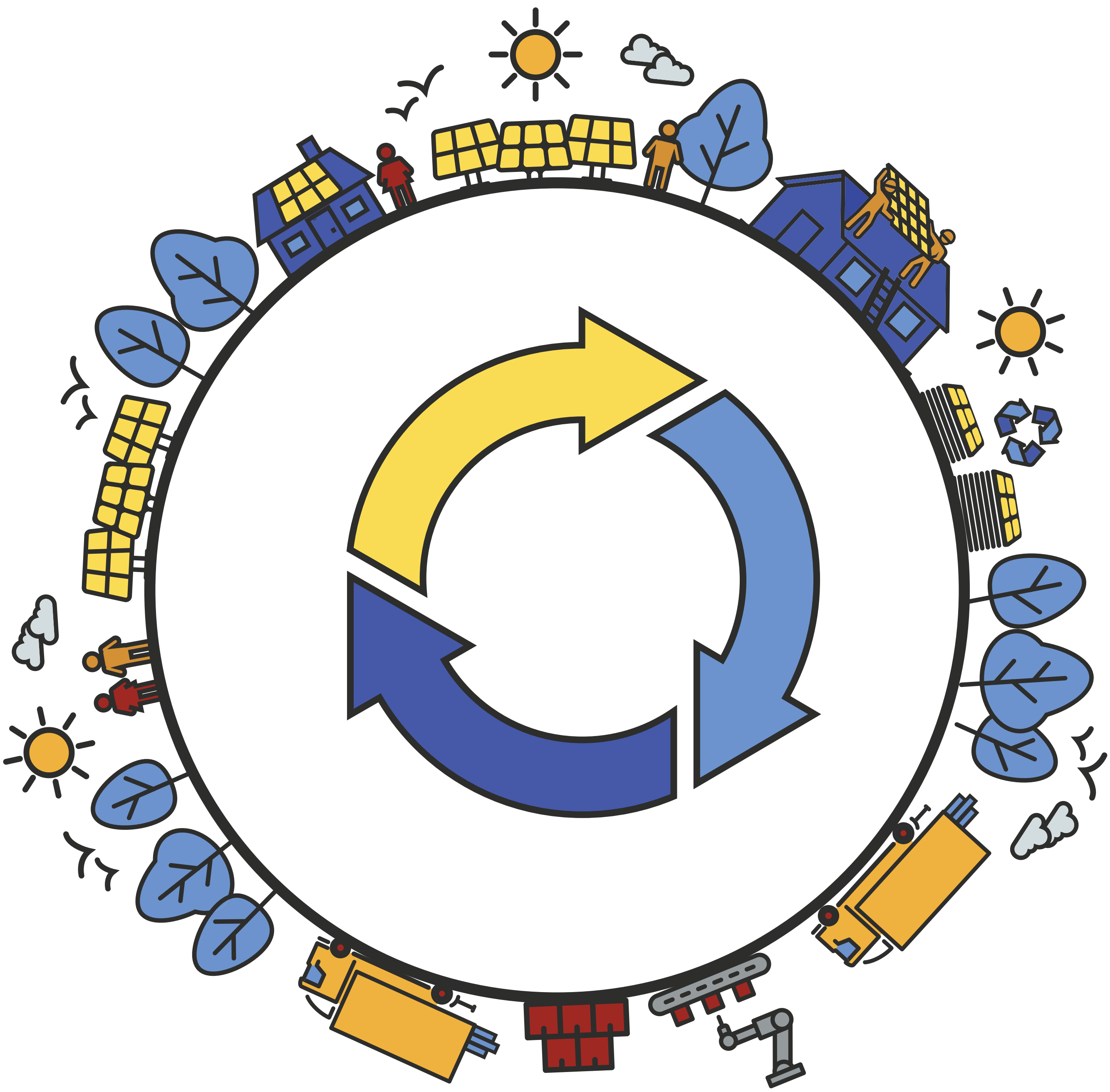
International Renewable Energy Agency

END-OF-LIFE MANAGEMENT FOR A CIRCULAR ECONOMY

SOLAR PV PANELS



ISBN: 978-92-9260-760-9

Citation: IRENA (2026), *End-of-life management for a circular economy: Solar PV panels*, International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

Acknowledgements

This report was developed under the guidance of Ute Collier (Deputy Director, Knowledge, Policy and Finance Centre). It was authored by Jinlei Feng (IRENA) with support from Peiyao Lyu (ex-IRENA). Modelling of the end-of-life solar PV panels and material recovery potentials was conducted by Karsten Wambach (consultant), who has also provided value inputs to the report.

IRENA would like to thank valuable insights and inputs provided by Garvin Heath, Taylor Curtis, and Phoebe O'Connor (National Laboratory of the Rockies), Stephanie Weckend (German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety), Qiong Li, Lu Zheng (State Power Investment Corporation), and Jan Clyncke (PV Cycle).

The report benefited from the reviews by Richard Corkish (Australian Centre for Advanced Photovoltaics), Rabin Basnet (Australian National University), Phil McKay (Canadian Renewable Energy Association), Hui Zhang (China National Resource Recycling Association, CRRA-CWSER), Vasilis Fthenakis (Columbia University), Akanksha Tyagi (Council on Energy, Environment and Water), Anna Heimsath (Fraunhofer Institute for Solar Energy Systems), Rebecca Rhodes (GOGLA), Rohit Sen, Kanak Gokarn, Magash Naidoo, Sastry Akella (ICLEI), Nanda Kumar Janardhanan, Premakumara Jagath Dickella Gamaralalage (IGES), Gurleen Kaur (International Solar Alliance), Alvin EE (National University of Singapore), Lin Sun, Hanbo Yu (Jinko Solar), Raffaele Rossi (Solar Power Europe), Rong Deng (University of New South Wales), Ke Wang, Shengnian Xu, and Tirthankar Mandal (World Resources Institute).

It was also reviewed by IRENA colleagues Ann-Kathrin Lipponer, Deborah Machado Ayres, Hannah Sofia Guinto, Jaidev Dhavle, Kamlesh Dookayka, Karanpreet Kaur, Mamadou Goundiam, and Ntsebo Sephelane. Technical review was provided by Paul Komor.

Editing and production were managed by Francis Field with the support of Stephanie Clarke. The report was copy-edited by Stefanie Durbin, with graphic design by Myrto Petrou.

IRENA would like to thank the Federal Government of Germany for its support in making this report possible.

For further information or to provide feedback: **publications@irena.org**.

This report is available for download: **www.irena.org/publications**

Disclaimer

CONTENTS

FIGURES

BOXES

ABBREVIATIONS

AUD	Australian dollar
CNY	Chinese Yuan renminbi
CPCB	Central Pollution Control Board (India)
c-Si	crystalline silicon
CSO	civil society organisation
ECOPV	PV Committee of China Green Supply Chain Alliance
EPR	extended producer responsibility
EU	European Union
EUR	euro
EVA	ethylene vinyl acetate
e-waste	electronic waste
FIT	feed-in tariff
G20	Group of 20
g	gramme
GW	gigawatt
HF	hydrogen fluoride
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
ILO	International Labour Organization
IRENA	International Renewable Energy Agency
kg	kilogramme
kg/kW	kilogramme per kilowatt
kg/m²	kilogramme per square metre
KRW	Republic of Korea won
kWh	kilowatt hour
kWp	kilowatt peak
LCOE	levelised cost of electricity
mono-Si	monocrystalline silicon
Mt	million tonne
multi-Si	multicrystalline silicon
MW	megawatt
MWh	megawatt hour
MWp	megawatt peak
NGO	non-governmental organisation
O&M	operation and maintenance
poly-Si	polysilicon
PV	photovoltaic
QR	quick response
R&D	research and development
RFID	radio-frequency identification
t	tonne
TW	terawatt
US	United States
USD	United States dollar
WEEE	waste electrical and electronic equipment
WEELABEX	WEEE label of excellence
Wp	watt peak

EXECUTIVE SUMMARY

An accelerated deployment of solar photovoltaic (PV) capacity remains key for the energy transition. Although critical for a successful transition, this deployment may also have undesirable effects, including intensified material demand and environmental impacts associated with retired solar PV panels. These impacts can be prevented or managed successfully if appropriate policies and regulatory frameworks are put in place in a co-ordinated and timely manner.

