recycling. EPR targets under the E-Waste Rules have been suspended, and currently not applicable on solar modules. However, the requirement to store EoL panels until 2035 is impractical. Although not specifically for solar, there is a scandal around EPR certificates issued by fake or ghost recyclers. The weak enforcement, as well as lack of strong auditing is identified as a big gap.
- **Data/knowledge gaps:** No granular mapping of India's deployed solar capacity at the localised level; stakeholders noted the importance of mapping the spatial distribution of waste to strategically deploy the waste management infrastructure, such as collection centres, dismantling and recycling facilities. There are widely varying estimates of solar PV waste generation and lack of specific data on environmental and social impacts – mostly generalised to e-waste impacts, rather than specifically on solar PV.
- **Supply chain and market constraints:** There is an absence of upstream value chain of solar module manufacturing in India as yet – limited off-takers or end-markets for the recovered materials from recycling, specially silicon.

3.5.4. Opportunities and priority actions

Opportunities

Immediate (0 to 2 years)

- Strengthen national data collection on PV module reliability and failure rates to improve forecasting of EoL volumes and inform infrastructure planning.
- Develop practical guidance on transport, packaging and preventive maintenance practices to reduce premature module damage and extend operational lifetimes.

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[1] Note: Figure converted from tons to tonnes.

- Support feasibility assessments for second-life PV applications, including technical standards, market demand and business model viability.

Medium term (2 to 5 years)

- Promote collaboration between industry, research institutions and recyclers to accelerate development and commercialisation of material recovery technologies.
- Pilot digital product passport systems to improve traceability of PV modules across deployment, reuse and recycling stages.
- Advance development of circularity indicators and technical standards aligned with emerging international and IEC frameworks.

Long term (5+ years)

- Support development of closed-loop material supply chains linking recyclers with domestic manufacturers to increase use of recovered materials.
- Establish material traceability and quality assurance systems enabling recycled materials to re-enter manufacturing value chains.

Priority Actions

- **Improve national data and forecasting systems for PV EoL:** Establish regular monitoring of module performance, failure rates and waste generation to support evidence-based infrastructure and policy development.
- **Develop technical standards for reuse and recycling:** Introduce nationally recognised standards governing testing, second-life applications, transport, and recycling of PV modules.
- **Strengthen skills and workforce capacity:** Expand training programmes for safe decommissioning, repair, refurbishment, and recycling across the solar and e-waste sectors.
- **Pilot second-life and refurbishment pathways:** Support demonstration projects assessing technical feasibility and commercial viability of repurposed PV modules in lower-demand applications.
- **Accelerate deployment of digital product traceability systems:** Pilot digital product passports or equivalent tracking mechanisms to improve life cycle accountability and compliance with future EPR requirements.
- **Support development of domestic recycling ecosystems**: Encourage investment in preprocessing and recycling infrastructure aligned with projected waste volumes and manufacturing demand.
- **Enable circular material markets within the solar industry:** Promote partnerships between recyclers and manufacturers to integrate recovered materials into domestic PV production and reduce reliance on virgin resources.

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3.6. Nepal

3.6.1. Country and PV market context

PV market overview

The solar PV market in Nepal has undergone a significant transformation over the past three decades, evolving from small-scale solar lanterns (tuki), SHS for rural electrification, solar irrigation, solar drinking water supply system, solar mini-grid, roof top solar to multimegawatt grid-connected systems [90]. As of the fiscal year 2079/80 (2022/23), Nepal's installed solar PV capacity is estimated at approximately 146 megawatts for ground-mounted systems and an extra 25 megawatts from rooftop and off-grid installations.[95][96] The market is accelerating rapidly, with the Nepal Electricity Authority (NEA) having auctioned a pipeline of nearly 960 megawatts of utility-scale solar projects, indicating a strong shift towards large-scale deployment.[95][96]

Market growth of PV is driven by several factors: declining global PV module costs, increased energy reliability concerns among industries and supportive government policies. The private sector, particularly C&I consumers, is leading investments in rooftop solar, with installations ranging from a few kilowatts to over 8 megawatts. In Nepal, PV market is making a transition from subsidy-dependent models to commercial financing, with industries achieving a payback period of four to five years. While rural SHS deployments continue, future growth is expected to be increasingly urban-centric, focused on meeting industrial demand, enhancing grid stability and supporting corporate sustainability goals under the 'go green' concept.

Relevant policies and initiatives

Nepal's policy framework actively promotes solar PV adoption. The Rural Energy Policy (2006) and amendments to the Electricity Act (1992) provide the foundation for private-sector investment in generation, including solar.[96] The Net Metering Guidelines have been instrumental in enabling grid-tied rooftop PV for residential, commercial and industrial consumers.[97]

Key implementing agencies include the Alternative Energy Promotion Centre (AEPC), which administers subsidy and soft loan programmes, and the NEA, which oversees grid integration and large-scale project auctions.[95] Development Partner (DP) programmes such as the Foreign, Commonwealth & Development Office's (FCDO) Nepal Renewable Energy Programme (NREP), GiZ's Promotion of Solar Energy in Rural and Semiurban Regions of Nepal (DKTI) and Promotion of Solar Technologies for Economic Development (POSTED), United Nations Development Progamme (UNDP), Asian Development Bank (ADB), and the World Bank have provided critical technical and financial support for market development and capacity building.

However, the policy landscape has critical gaps concerning EoL management. While the Environment Protection Act (2019) [98] and the Solid Waste Management Act (2011) provide a broad framework for waste management, they lack specific provisions, standards or enforcement mechanisms for PV waste.[99] There is no EPR scheme for solar components, and PV waste is not classified or tracked within e-waste monitoring systems. There is absence of a clear regulatory mandate for PV EoL as the most pressing policy gap. [99]

3.6.2. Current PV EoL practices

Existing EoL pathways

Current EoL management for PV components in Nepal is predominantly informal, unstructured and environmentally unsound. For PV panels, common practices include indefinite on-site storage by businesses, disposal in municipal solid waste streams or abandonment. There is no formal collection, transportation or processing infrastructure. Batteries, primarily lead-acid from SHS and backup systems, are sometimes collected by informal scrap dealers. Valuable metals such as lead are extracted through rudimentary, often hazardous, processes within Nepal or the units are exported to India for recycling. The remaining acid and casing are frequently dumped, leading to soil and water contamination. Other components such as inverters, charge controllers and cables are either stored, discarded with general waste, or partially dismantled for valuable metals (copper, aluminium), with residual materials landfilled.