Solar PV is one of the most widely deployed renewable energy technologies worldwide. It contributes almost half of the global total installed renewable capacity and is expected to play a major role in meeting the renewable deployment needed for the energy transition. In its rise to prominence in the energy transition, the solar PV industry's demand for materials has gradually increased its share of total industrial demand. This material demand is expected to increase further, requiring more than 31 million tonnes (Mt) of materials for solar module production in 2030, a fourfold increase compared to the 2020 level.

Solar PV's increasing material demand has triggered concerns about potential supply chain pressure, the availability of critical materials, the environmental impacts associated with mining activities, and local community impacts. From a global perspective, demand for major energy transition technologies, including solar panels, will not face supply shortages in the near or medium term. However, supply chains can be disrupted by trade barriers and geopolitical tensions. Furthermore, mining activities linked with the solar PV supply chain can have a wide range of adverse effects on local environments and communities. Addressing these environmental impacts requires policies and measures to minimise virgin material demand and the adoption of vigorous mitigation measures. Measures are also needed to share benefits with local communities, improve environmental regulations and leverage third-party sustainability frameworks.

Other concerns revolve around the waste generated by solar PV panels that have reached the end of their useful lifecycles. These end-of-life panels will generate a significant amount of waste stream in the future. By 2050, the global cumulative weight of end-of-life solar PV panels is expected to surpass 200 Mt in the 1.5°C Scenario. Meanwhile, the global annual volume of end-of-life solar PV panels is projected to surge to over 25 Mt by 2050. While most of the currently deployed solar PV capacity has not yet reached the end of its service time, several markets, including China, the European Union, India and the United States, will likely need to handle over a million tonnes of solar PV waste annually as of 2043. Furthermore, solar PV waste is projected to contribute over 21% to the global total weight of electronic waste (e-waste) by 2050, rising from less than 1% now. These are all indicators of an urgent need to invest in infrastructure for the transport and treatment of this e-waste stream.

The collection and treatment of existing end-of-life solar panels vary significantly across regions and countries, depending on their existing regulatory frameworks. Even though most markets do not have specific regulations for the end-of-life management of solar PV panels, an increasing number of markets are establishing policy frameworks and infrastructure dedicated to the collection and treatment of end-of-life solar panels, with efforts observed in some countries and subnational governments. However, most solar PV waste ends up in landfills, along with other e-waste, except in China, the European Union and several developed markets.

In many developing markets, a significant share of waste streams are from off-grid solar PV appliances. Sub-Saharan Africa has an estimated 10 000-12 000 tonnes (t) of end-of-life off-grid solar products. In a region that may lack local technical expertise or have limited access to maintenance services, off-grid solar equipment that cannot be repaired is often disposed of in open dumpsites or landfills, causing significant environmental and public health impacts. In response, countries such as Kenya, Nigeria and Rwanda have taken proactive measures, promoting partnerships and business models to support the formal recycling of end-of-life off-grid solar appliances. However, investments and international development support are still needed to bridge financial and capacity gaps and further support the expansion of these sustainable practices.

Circular economy principles, such as "reduce", "reuse" and "recycle", play a key role in promoting the sustainable management of end-of-life solar PV and preventing most unwanted environmental and social impacts. "Reduce" involves measures to minimise waste generation from the design and production phases and to make solar PV easier to reuse and recycle without compromising performance. "Reuse" aims to extend the service life of decommissioned solar PV panels and components based on repairing, refurbishment, testing and certification. "Recycle" focuses on the recovery of metals and materials through mechanical, chemical and thermal treatment processes. The recovered materials can then be purified and used to manufacture new products, avoiding the need for virgin materials. Promoting the circular economy for end-of-life solar PV requires the engagement of stakeholders from government, industry, non-governmental organisations (NGOs), communities, and formal and informal e-waste recyclers.

"Reduce", "reuse" and "recycle" approaches have received uneven attention from industries. While solar PV producers in China and the European Union – guided by regional and national policies – are integrating circularity into new solar PV technologies, elsewhere, high costs and a lack of technology and quality infrastructure remain barriers to reusing solar PV components. The industrial sector has invested more in recycling than reuse, and commercialised, circularity-aligned solar PV recycling projects have been established in major markets. However, in the medium and long term, more efforts will be needed to prioritise the "reduce" and "reuse" approaches.

In addition to their sustainability credentials, circular economy practices can also bring economic benefits. Recycled and recovered PV materials include glass, silicon, aluminium, and valuable metals like silver and copper. By 2050, the market value of these recovered materials could exceed USD 20 billion (United States dollars).

Despite its economic and environmental advantages, the circular economy faces many barriers that impede the adoption and expansion of end-of-life solar PV management. These barriers relate to unregulated e-waste recycling; limited information, financial resources, infrastructure capacity and feedstock; the absence of market demand and standardisation; and low technological readiness.

A holistic policy framework is needed to overcome these barriers and enable the circular economy for end-of-life solar PV panels. Key policies include strategies, targets and road maps, as well as appropriate environmental regulations to prevent unsustainable, unregulated collection and treatment of solar PV panels. Extended producer responsibility (EPR) and similar policies are proven and effective measures for defining the financial and implementation responsibilities for the takeback and treatment of end-of-life solar PV panels. Some markets have taken other routes, such as banning solar PV waste landfilling and providing incentives for voluntary takeback and treatment programmes led by industrial players.

The reuse market can be further enabled by independent testing and certification schemes. Innovations in technology and business models, as well as an integrated digital platform for data collection, reporting and monitoring, also play important roles. Financial and fiscal incentives can support research, development and the demonstration of new solutions. Finally, international co-operation and stakeholder engagement, including with vulnerable groups and informal recyclers, remain key to ensuring an inclusive and just transition of the sector.

INTRODUCTION

Solar photovoltaic (PV) remains one of the most promising technologies to tackle global climate change by providing sustainable and affordable electricity. In 2024, the global weighted-average levelised cost of electricity (LCOE) for utility-scale solar PV was 41% lower than the cheapest fossil fuel-fired alternative (IRENA, 2025a). In addition, the solar PV industry offers various socio-economic benefits. It provided 7.2 million jobs globally in 2024 in sectors including manufacturing, construction, operation and maintenance (O&M), and decommissioning (IRENA and ILO, 2026). Solar PV can improve agricultural resilience in developing markets by powering irrigation systems, as well as processing and refrigeration in the agri-food value chain. Further, solar energy can strengthen energy security due to the widespread availability of solar resources across markets, and the modular nature of solar PV increases its reliability.