Policy and institutional framework

No policy, regulation or guideline specifically addresses PV EoL in Nepal. [97] The Solid Waste Management Act (2011) and its regulations mention e-waste but are not implemented for solar components. The Environment Protection Act (2019) requires Environmental Impact Assessments (EIAs) for large projects but does not mandate EoL plans for PV systems.[98] Institutions such as the Ministry of Forests and Environment (MoFE), AEPC, and NEA have overlapping yet unclear mandates regarding PV waste, resulting in enforcement issues. It is observed that EoL is a 'neglected topic' with no dedicated data collection, monitoring, or compliance mechanisms.[97]

Market and supply chain considerations

Nepal's PV sector is almost entirely import-dependent, with panels, inverters and advanced batteries sourced mainly from China and India. This creates a disconnect between manufacturers (who may have EPR policies in their home countries) and the Nepali market, where take-back schemes are nonexistent. In Nepali market, there are numerous importer and installer private companies that sell, install and provide post installation services. These companies are connected with the consumers and feel moral obligation for EoL management. While the Renewable Energy Test Station (RETS) conducts quality testing for imports, however, there are challenges with substandard and counterfeit components entering the market, which may fail prematurely and increase waste volumes. The informal sector dominates the recovery of valuable materials, but this 'cherry-picking' leaves hazardous residues unmanaged. The lack of economies of scale, high logistics costs for collecting scattered waste and the absence of a formal recycling market leaves the proper EoL management commercially unviable for the private sector.

Social and environmental impacts

The informal and unregulated disposal of PV waste poses significant risks. Environmental impacts include soil and water pollution from lead and cadmium leaching from batteries, contamination from broken glass and silica dust from panels, and toxic emissions from the open burning of plastic components. Social impacts disproportionately affect vulnerable groups: informal waste pickers face direct health hazards from exposure to heavy metals and acids; rural communities with limited waste management services are forced to live near dumping sites; and fertile agricultural land, is at risk of degradation. The health and environmental costs are transferred, with the most marginalised communities bearing the greatest burden.

The improper management of PV waste leads to direct and cumulative harms. Environmental degradation occurs through the leaching of heavy metals into soil and groundwater, and air pollution from open burning. Public health is jeopardised, with risks of respiratory diseases, cancers and poisoning for informal workers and communities living near disposal sites. Social inequity is exacerbated in remote and low-income communities, who were primary beneficiaries of early SHS programmes, now lack safe disposal options, turning sustainable energy solutions into potential environmental liabilities.

3.6.3. Market strengths and weaknesses

Areas of good practice

- **Policy and institutional:** Growing recognition of the issue in stakeholder dialogues and some development partner programmes beginning to consider CEE principles.
- **Industry and market**: Leading private solar companies and developers express moral responsibility and willingness to collaborate on EoL solutions if a clear framework is established.
- **Circular economy and waste:** Existence of informal recycling networks for lead-acid batteries and metals, which could be formalised and trained.
- **Community and social:** High levels of local technical skill in PV system installation and maintenance, providing a base for training in safe decommissioning.

Key challenges

- **Technical:** Complete lack of PV panel and Li-ion battery recycling technology and infrastructure in Nepal. Widespread use of substandard components shortens product life.
- **Economic:** No viable business model for formal recycling due to low current waste volumes, high costs and lack of market for recovered materials (for example silica glass).
- **Regulatory and institutional:** Critical absence of PV-specific EoL regulations, EPR mechanisms, limited product standards, and enforcement capacity.
- **Knowledge and data:** No national inventory of installed PV systems or generated waste. Extremely low awareness of EoL hazards among consumers, installers and policymakers.
- **Supply chain:** Complex, import-dependent supply chain with no producer responsibility. Informal sector handles hazardous waste without safety protocols.

3.6.4. Opportunities and priority actions

Opportunities

- **Immediate (1 to 2 years):** Leverage high stakeholder concern to initiate multistakeholder dialogue. Use existing academic institutions for preliminary research and awareness campaigns.
- **Medium term (3 to 5 years):** Develop and pilot a decentralised collection model in partnership with local government and the private sector. Draft a PV-specific EPR regulation applicable to the PV suppliers, installers and manufacturing companies.
- **Long term (5+ years):** Establish a formal recycling ecosystem, possibly through regional collaboration, integrating PV waste into a national CEE strategy.

Priority actions

- **Conduct a national PV waste flow study:** Led by academia (Kathmandu University (KU), Institute of Engineering (IOE), Nepal Academy of Science and Technology (NAST)) with AEPC, to quantify existing and future waste streams and map disposal practices, creating an evidence base for policy.
- **Develop and pilot a decentralised collection system:** Partner with municipalities, private companies, and local governments to establish certified collection points for EoL PV components, starting in major urban and industrial hubs.
- **Formulate and enact an EPR framework for solar PV:** Mandate importers, manufacturers, and installers to finance and manage the collection and environmentally sound processing of PV waste, integrating it into national e-waste policy.
- **Launch capacity building and awareness programmes:** Train PV technicians, installers and informal waste collectors on safe decommissioning, handling and hazards. Run public campaigns on responsible disposal.
- **Foster public-private partnerships for pilot recycling:** Incentivise the private sector with blended finance (grants, concessional loans) to establish small-scale, technologically appropriate pilot facilities for processing specific streams such as lead-acid batteries or aluminium frames.
- **Strengthen quality and standards enforcement:** Empower RETS and the Nepal Bureau of Standards & Metrology (NBSM) to rigorously enforce import standards to extend product lifespans and reduce premature waste.
- **Align development partner funding with circularity:** Engage DPs (GIZ, UNDP, ADB, WB) to earmark funding within energy projects for EoL management components, supporting research, pilot projects and policy development.

3.7. Synthesis of case studies

- **PV EoL is emerging faster than policy and infrastructure:** All case studies show PV deployment accelerating (especially off-grid solar and C&I), while EoL governance, collection systems, and treatment capacity lag behind, creating a predictable 'waste gap' as early installations reach replacement cycles.
- **Two distinct waste dynamics are evident:**
    - **Near-term, off-grid, solar waste** driven by short lifetimes (especially batteries and small electronics) and frequent replacement cycles (Malawi, Kenya, Rwanda, Nepal).
    - **A latent future module wave l**inked to C&I and utility-scale PV (Kenya, Nepal, India), where large volumes are expected from approximately 2030 onwards, but planning is minimal today.
- **Batteries dominate risk and system pressure:** Across contexts, battery failures occur far earlier than modules, shaping both the volume and hazard profile of PV-related waste. Malawi LCA evidence shows lead-acid handling is a major toxicity driver when managed informally.
- **'Hibernation' and stockpiling are widespread:** Households and institutions frequently store failed OGS devices for long periods because of uncertainty, residual value or lack of return options, delaying but not solving the EoL problem (especially Kenya, also seen in Malawi and Nepal).


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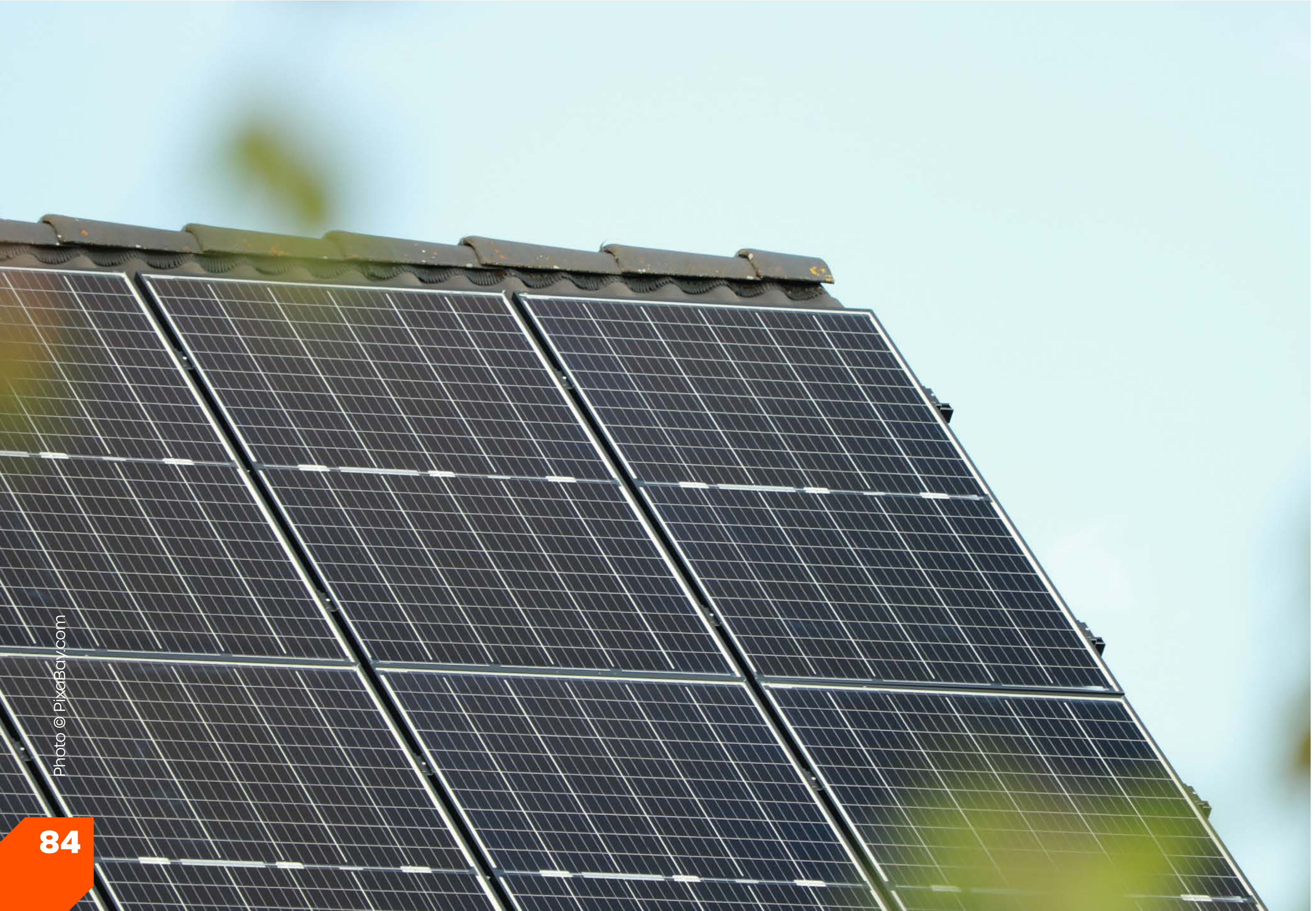
- **EoL pathways default to informal or ad-hoc routes unless formalised:** Malawi and Nepal show fragmented disposal and informal recovery; Kenya shows ad-hoc storage and disposal plus limited WEEE aggregation; Rwanda is the outlier with a formal, centralised pathway anchored in a licensed operator.
- **Institutional responsibility is often unclear and fragmented:** Most countries exhibit overlapping mandates between environment, energy regulators, standards bodies, and local government, with no single accountable actor for PV EoL (notably Malawi and Kenya). Rwanda's clearer institutional model demonstrates the value of a designated endpoint and coordination mechanism.
- **Policy frameworks exist, but PV-specific operationalisation is limited:** E-waste strategies and energy policies generally acknowledge WEEE and renewables, but rarely specify PV modules, inverters or BoS pathways, treatment standards, and financing mechanisms, creating implementation ambiguity (Malawi, Kenya, Nepal).
- **Donor conditionality can rapidly 'create' compliance:** Rwanda shows that results-based financing and development-bank requirements can embed EoL planning early (for example memorandums of understanding with licensed recyclers), producing higher compliance than inspection-led enforcement alone.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- **Economics remain the binding constraint:** PV modules are bulky and low-value by mass, making collection and export expensive; nonvaluable fractions (glass, mixed plastics) have few viable outlets; and without incentives or obligations, firms have weak reason to participate (strongly evident in Malawi and Kenya; also relevant to Nepal).
- **Reverse logistics is the missing system layer:** All contexts highlight the absence (or early-stage nature) of affordable, national reverse-logistics models linking users to aggregators, preprocessing, then recycling/export hubs. Practical 'entry points' repeatedly identified include municipal transfer stations (Malawi) and urban WEEE centres (Kenya).
- **Data scarcity undermines planning and policy design:** Countries lack consistent datasets on installed PV stock by any of geography, age, failure rates and waste volumes, limiting forecasting, EPR design and infrastructure investment decisions (Malawi, Kenya, Nepal; Rwanda relatively stronger but still scaling).
- **Equity and environmental justice risks are recurring:** Where informal disposal dominates, health and environmental burdens are likely to concentrate among informal workers and communities near dumpsites—while the benefits of electrification accrue elsewhere (clearest in Malawi; a future risk in Kenya as volumes rise).
- **Common 'no-regrets' priorities emerge across countries:** (i) Strengthen quality and standards enforcement to reduce premature failures, (ii) scale repair and refurbishment as a first-line circular strategy, (iii) pilot collection and preprocessing hubs, (iv) establish PV waste tracking linked to imports/installation records, and (v) phase in EPR only once basic systems and data are operational.
- **The informal sector plays a foundational role:** Collection, aggregation and material recovery, particularly for high-value fractions such as aluminium and copper, is a key role for the informal sector. While often operating outside formal regulatory systems, these actors provide essential services in contexts where formal infrastructure is absent. Women are active across sorting, aggregation and micro-enterprise roles, though their contributions remain under-recognised in policy design. Effective PV EoL strategies should therefore prioritise integration, training and safer formalisation pathways rather than displacement.