Solar PV deployment has been increasing rapidly worldwide. By the end of 2025, global solar PV capacity accounted for 46% of global total installed renewable capacity and 74% of new additions (IRENA, 2026a). The majority (over 90%) of this capacity was installed in the last ten years, indicating that many of the existing solar PV plants will operate for another twenty years or so before reaching the end of their service life. Markets with the largest installations include China, the European Union, India, Japan and the United States. In the International Renewable Energy Agency's (IRENA's) 1.5°C Scenario, global installed solar PV capacity will need to increase from 2 383 gigawatts (GW) in 2025 to over 5 terawatts (TW) by 2030 and more than 18 TW by 2050, providing half of the needed renewable capacity by mid-century (IRENA, 2024a).

The rapid expansion of solar PV projects impacts the local environment. This occurs across the entire supply chain and project life cycle, including the mining and processing of raw materials, manufacturing and transportation, deployment, O&M, and the decommissioning of power plants and treatment of panels. To examine some of these impacts, in 2016, IRENA and the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) jointly published the report *End-of-life management: Solar photovoltaic panels* (IRENA and IEA-PVPS, 2016). That report was the first-ever projection of PV panel waste volumes to 2050 at the global level. This report constitutes the second edition of IRENA's analysis of the end-of-life management of renewable technologies, examining future waste streams from solar PV plants under the 1.5°C Scenario. While the 2016 report focused on technical discussion and waste modelling methodology, this report involves more policy perspective and recommendations. It aims to present a forward-looking picture of end-of-life solar PV panels through 2050 and the potential impacts on local environments and raw material demand. To address these potential impacts linked to future waste streams, this analysis provides a comprehensive and in-depth policy analysis on promoting the circular economy for solar PV technologies, as well as the co-benefits they may bring to society and communities.

The structure of the report is as follows:

Chapter 1 provides an overall estimate of the material demand for solar PV, as well as possible environmental impacts associated with that demand.

Chapter 2 estimates the volume of end-of-life solar panels from 2030 to 2050 based on IRENA's 1.5°C Scenario at the global level and in selected markets.

Chapter 3 outlines the current status of end-of-life solar PV treatment and its negative impacts on the environment and local communities.

Chapter 4 examines circular economy approaches and implications for solar PV panels.

Chapter 5 proposes a policy framework that aligns with a circular economy for the solar PV industry.

Chapter 6 discusses key considerations for the way forward.

CHAPTER 1

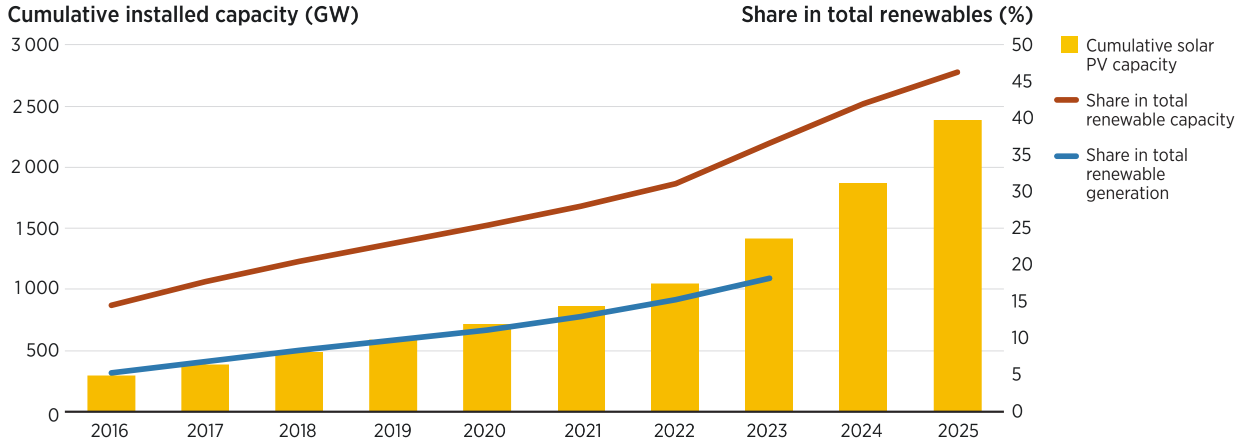
SOLAR PV IN THE ENERGY TRANSITION: CAPACITY AND MATERIAL DEMAND

1.1 SOLAR PV DEPLOYMENT IN THE ENERGY TRANSITION

CURRENT STATUS

Solar PV is one of the most widely deployed renewable energy technologies worldwide. From 2016 to 2025, global deployment increased from 293 GW to 2 383 GW, indicating a 26% average year-on-year increase or eightfold capacity increase in the last decade (see Figure 1). By the end of 2025, solar PV contributed 47% of global total installed renewable power capacity and 74% of new additions (IRENA, 2026a). In 2023, solar PV electricity provided 5% of global total electricity generation and 18% of renewable electricity generation (IRENA, 2025b). Within total renewable energy investment in 2024, around 69% of the total, or USD 554 billion (United States dollars) out of the USD 807 billion for all renewables went to solar PV (IRENA and CPI, 2025). The global average total installed cost of solar PV projects declined by 87% in 2024 compared to the 2010 level. Concurrently, the LCOE for utility-scale solar PV also fell by 90% from USD 0.417 per kilowatt hour (kWh) to USD 0.043/kWh, making it 41% cheaper than the cheapest fossil fuel-fired alternatives (IRENA, 2025a). Furthermore, the solar PV industry has provided over 7.2 million jobs globally, accounting for more than 43% of total renewable energy jobs in 2024 (IRENA *et al.*, 2026).

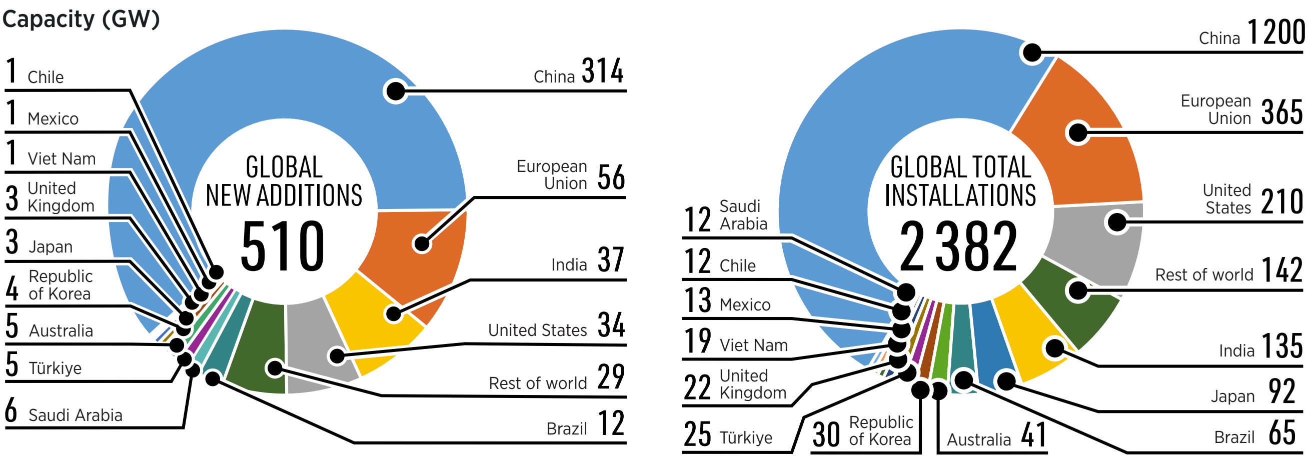
Figure 1 Solar PV installed capacity, share in total renewable capacity and electricity generation globally, 2016-2025



Source: (IRENA, 2026a).