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4. Conclusions

4. Conclusions: Key recommendations for strengthening PV EoL systems in LMICs

4.1. Why PV EoL needs a systems approach

A key finding from both the literature review and the country case studies is the need to distinguish between two different but interconnected EoL challenges. In the near term, the most acute risks are driven by batteries and BoS components (such as inverters, charge controllers and cabling), which fail earlier than PV modules and are already entering informal repair, reuse and disposal pathways. These components often contain hazardous materials and can pose immediate safety and environmental risks if mishandled. In contrast, PV modules are primarily a longer-term challenge, driven by scale and volume: waste quantities are expected to increase significantly over the coming decade as installed PV stock grows, even though module lifetimes are typically longer and large-scale recycling systems may not yet be economically viable in many LMIC contexts.

These dynamics mean that PV EoL cannot be treated solely as a downstream recycling problem. Instead it requires a systems approach that considers the full life cycle of PV assets, including procurement and product design, repair and refurbishment ecosystems; collection and aggregation mechanisms; and the interfaces between formal and informal sector actors. No single model will fit all contexts: viable approaches will vary depending on market structure, geography, institutional capacity, and maturity of both energy and waste sectors. Recommendations therefore prioritise sequencing, feasibility and risk reduction, while creating foundations that enable more robust systems to develop over time as waste volumes increase.

4.2. How to read these recommendations

The recommendations in this section are presented as a single prioritised list, based on the strength of evidence from the literature review and country case studies, and informed by feasibility in LMIC contexts. Table 3 provides a summary overview of the priority recommendations. They are intended to support action by a range of stakeholders across the PV value chain, including government, industry, donors, development-finance institutions, and waste-sector actors. For ease of navigation, the recommendations are grouped under three headings:

- **Foundations:** Actions that establish the minimum system conditions required for safe and responsible PV EoL management and that enable later policy, investment and infrastructure development.
- **Delivery pathways:** Practical actions that can strengthen existing systems and reduce risk in the near term, particularly through repair, safe handling, and collection and aggregation mechanisms.
- **System shifts:** Longer-term structural changes required for PV EoL systems to function sustainably at scale as waste volumes increase, including regional coordination and upstream design and planning measures.

Table 3: Summary of recommendations

Recommendation	Lead	Level	Horizon	Indicative scale
Foundations				
Establish LMIC-appropriate PV EoL system design principles	Convenors + technical bodies	Cross-country	Near	Low
Build precompetitive PV EoL data and system visibility	Shared (public + private)	Country + cross-country	Near	Low–Moderate
Prioritise batteries and BoS components as the entry point	Governments + industry	Country	Near	Low
Delivery Pathways				
Professionalise and scale safe repair and refurbishment ecosystems	Solar industry + training institutions	Country	Near–Medium	Moderate
Leverage existing infrastructure for collection and aggregation	Industry + municipalities	Country	Near	Low–Moderate
Use donor and DFI conditionality to embed EoL requirements early	Donors + DFIs	Programme / country	Near	Moderate
System Shifts				
Derisk multi-actor pilots and system experimentation	Convenors + implementation partners	Country / regional	Medium	Moderate–High
Enable longer-term system shifts (regionalisation, circular design, second-life pathways)	Governments + industry	Regional / cross-country	Long	High

Each recommendation includes an indication of: (i) the primary lead actors best placed to drive implementation; (ii) the most relevant level of action (country, regional or cross-country); (iii) an indicative time horizon; and (iv) an indicative scale of resources and coordination required. This is intended to support decision-makers in identifying which actions are feasible in the near term and how short-term priorities can contribute to longer-term system development.

4.3. Foundations: What must be in place first (near term, low regret)

The following actions represent foundational interventions that enable later policy development, investment and infrastructure build out. They are deliberately low regret: they can be implemented at relatively low cost, do not depend on high waste volumes or advanced recycling capacity, and reduce immediate environmental, health and safety risks. Across the case studies, the absence of these foundations consistently constrained more ambitious EoL solutions. Establishing them early helps prevent future lock-in to unsafe or inequitable systems.

4.3.1. Establish LMIC-appropriate PV EoL system design principles

Rationale

PV EoL challenges in LMICs are frequently approached using frameworks and assumptions derived from high-income countries, particularly those based on mature EPR and domestic recycling infrastructure. In practice, these models are often misaligned with LMIC contexts, where PV systems are highly distributed, markets are fragmented, informal repair and reuse are widespread, and institutional capacity is limited.

The absence of shared, LMIC-appropriate design principles leads to piecemeal interventions, unrealistic policy expectations and premature focus on recycling solutions that are not yet viable. Establishing a small set of agreed system principles helps align stakeholders around sequencing, risk prioritisation and feasible pathways, while avoiding one-size-fits-all solutions.

Recommended actions

- Bring together cross-sector stakeholders (energy, environment, waste, industry, donors) to articulate a concise set of PV EoL system design principles tailored to LMIC contexts.
- Ensure principles explicitly address:
  - phased system development rather than immediate full recycling
  - coexistence of formal and informal actors
  - prioritisation of safety, repair and life extension before material recovery.
- Use these principles to guide:
  - national policy discussions
  - odonor and development-finance programme design
  - early pilots and demonstrations.
- Keep principles nonprescriptive and adaptable, allowing country-specific implementation pathways.

4.3.2. Build precompetitive PV EoL data and system visibility

Rationale

Across all case studies, a lack of basic data on installed PV stock, component lifetimes, failure rates, and waste flows was identified as a critical barrier to effective planning and investment. This data gap affects governments, industry, donors, and recyclers alike, leading to uncertainty, duplicated effort and delayed action.

Importantly, much of the data required to improve system visibility is precompetitive: it does not undermine commercial advantage but instead enables collective planning and risk reduction. Without a shared minimum evidence base, more advanced interventions such as EPR, infrastructure investment or regional coordination remain speculative.

Recommended actions

- Define a minimum PV EoL dataset that can be feasibly collected in LMIC contexts, focusing on:
  - PV imports and installations by technology and geography
  - typical component lifetimes and failure modes
  - observed EoL handling practices.
- Link data collection to existing systems where possible (for example import licensing, product standards, utility or regulator records, donor programme reporting).
- Encourage aggregation and sharing of anonymised, noncommercially sensitive data across public and private actors.
- Use improved system visibility to:
  - inform realistic policy sequencing
  - support waste-flow forecasting
  - derisk early pilots and investment decisions.

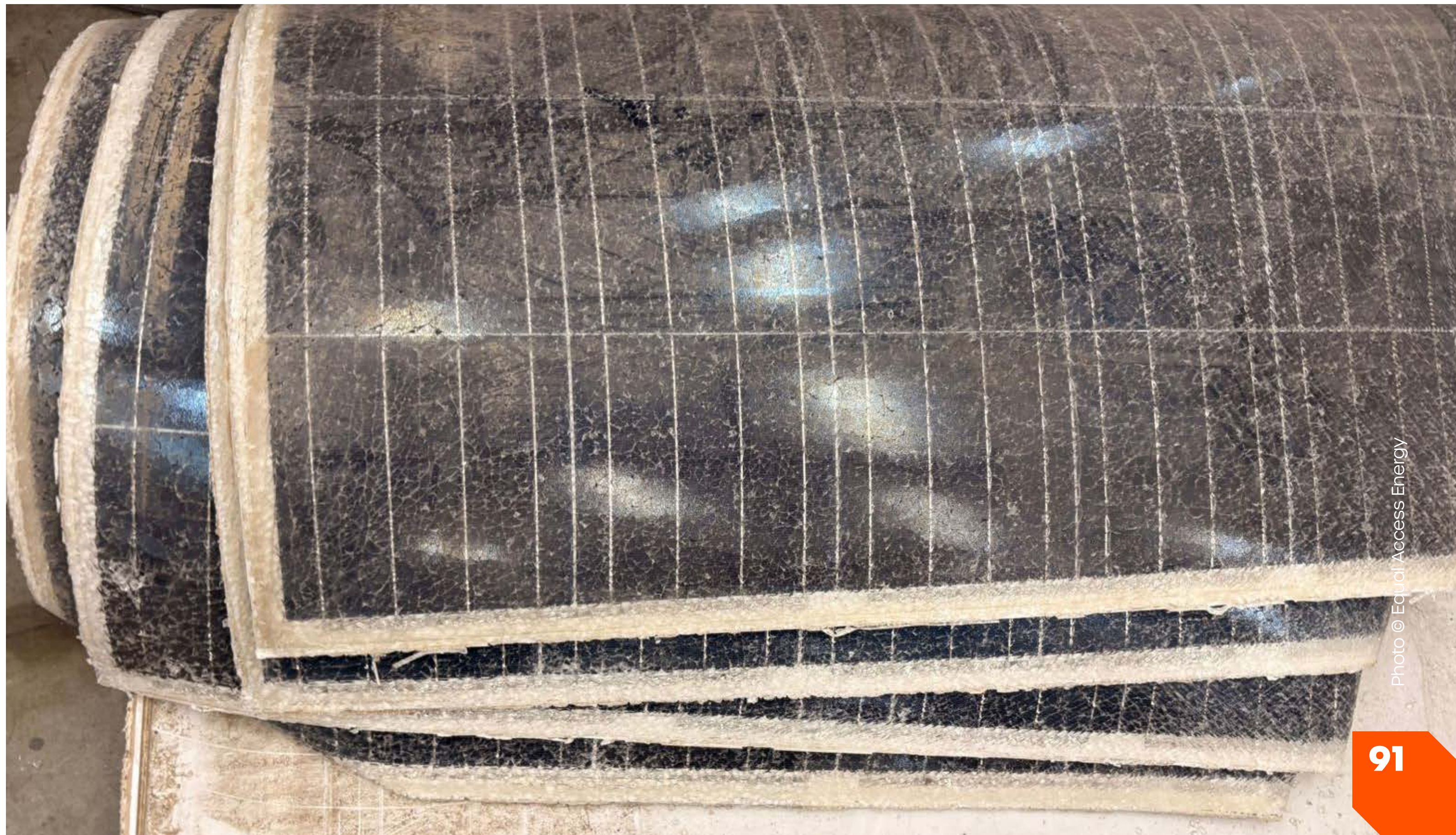
4.3.3. Prioritise batteries and BoS components as the entry point