Regional deployment has been uneven, with Asia leading the global expansion. By the end of 2025, Asia had installed 1 528 GW of solar PV projects, accounting for 62% of global installed capacity and 54% of new additions. Within the Asia region, China, India, Japan, the Republic of Korea and Viet Nam are leading the expansion. Outside of Asia, Europe and North America are other major markets, where total installed solar PV reached 405 GW and 229 GW, respectively. Together, these three regions accounted for more than 90% of the global installed capacity and 91% of new additions in 2025 (see Figure 2). In the rest of the world, several markets emerged with rapid expansion in their regions. For example, in Latin America, Brazil deployed more than 11 GW of new solar PV capacity in 2025, representing a 22% year-on-year increase. In the Middle East, Saudi Arabia added more than 5.7 GW of solar PV capacity in 2025. In Africa, South Africa added more than 2.2 GW of new solar PV capacity, making this country host to half of the total deployed solar PV capacity in Africa (IRENA, 2026a).

Figure 2 Total and newly added solar PV capacity in selected markets, 2025



Source: (IRENA, 2026b).

It is estimated that utility-scale solar PV projects (larger than 1 megawatt [MW] of capacity) accounted for the majority of solar PV deployment, in particular for markets with larger installations of solar PV projects. When deployed on land, these utility-scale projects can cover an average of 2-4 hectares per MW (IRENA, 2026b). In many cases, utility-scale solar PV projects are deployed away from energy consumption centres (*e.g.* urban areas, industrial areas), requiring long-distance grid infrastructure for transmission and distribution. In particular, an increasing number of GW-level solar PV projects have been installed in Brazil, China, Egypt, India, Saudi Arabia, Türkiye and the United Arab Emirates (Egyptian Presidency, 2018; Global Energy Monitor, 2026; Neris, 2025). Some of these projects are deployed on degraded land, indicating potential co-benefits for restoring degraded land during the O&M stage if proper measures and solutions are adopted (IRENA, 2026b).

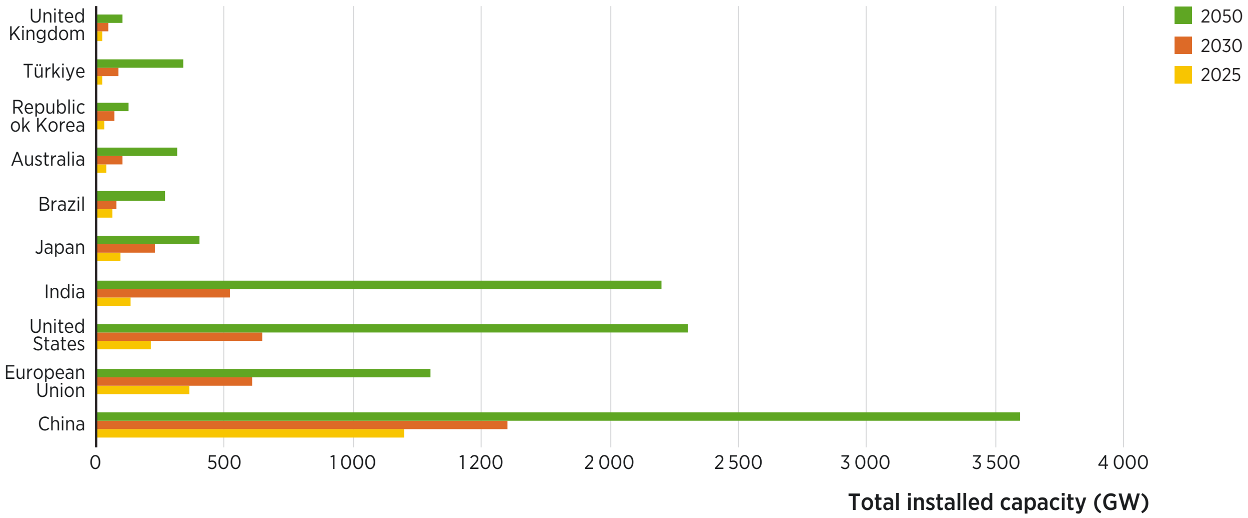
Off-grid solar PV applications play a crucial role in providing electricity access, particularly in developing countries. These applications encompass solar lights, solar home systems, solar mini-grids, solar pumps for water supply and agriculture, and various other off-grid solar PV systems. According to IRENA data, the global total installed capacity of these off-grid solar PV systems reached approximately 4.1 GW by the end of 2024. Half of these reported off-grid solar applications are used for agriculture and mini-grids. India installed about 90% of all solar pumps for agriculture, supported by national programmes such as the PM-KUSUM scheme. Indonesia installed two-thirds of the global total of solar mini-grids, many supporting rural livelihoods (IRENA, 2025c).

FUTURE DEVELOPMENT TO 2050

Solar PV remains one of the most promising renewable technologies in the global energy transition, aligning with the Paris climate targets. This is not only because of the more affordable electricity solar PV can provide, but also because of the employment and economic opportunities it can create along the whole value chain. Meanwhile, solar radiation is geographically widespread, and solar energy is among the most readily accessible renewable energy technologies. It can contribute to improved energy security and prosperity (IRENA, 2025d).

According to IRENA's 1.5°C Scenario, global installed solar PV capacity needs to increase from 2 383 GW in 2025 to over 5 TW by 2030 and more than 18 TW by 2050 (IRENA, 2024a). Achieving these targets would require doubling solar capacity over the next four years and increasing it by more than sevenfold by 2050 compared to the 2025 level. It is estimated that Group of 20 (G20) members will lead the needed deployment due to their greater financial resources and more advanced policy frameworks (see Figure 3).

Figure 3 Cumulative solar PV installations in selected markets by the end of 2025 and estimates for 2030 and 2050 in IRENA's 1.5°C Scenario



Source: (IRENA, 2024a, 2026a).

1.2 MATERIAL DEMAND OF SOLAR PV DEPLOYMENT

While solar PV deployment is expanding rapidly, the industry has placed a strong emphasis on technological innovations to reduce material consumption, achieving notable progress through advances in wafer thinning, kerf loss reduction and overall process optimisation (IRENA, 2025a). However, overall material demand for manufacturing solar PV will likely continue to increase, given the large-scale deployment needed to replace fossil fuels and improve access to electricity. This section aims to provide an estimate of current and future material demand for solar PV panels, as well as the potential competition between material use in solar PV and broader economic uses. It intends to provide policy makers with an overview of the material sufficiency needed for solar PV deployment in the energy transition. The assessment is focused on the dominant technology, crystalline silicon (c-Si) solar panels.