Rationale

Although PV modules dominate long-term waste projections, the review consistently finds that batteries and BoS components (inverters, charge controllers, cabling, and lamps) represent the most immediate and acute risks in LMIC contexts. These components fail far earlier than modules, contain higher concentrations of hazardous materials and are already entering informal repair, reuse and disposal pathways. Focusing early EoL interventions on PV modules alone risks misallocating limited resources while leaving the most harmful waste streams unmanaged. A risk-based approach that prioritises batteries and BoS components provides a practical and safety-oriented entry point for system development.

Recommended actions

- Explicitly sequence PV EoL strategies to address batteries and BoS components first, before large-scale module recycling.
- Develop and disseminate clear safety guidance on handling, storage and aggregation of batteries and electronic components.
- Align early collection, repair and aggregation pilots around these components, where volumes are already material and impacts are highest.
- Use lessons from battery and BoS management to inform later expansion to PV modules as waste volumes increase and system capacity matures.



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4.4. Delivery pathways using existing systems

The delivery pathways below focus on strengthening and making safer what is already happening across LMIC PV markets. Repair, informal reuse and ad-hoc collection are widespread responses to system failure, even where no formal EoL framework exists. Rather than displacing these activities, near-term action should improve their safety, effectiveness and visibility, reducing waste generation and preventing hazardous components from entering unmanaged disposal pathways.

4.4.1. Professionalise and scale safe repair and refurbishment ecosystems

Rationale

Repair and refurbishment are already the dominant responses to PV system failure in LMIC contexts, particularly for off-grid and decentralised systems. Informal technicians, small workshops and mobile repair agents extend system lifetimes and provide affordable services to users. However, these activities often occur without access to training, spare parts or safety guidance, increasing risks to workers and users, particularly when handling batteries and electronic components. Evidence across the case studies shows that where repair is better supported, system lifetimes increase and premature disposal is reduced. Strengthening repair ecosystems therefore represents one of the most cost-effective delivery pathways for reducing near-term EoL risks.

Recommended actions

- Support basic training and accreditation for technicians and repair agents, emphasising:
    - safe handling of batteries and electronic components
    - identifying when repair is no longer safe or viable
    - appropriate storage and transfer of failed components.
- Improve access to spare parts, diagnostics and simple testing tools to reduce unsafe improvisation.
- Encourage solar companies, programmes and industry associations to recognise and engage independent repair actors, including beyond warranty periods.
- Link repair activities to light-touch data collection on common failure modes to inform future system design and planning.

4.4.2. Leverage existing infrastructure for collection and aggregation

Rationale

A major barrier to safe PV EoL management is the lack of dedicated collection and reverse-logistics systems. However, the review finds that many LMICs already possess infrastructure that can be repurposed or adapted for early-stage aggregation of PV waste. These include municipal waste facilities, WEEE collection points, solar company warehouses, service centres, and logistics networks. Using existing infrastructure avoids the cost and delay of building new facilities and allows early action to focus on the most hazardous components, particularly batteries and small electronics.

Recommended actions

- Identify and pilot PV waste aggregation through existing facilities, such as:
    - municipal waste transfer stations
    - urban WEEE centres
    - solar company depots or service hubs.
- Prioritise aggregation of batteries and BoS components, where volumes and risks are already significant.
- Develop simple, practical guidance for safe handling, storage and labelling of collected components.
- Use early pilots to generate evidence on volumes, logistics costs and operational challenges to inform future system design.

4.4.3. Use donor and development-finance conditionality to embed EoL requirements early

Rationale

In many LMIC PV markets, donor programmes and development finance play a central role in shaping system design, procurement practices and operational standards. The case studies show that when EoL considerations are included as programme conditions, compliance and consistency are significantly higher than when relying on regulation alone. Embedding EoL requirements early helps normalise good practice, creates incentives for coordination and avoids retrofitting obligations once waste volumes have already accumulated.

Recommended actions

- Encourage donors and development-finance institutions to include basic EoL requirements in programme and project design, such as:
    - documented plans for handling failed components
    - clear allocation of responsibilities across project actors
    - evidence of links to repair, aggregation or recycling pathways where available.
- Harmonise EoL requirements across programmes to reduce administrative burden and avoid conflicting expectations.
- Focus early conditionality on planning, safe handling and data reporting, rather than mandating full recycling solutions that may not yet be feasible.
- Use programme monitoring and reporting systems to improve sector-wide visibility of PV EoL practices.


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4.5. System shifts: What will be needed as PV waste volumes increase

The system shifts outlined below are unlikely to be fully feasible today in many LMIC contexts, particularly where PV waste volumes remain low and institutional capacity is constrained. However, the evidence shows that failing to plan for these shifts early increases the risk of future harm, including unsafe disposal, environmental contamination and costly retrofitting of policy and infrastructure. Early planning and experimentation can reduce lock-in, build confidence among actors and enable smoother transitions as PV waste volumes grow.

4.5.1. Derisk multi-actor pilots and system experimentation

Rationale

Many of the system elements required for effective PV EoL management, including reverse logistics, coordination between energy and waste actors, engagement with informal repair networks, and testing of second-life pathways, have limited real-world evidence in LMIC contexts. As a result, policymakers and investors face high uncertainty regarding costs, responsibilities and outcomes, which can stall action.

Well-designed pilots can reduce this uncertainty by generating practical learning under controlled conditions. Importantly, such pilots should be treated as experiments rather than prototypes for immediate scale-up, with success measured in learning and risk reduction rather than throughput or profitability.