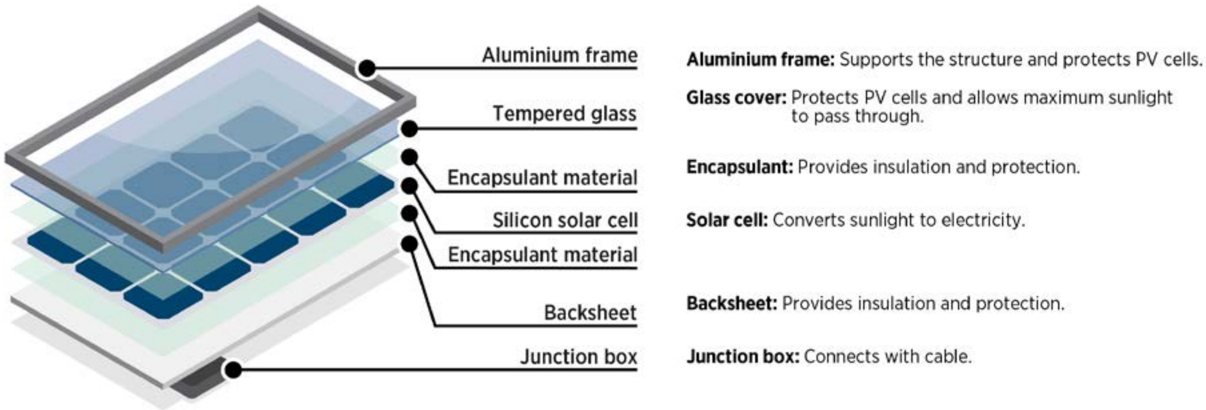
MATERIALS NEEDED FOR SOLAR PV PANELS

Currently, the dominant solar PV panels are c-Si panels due to their higher energy efficiency, better durability and longer service life. In 2024, c-Si accounted for approximately 98% of global PV cell and module production, while other technologies (*e.g.* thin-film) accounted for only around 2% (VDMA, 2025). The c-Si solar panels include monocrystalline (mono-Si) and multicrystalline silicon (multi-Si) technologies. Over the past decade, the market has undergone a significant shift from multi-Si to mono-Si. Multi-Si accounted for around 70% of global PV production in 2014, but by 2024 it had almost disappeared from new deployments, and the market has been dominated by mono-Si (Fraunhofer ISE, 2025).

A typical solar PV system's key components include solar PV panels (including junction boxes), mounting structures, inverters and cables.[1] These components require different raw materials and have different lifespans. For example, inverters typically last only 10-15 years, whereas solar panels can last over 25 years. In practice, after reaching the end of their service life, components of solar PV systems need to be classified and processed accordingly. Mounting structures are usually made of steel, aluminium or concrete and are defined as non-hazardous solid waste when disposed of. Solar panels and inverters may be collected and processed as separate electronic waste (e-waste) streams, indicating the need for tailored policies and measures for their treatment (see Chapter 5).

Solar PV modules typically include several layers, such as an aluminium frame, glass cover, encapsulant, solar cells and a backsheet (see Figure 4). Despite their relatively simple configuration, manufacturing these panels involves the use of a variety of materials. Aluminium is the dominant frame material, with a 94% market share in 2024 (VDMA, 2025). Glass is used as front-side cover in standard modules and as both front- and back-side covers in glass-glass modules. Polysilicon (poly-Si) is the major and also the most expensive material in c-Si solar cells. Silver and aluminium are used in metallisation pastes for electrical conductivity. Copper is used for cables and connectors. Multiple metals and materials are used for coating and solder alloy. Organic materials are also used for encapsulation and backsheets. Some of these materials, even at low concentrations, are needed for semiconductors, coating alloys or solder alloys. Notably, some elements (*e.g.* fluorine-based backsheets) play critical roles in improving the performance and durability of solar PV panels, but can be hazardous[2] to human health and the local environment if they are not treated properly. Therefore, solar PV technology development must consider the possible trade-off between performance and environmental impacts. Future technology innovations should strive to enhance energy performance without increasing the environmental burden (see Chapter 1, Section 4).

Figure 4 Structure and materials used for a solar panel



Source: (Shafie *et al.*, 2025; Taylor *et al.*, 2025).

Note: The figure illustrates the structure of standard glass-backsheet solar panels. In double-glass solar panels, the backsheet is r replaced with a glass cover.

[1] This study focused on solar PV panels. Other components, such as inverters, cables or mounting structure, will be analysed separately in the future.

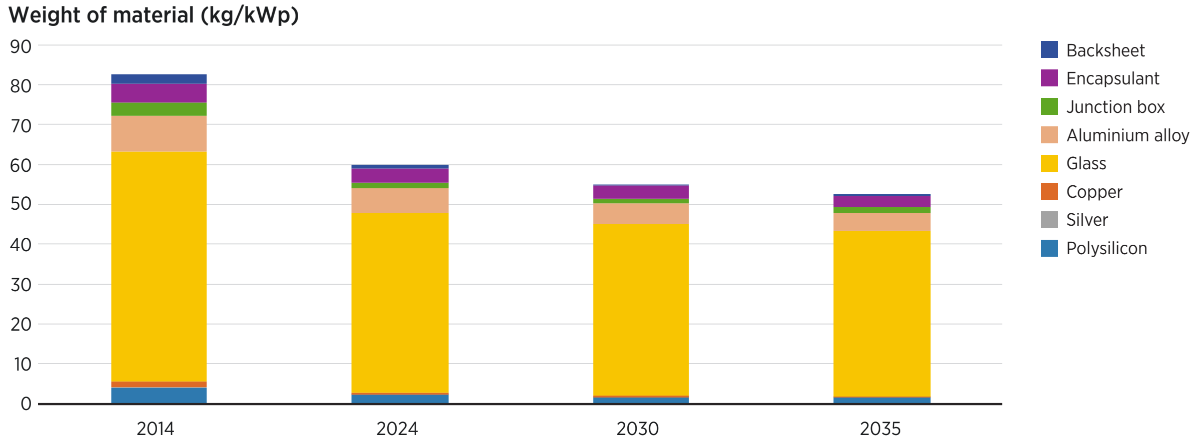
[2] According to the United Nations Environment Programme, hazardous waste is waste with properties capable of having a harmful effect on human health or the environment and is regulated and controlled by law. Hazardous waste may come in many forms, including liquids, solids, gases and sludge (UNEP, 2026). Waste listed in Annex VIII of the Basel Convention is presumed to be hazardous.

ESTIMATE OF MATERIAL QUANTITY FOR SOLAR PV PANELS

The quantities of materials used in solar panels can vary significantly, making it important to understand their material composition. In general, material inputs can be estimated based on the bill of materials, which provides a comprehensive list of all module components and the associated quantities of materials used in their production. However, in practice, detailed bill of materials information is generally not publicly available for consumers or recyclers. Even when data are available, the material composition of modules manufactured by different companies can vary due to factors such as costs, durability and local industrial regulations. Moreover, as solar PV technologies continue to evolve, material compositions also change over time.

Material efficiency has been increasing along with solar PV technology development. Solar PV technologies are now more energy efficient and consume fewer materials to achieve the same performance as previous solar PV technology. For example, silicon solar PV generation efficiency in commercial projects increased from around 16% in 2014 to over 24% in 2024 (Fraunhofer ISE, 2025). In the same period, silicon wafers and protection glasses have become much thinner than they were ten years ago. The current design of solar PV panels requires less material to generate the same level of solar electricity. In 2024, each megawatt peak (MWp) of solar PV panels contained approximately 60 t of materials, about 27% lower than in 2014, – reflecting improvements in module efficiency and technological innovation (Fraunhofer ISE, 2025; VDMA, 2022, 2025). It is estimated that this downward trend will continue in the near future, but at a slower rate due to the efficiency constraints of silicon-based solar PV technologies. Nevertheless, the weight of solar modules per MWp is expected to decline by around 12% by 2035 compared to the 2024 level (see Figure 5).

Figure 5 Estimated weight of materials for c-Si-based solar modules, 2014, 2024, 2030 and 2035



Based on: (Fraunhofer ISE, 2025; VDMA, 2022, 2025).

Notes: Polysilicon refers to the average weight of poly-Si feedstock needed to produce silicon wafer, taking into consideration manufacturing losses. Silver is used as conductive paste during the metallisation process of solar cells. Glass includes both front-side and rear-side glass used in solar modules. Copper refers to the copper used for cell interconnection. Kg/kWp = kilogramme per kilowatt peak.

Silicon is one of the most important materials for solar modules because it is the main material used to produce solar cells that convert sunlight to electricity. Solar cells account for less than 3% of the total weight of solar modules, but represent more than half (around 55-60%) of total module manufacturing costs (CPIA, 2024; VDMA, 2025). Most of the global poly-Si used in solar panels is produced in China (Bhambhani, 2025). The main feedstock (and majority of costs) for manufacturing c-Si solar cells is ultra-high purity level poly-Si (above 99.9999% [6N] to 99.999999% [8N]). Achieving such purity requires a highly energy-intensive process. Producing each kilogramme (kg) of poly-Si[3] consumed around 40 kWh of electricity in 2025

[3] Around 1.9 kg of poly-Si is needed to produce solar cells for a solar module with 66 cells and 430 watts of capacity. This considers 35% of material loss (Tongwei, 2023).

(IRENA, 2026c; Taylor *et al.*, 2025). Along with technological advancements, poly-Si consumption per kW of solar panel declined by 46% in 2024 (2.2 kg per kilowatt [kg/kW]) compared to the 2014 level (around 4 kg/kW) (VDMA, 2025). In 2024, solar PV was estimated to account for 35% of the global total demand of silicon metal.

Silver is usually used as a conductive paste for cell metallisation to conduct the generated electricity. In 2024, the weight of silver (Ag) used for solar panels was around 13 grammes (g) per kW, less than half the consumption level in 2014. In 2024, the solar PV industry accounted for 29% of global total industrial demand for silver, up from 11% in 2014 (Silver Institute and Oxford Economics, 2025). When compared with silver demand by the electric and electronics sector, solar PV contributed around 43%, which is much larger than silver demand for brazing alloys, solders and other industries (The Silver Institute, n.d.). Given the high cost of silver compared to other materials used for solar PV modules, the solar PV industry has made efforts to reduce silver consumption per solar panel, driven by technological improvements in metallisation pastes and screen-printing.

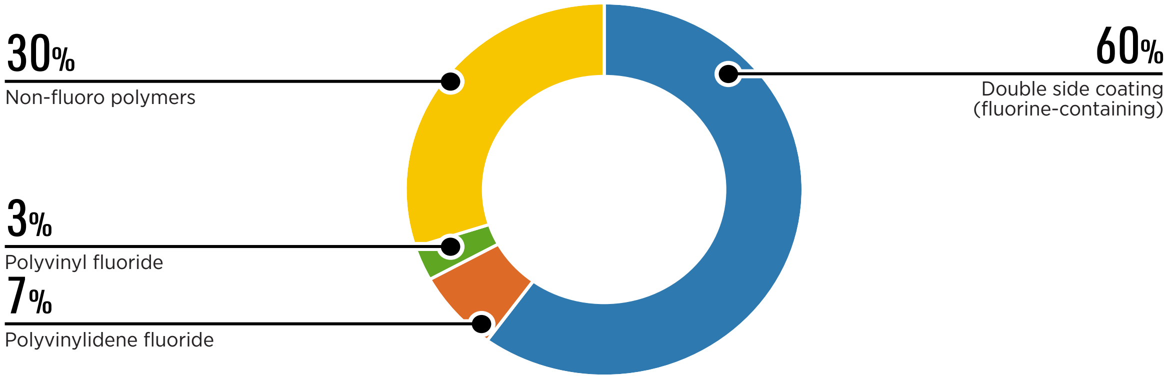
Glass and antimony are important materials for solar module covers. In 2024, glass contributed around 75% of the total weight of a solar PV module. Along with technology development, the thickness of the glass cover for solar panels has decreased by around 37% from 2015 (around 3.2 millimetre thickness) to 2025 (around 2 millimetre thickness). However, with the increasing adoption of double-glass modules, the glass share in the total weight will remain stable or become even higher (VDMA, 2025). Antimony is an element needed for the production of the solar PV glass cover to enhance its transmittance and durability. It usually accounts for less than 0.1-0.3% of the total weight of glass. However, given the large amount of glass used for solar PV panels, antimony consumption for solar PV accounted for over 31% of global total production in 2024 (National Minerals Information Center, 2026a).

Lead is often used for solders due to its reliable and cost-efficient interconnection of c-Si solar cells and for string interconnections during module manufacturing. Currently, around 50 g of lead is used for each kW of solar panel, mainly as lead-based solder for interconnections (Fraunhofer ISE, 2025). Although the quantity is relatively small, lead is widely recognised as a toxic substance that can pose risks to public health and the environment.

Aluminium and copper are two other important materials used for solar PV panels and many other electrical and electronic applications. The aluminium frame holds the second largest share (around 10%) in the total weight of solar modules. In 2024, aluminium consumption for solar PV accounted for 4% of global aluminium demand. The majority of aluminium demand came from other sectors, including transport, construction, packaging and other electric sectors. Copper is used for cell interconnection and wiring. Copper consumption by the solar PV industry accounted for less than 1% of global total demand in 2024, with the majority of demand coming from building construction, electronics and power grids. It is estimated that, by 2030, the share of copper consumption for solar PV (0.4%) in global total demand will be double that in 2020 (IAI, 2026; ICA, 2022; National Minerals Information Center, 2025). Since aluminium and copper are widely used in the electrical and electronics industry, their recycling technologies are advanced, and their secondary markets are mature globally.

Encapsulants and backsheets in solar PV modules are typically made of polymeric materials. In 2024 and 2025, the most widely used encapsulation materials were ethylene vinyl acetate (EVA), polyolefin elastomers and mixed materials. Most of these organic materials have high durability. Similarly, backsheets are typically multilayer polymer laminates designed to provide protection and electrical insulation for solar cells. Currently, the majority of backsheet used for solar PV panels contains fluoropolymer (see Figure 6). Fluoropolymer can pose health and environmental risks and generates toxic gas in high temperatures. Improper disposal or treatment of end-of-life backsheet causes significant environmental pollution and is a threat to public health.

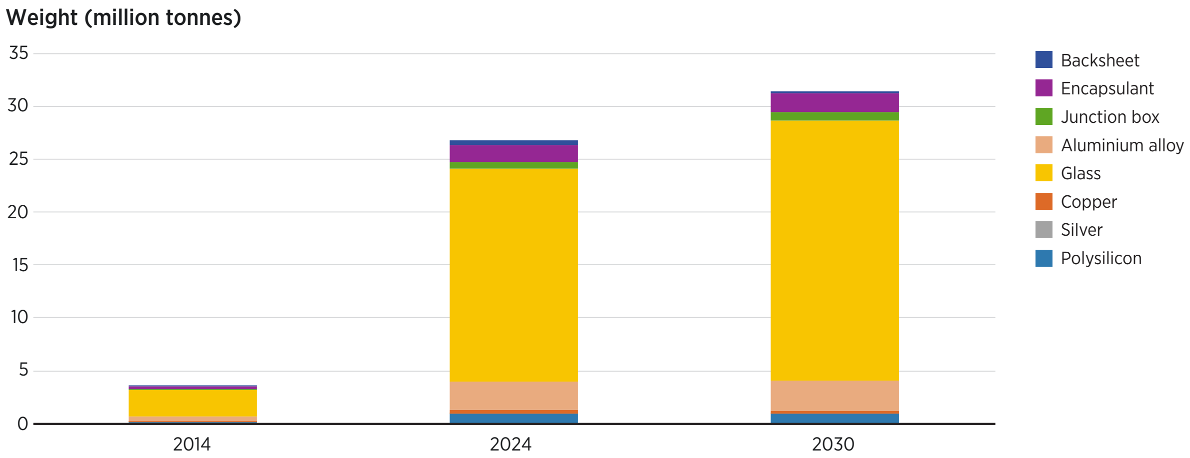
Figure 6 Market share of backsheet by material, 2024



Source: (Chunduri and Schmela, 2025).