Recommended actions

- Support a small number of time-bound, learning-oriented pilots that involve multiple actors across the PV value chain.
- Focus pilots on specific system questions, such as:
  - safe aggregation and preprocessing of batteries
  - coordination between solar companies and waste authorities
  - hybrid models linking informal repair and formal treatment.
  - Build monitoring and documentation into pilot design to capture:
  - operational challenges
  - cost drivers
  - unintended risks or behaviours.
- Share findings openly to inform policy discussions and reduce duplication across countries.

4.5.2. Enable longer-term system shifts

Rationale

As PV deployment continues to scale, LMICs will eventually need system-level solutions that go beyond repair and ad-hoc aggregation. However, many of these solutions, such as domestic recycling facilities, advanced material recovery or full producer-responsibility schemes, require waste volumes, coordination and financing that are not yet present in most contexts. The review highlights three areas where early planning can significantly reduce future barriers: regional approaches to scale, circular design and procurement, and structured second-life pathways.

Recommended actions

- **Plan for regionalisation:** Explore regional or cross-border approaches to PV EoL management, recognising that national waste volumes may be insufficient to justify standalone facilities. Early dialogue can help align standards, logistics and regulatory expectations.
- **Encourage circular design and procurement:** Promote design and procurement practices that consider repairability, modularity and disassembly, particularly in donor-funded and publicly procured systems. This reduces future EoL costs and improves system longevity.
- **Develop second-life pathways cautiously:** Support controlled testing and grading of used PV modules and batteries for second-life applications, ensuring safety and performance are prioritised over diversion from waste alone. Clear criteria are essential to avoid shifting risk to new users.
- **Sequence policy ambition:** Use learning from pilots and improved data visibility to phase in more ambitious policy instruments over time, avoiding premature regulation that may be unenforceable or distort markets.

Photo © Kit Oates

5. Appendices

5. Appendices

5.1. Data extraction and search terms

The data framework was designed to extract data under the following headings:

- Article scope (including case study, original research article, academic review, perspective)
- Geographic scope
- Who funded the work?
- Methodology
- Infrastructure considered (for example SHS, solar lanterns, mini-grids, panels, batteries)
- Describe relevant product circular design attributes (such as was the product designed modularly with disposal in mind)
- Type of system examined (formal versus informal)
- Any resource extension considerations (such as reuse / repair / remanufacture)
- Whose voices were included in the research (for example donor, government, private sector, waste collectors)?
- What makes up the system?
  - Primary assessment and separation
  - Collection and transportation
  - Secondary assessment and separation
  - Processing and recycling
  - Disposal
- What are the impacts of the system on:
  - People working in this sector?
  - Local communities?
  - International communities?
  - Governments?
  - Environment?
- Factors that are enablers/barriers or recommendations for the EoL system:
  - Social or health
  - Technical
  - Economic
  - Financial
  - Political
  - Policies and regulations
  - Environmental
  - Supply chain or infrastructural
  - Legal or ethical
  - Data and knowledge
  - Other
- Key players, programmes and initiatives in this area mentioned or referred to in the document
- Specific engineering issues of note
- Search terms used were:

  ("solar panel*" OR "solar module*" OR "solar cell*" OR "photovoltaic module*" OR "photovoltaic panel*" OR "photovoltaic cell*" OR "PV module*" OR "PV panel*" OR "PV cell*" OR "solar PV*" OR "solar photovoltaic*")

AND

("recyc*" OR "end of life" OR "end-of-life" OR "life cycle" OR "life-cycle" OR "waste management" OR "waste*" OR "material recovery" OR "resource recovery" OR "material reuse" OR "reuse" OR "re-use" OR "reprocessing" OR "remanufactur*" OR "rework*" OR "dispos*" OR "waste" OR "e-waste" OR "hazardous waste" OR "circular economy" OR "stewardship" OR "take-back" OR "extended producer responsibilit*" OR "EPR" OR "dispos*" OR "scrap*" OR "dump*" OR "discard*" OR "informal" OR "wastepicker*" OR "waste picker*" or "waste-picker*")

AND

("List of specifically named LMICs*" OR "Africa*" OR "Sub-Saharan Africa*" OR "North Africa*" OR "West Africa*" OR "East Africa*" OR "Asia*" OR "South Asia*" OR "East Asia*" OR "North Asia*" OR "West Asia*" OR "South America*" OR "Latin America*" OR "LATAM*" OR "Central America*" OR "LMIC*" OR "Low Income Countries" OR "Middle Income Countries" OR "Low and Middle Income Countries" OR "Developing Nation*" OR "Developing Countr*" OR "Emerging Econom*" OR "Developing Econom*").