Other materials account for a small share of the total weight of solar PV panels. However, they play an important role in manufacturing solar panels. Boron and gallium are used as p-type[4] dopants and phosphorus as an n-type dopant. They are present only at the parts-per-million level in solar cells, but they create the p-n junctions that make silicon conductive. Similarly, small quantities of indium are utilised in certain PV technologies to create transparent and conductive coatings. As mentioned earlier, silver, lead and antimony are also present in small quantities but have specific functions. Looking beyond the module level, the broader PV systems also rely on materials including iron, nickel, zinc and tin. Despite their small quantities, some of the materials, especially lead and antimony, are toxic to humans and wildlife and therefore require proper treatment.

Figure 7 Material consumption for solar module production, 2014, 2024 and 2030



Based on: (Chunduri *et al.*, 2025; IRENA, 2024a, 2025b; VDMA, 2022, 2025).

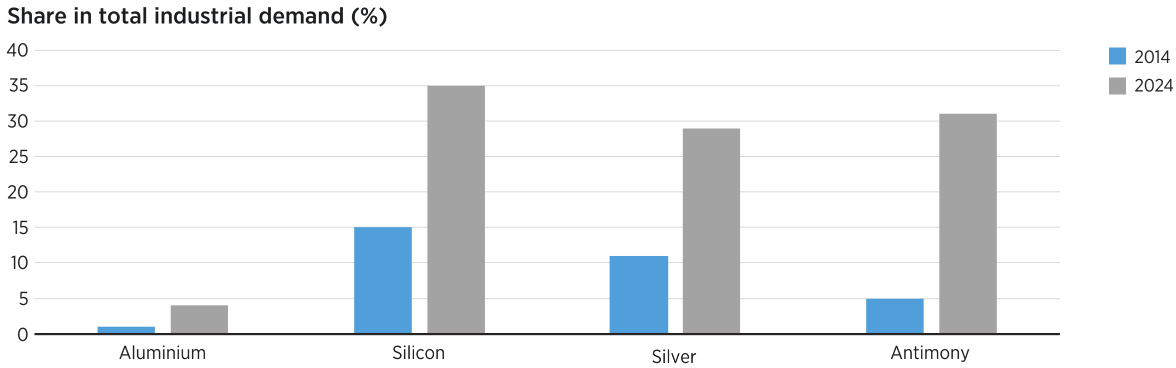
The overall demand for materials for solar PV installations has been growing. In 2024, the overall weight of materials used for solar modules increased by more than sevenfold compared to the 2014 level (see Figure 7). Even though recent solar PV technologies require less material to generate more electricity, the rapid expansion of solar PV deployment in the coming decade will still drive an increase in material demand. IRENA's 1.5°C Scenario estimates that, in a single year, the newly deployed solar PV panels will consume more than 31 Mt of materials by 2030, indicating an 18% increase compared to the material weight needed in 2024. By 2030, solar PV panels will require at least 24 Mt of glass, 2.8 Mt of aluminium, 0.3 Mt of copper, 0.9 Mt of silicon, 6 200 t of silver, and more than 2 Mt of encapsulant and backsheet per year (IRENA, 2024a; VDMA, 2025).

---

4 P-type and n-type are two different types of solar panel that use different doping materials. P-type solar panels are doped with boron or gallium and n-type with phosphorus.

The share of material demand for solar panels in total industrial demand has increased for some materials. For example, antimony demand for the solar industry accounted for 31% of global total industrial demand in 2024, rising from 5% in 2014. During the same period, silver and silicon accounted for 29% and 35% of global total industrial demand, rising from 11% and 15%, respectively, in 2014 (see Figure 8) (Chunduri *et al.*, 2025; IAI, 2026; IRENA, 2024a; National Minerals Information Center, 2026a, 2026b; Silver Institute *et al.*, 2025; VDMA, 2025). Even though these shares are not dominant, when combined with the material demand from all other industries and other energy transition technologies, the overall material demand in the future will need to be properly assessed to address concerns and inform policy makers.

Figure 8 Share of solar PV material demand in global total industrial demand, 2014 and 2024



Based on: (IAI, 2026; National Minerals Information Center, 2026a, 2026b; Silver Institute *et al.*, 2025).

1.3 CRITICAL MATERIALS AND THE SOLAR PV INDUSTRY

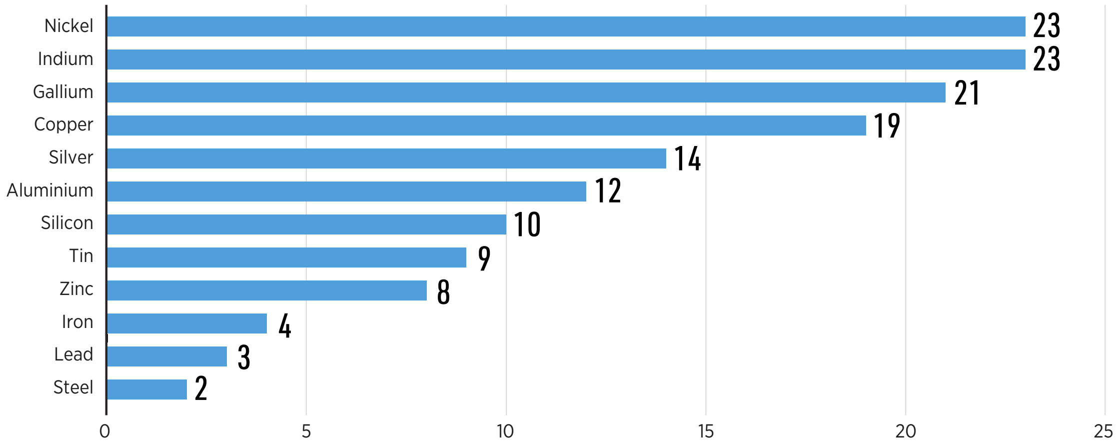
The expected increase in solar PV deployment has raised questions about the sufficiency of raw materials and the resilience of global supply chains. The critical materials used in solar PV have therefore been the subject of significant attention and discussion.

Currently, no widely agreed definition of critical materials exists. This is because the extent to which a material can be sufficient or critical mainly depends on a country's context, which can be further complicated by geopolitical dynamics (IRENA, 2023). Many countries define critical materials as materials used for fossil fuel extraction or military, medical or electronics uses or other purposes. These uses are easily influenced by geopolitical dynamics and changes of policies and markets (IRENA and NUPI, 2024).

Several markets define materials as critical when they are direct inputs to important industrial activities but are not available domestically, and therefore are dependent on importation. For example, European countries, Japan and the United States have focused on concerns about the vulnerability of international supply chains and risks associated with imported materials. Meanwhile, countries with abundant mineral reserves or high production capacities see a strategic interest in playing key producer roles for global mineral supply chains, aiming to capture market value and local industrial development (IISD, 2023).

In the energy transition context, critical materials are the resources needed to produce renewables and other key energy transition technologies, such as wind turbines, solar panels, batteries, electric vehicles and electrolysers for green hydrogen production. They may include lithium, nickel, cobalt, copper and rare earth elements. Since aligning the global energy transition with Paris Agreement climate targets requires significant amounts of critical minerals, it is crucial to ensure their availability and affordability for a successful transition (IRENA, 2023). In terms of solar PV, many minerals can be crucial, including nickel, indium, gallium, copper, silver, aluminium, silicon, tin, zinc, iron and lead (see Figure 9). An increasing number of countries and markets have included some of these materials into national policies related to critical materials. For example, India has identified silicon, indium and gallium as critical for the solar PV industry (Ministry of Mines, 2025).