5.2. Key PV EoL stakeholders

- **Global Off-Grid Lighting Association (GOGLA):** The global trade association for the off-grid solar industry. GOGLA has developed an e-waste toolkit to support responsible waste management in the off-grid sector and promotes producer responsibility among distributed energy companies.
- **Global Solar Council:** An international nonprofit organisation representing the global solar PV industry and supporting policy harmonisation and market development.
- **International Renewable Energy Agency (IRENA):** Has published multiple global reports on PV waste projections and EoL management pathways, helping frame the scale and urgency of future waste flows.
- **International Solar Alliance (ISA):** A member driven intergovernmental organisation that promotes global solar deployment. In October 2025, ISA launched SUNRISE – the Solar Upcycling Network for Recycling, Innovation and Stakeholder Engagement. SUNRISE aims to connect governments, industry and innovators to unlock economic value from solar waste, positioning EoL management as a driver of green jobs, industrial development and CEE growth.
- **International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS):** A programme that facilitates international collaboration and knowledge exchange on PV sustainability, including environmental and social dimensions of PV life cycle management.
- **Efficiency for Access Coalition and CLASP:** Funder of the 2019 Solar e-Waste Challenge, stimulating innovation in e-waste management solutions in sub-Saharan Africa.
- **Multilateral development banks:** These include the World Bank, International Finance Corporation (IFC), African Development Bank (AfDB), and Asian Development Bank (ADB). These institutions influence EoL practices through policy advisory work, environmental safeguard requirements and project financing structures. Within the World Bank Group, Lighting Global supports off-grid market development and sets quality standards for solar products, indirectly affecting durability and waste generation patterns.
- **UN agencies:** Including United Nations Development Programme (UNDP), United Nations Institute for Training and Research (UNITAR), United Nations Industrial Development Organization (UNIDO), and United Nations Environment Programme (UNEP). These agencies fund pilot projects, deliver policy and capacity-building initiatives and support CEE programming. UNEP's e-Waste Africa Programme represents a regional effort to strengthen Basel Convention enforcement and improve e-waste governance frameworks.
- **Bilateral development agencies:** Such as Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), FCDO, and Swedish International Development Cooperation Agency (SIDA). These agencies provide technical advisory support, fund policy reform and implement awareness and capacity-building programmes relevant to EoL systems.
- **Regional bodies:** For example, Economic Community of West African States (ECOWAS), which can shape regional regulatory alignment and influence EoL practices through harmonised policy requirements.
- **National governments and regulatory authorities:** Country-level stakeholders include: Ministries of Energy, Ministries of Environment, Energy Commissions and Utilities Regulatory Authorities, Environmental Protection Agencies and Public energy corporations. These actors establish waste regulations, licensing frameworks, import/export controls, and enforcement mechanisms that determine how PV waste is managed domestically.
- **E-waste and PV recycling companies (LMIC-based):** Emerging recyclers operating in LMIC contexts include: WEEE Centre (Kenya), East African Compliant Recycling (Kenya), Enviroserve Rwanda (Rwanda), Recykla International (Kenya), E-Waste Initiative Kenya (EWIK, Kenya), Regain Technologies (India, PV-focused), Paraenergia (India, PV-focused). These companies represent early-stage domestic capacity for formalised recycling and material recovery.
- **Off-grid companies, producers and manufacturers:** Although representing a relatively small share of total national e-waste volumes, off-grid companies have often led voluntary recycling initiatives because of EPR pressures and donor requirements. Examples include: M-KOPA, Fenix International, Mobisol, ZOLA Electric, d.light, EasySolar.
- **PV module manufacturers:** Waaree Energies, First Solar. Some manufacturers, notably First Solar, operate established recycling schemes, recovering up to 90% of material from cadmium telluride thin-film modules.
- **International recycling companies:** PV CYCLE, SolarCycle, 2ndLifeSolar. These companies represent more mature recycling ecosystems, primarily located in high-income countries, and provide insight into potential technology transfer pathways.
- **Research organisations and think tanks:** The Energy and Resources Institute (TERI), Bridge to India, University of California Berkeley, Strathmore University, World Resources Institute (WRI). These

institutions contribute life cycle analysis, policy research and market intelligence on PV deployment and circular economy strategies.

- **Consumers and asset owners:** Utility-scale developers, commercial and industrial rooftop owners, telecom operators, and institutional PV asset holders represent concentrated future EoL volumes. Households consumers including rooftop PV adopters and off-grid solar home system users. In many LMICs, these dispersed users generate small but widespread waste flows, often entering informal waste streams.
- **Key programmatic initiatives:** ISA's SUNRISE programme (2025 launch), promoting solar upcycling and green job creation, Solar e-Waste Challenge (Efficiency for Access / CLASP, 2019), UNEP's regional e-waste programmes supporting Basel Convention compliance, Donor-funded pilot and capacity-building initiatives led by UN agencies and bilateral partners.

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5.3. List of stakeholder organisations

Organisation	Specific themes
Malawi	
Lilongwe City Council	Council recycling infrastructure and plans
Malawi Environmental Protection Authority	Regulatory issues – Environmental
RECAPO Solar Systems	Off-grid solar Provider (SHS)
Malawi Energy Regulatory Authority (MERA)	Regulatory issues – Energy
Omicron Malawi	e-waste recycler in Malawi
Solar AID Malawi	Off-grid solar Provider (SHS)
Ministry of Energy	Policy and regulatory (Energy)
Rwanda	
Energy Private Developers	Links to private-sector player – more stakeholders
Rwanda Ministry of Infrastructure (MININFRA)	Policy and regulatory (Infrastructure/recycling)
Rwanda Utilities Regulatory Authority (RURA)	Policy and regulatory (Energy)
EnviroServe	Experience of recycling PV in Rwanda
Nepal	
WECS, Ministry of Energy, Water Resources and Irrigation, Nepal	Policy and regulatory (Energy)
Nepal Electricity Authority (NEA)	Policy and regulatory (Energy)
Nepal Academy of Science and Technology (NAST)	Research and policy on Solar PV
Alternative Energy Promotion Centre in Nepal	Policy and regulatory (Energy)
Solar Electric Manufacturers Association Nepal (SEMAN)	Private sector insights
Doko Recyclers	Recycling of e-waste (PV)
Simple Energy Pvt. Ltd	Private sector
British Embassy Kathmandu	Development partners on policy and recycling, investment in e-waste management
NEEP/GIZ	Development partners on policy and recycling, investment in e-waste management
Green Growth Nepal	UK-funded project
ICIMOD	Regional development agency
Kathmandu University	Academic research
Tribhuvan University	Academic research
Kenya	
Kenya Renewable Energy Association (KEREA)	Private sector
National Environment Management Authority (NEMA)	Policy and regulatory
Kenya Climate Innovation Centre (KCIC)	Research
ACEN / KEPSA Circular Economy Taskforce	Relevant local initiatives
E-waste initiative Kenya (Ewik)	Existing recycling
India	
CEEW	Private sector
NSEFI	Policy and regulatory
SERI	Research
Para Energia Pvt Ltd	Solar PV recycler
CEEW	Author of recently published study on solar waste in India
Beyond Renewables	Solar PV recycler

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6. References

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7. Acknowledgements

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Equal Access Energy is a social enterprise providing technical support, capacity building and investment to accelerate off-grid energy access in Africa. We contribute to our vision of low-carbon, affordable and sustainable energy access for all by building partnerships with local organisations in Sub-Saharan Africa and supporting them to deploy and operate off-grid renewable energy systems serving rural communities.

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>
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