Figure 9 Solar PV-related materials defined as critical by number of countries or organisations, 2023



Source: (IRENA, 2023).

An assessment of global material demand and supply related to solar PV panels estimated that the materials supply for the solar PV industry is unlikely to face shortages in the near and medium term (IRENA, 2023). However, the progress of the energy transition in markets that rely on importing solar PV technologies may be impacted when supply chains are disrupted and global trade flows of renewable energy technologies are obstructed (IRENA, 2023). Furthermore, the disruption of critical mineral supplies can increase consumer prices. For example, a sustained supply shock for battery metals could increase global average battery pack prices by around 40-50% (IEA, 2025). Given the intensified geopolitics, trade conflicts and price fluctuation trends of key materials, more measures are needed to strengthen resilience and mitigate impacts.

While resource-rich countries are considering expanding their mineral supplies in the global market, more emerging and developing economies have also taken action to build up their local PV capacity (IRENA, 2024b). The expansion of mining activities can benefit from improved environmental and social governance and best practices found in countries with strong PV manufacturing capacity. Therefore, international collaboration remains key to addressing these challenges and improving the resilience of solar PV supply chains.

1.4 ENVIRONMENTAL IMPACTS RELATED TO RISING MATERIAL DEMAND

The solar PV industry's demand for materials may drive the expansion of new mining activities and significantly impact local environments and biodiversity. Currently, environmental impacts linked with solar PV industry's material demand contribute a small share to the overall environmental impacts linked with the mining sector. However, given the capacity needed in the near future and the overall increase of material demand for the energy transition, solar PV's demand for minerals may further intensify the environmental impacts associated with the expansion of mining activities.

ENVIRONMENTAL IMPACTS LINKED WITH MINING ACTIVITIES

Mining activities can have a wide range of adverse effects on local environments and communities. Over the past two decades, metal mining has expanded into ecosystems with high biodiversity and has contributed directly and indirectly to deforestation. Other environmental impacts linked with mining activities include land degradation; water, air and soil pollution; land-use conflicts; and loss of wildlife habitat and biodiversity (Riedl *et al.*, 2026). While the current impacts of solar PV-related mining activities may be limited compared to other industries, the solar PV industry could further intensify the environmental footprints of expanded mining if new material demands come mainly from virgin minerals.

The possible environmental impacts linked with solar PV are most pronounced in the extraction of minerals, where they contribute a large share of demand. For example, solar PV accounted for over 30% of industrial demand for silver and antimony in 2024. Therefore, it may have a stronger link to the environmental impacts of mining activities for these two minerals. Similar to other mining activities, the mining of silver and antimony often involves the removal of forestry and wildlife habitat, causing soil erosion, soil and water pollution, habitat loss, and the endangerment of wildlife. Further, mining activities can lead to land-use conflicts between mining companies and local communities. Without proper mitigation and recovery measures, these activities can cause permanent damage to local nature.

Figure 10 Environmental impacts of mining activities

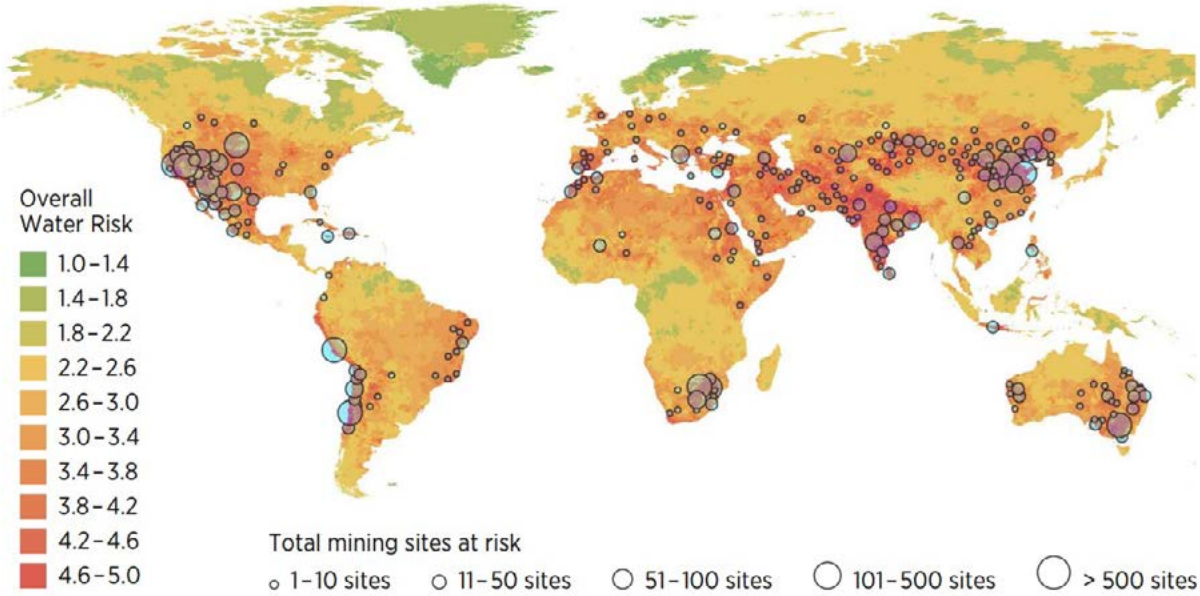
Waste generation	Pollution and ecological impact	Pressure on water resources
• Waste rock (the material extracted along with the ore) • Tailings (waste generated from processing) • Wastewater from extraction and processing	• Release of heavy metals and toxic chemicals • Potential water, soil and air pollution • Wildlife habitat loss and fragmentation • Land degradation and soil erosion	• Freshwater contamination • Groundwater depletion • Increased water stress in water-scarce regions • Competition with other water uses, including agriculture

Mining waste can significantly impact the local environment because it often contains large quantities of toxic substances, including heavy metals, acidic materials and alkaline drainage (see Figure 10) (European Commission, 2026a). Heavy metal pollution can further affect nearby agricultural land, food productivity and public health. For example, silver and copper mining usually involves heavy metals (*e.g.* arsenic, lead and cadmium), sulphur dioxide and acid mine drainage. Wastewater generated by the antimony mining process can be highly hazardous. Similarly, mining for aluminium and its processing can generate toxic dust and wastewater, as well as hazardous solid waste, such as aluminium dross. If not properly treated, dust pollution and water containing these toxic substances can threaten wildlife habitat and public health.

Water stress can be further exacerbated if mining activities overlap with areas designated as high water-stress areas. The metals and mining sector, including silver and antimony mining, is heavily reliant on water for various essential procedures, including mineral processing, dust control, slurry transportation and storage, extraction processes, and general site use. Ore mining and processing can consume substantial amounts of water and therefore can compete with water demand in other sectors, including agriculture. Meanwhile, the disposal of mining waste and tailings can pollute local freshwater systems and therefore further intensify water stress, leading to potential conflicts with agricultural communities.

It is estimated that over 16% of the world's land-based critical minerals are located in areas that have already faced high levels of water stress (Lakshman, 2024). Regions including the Andes, Australia, Central Asia, the Middle East, the western part of North America, South Asia and southern Africa have been identified as both mining hotspots and regions with high water stress (IRENA, 2023). Further increasing mining activities in these regions will pose significant risks to the local freshwater system and the agriculture sector (see Figure 11). For example, Chile is the world's largest copper production country, but some 80% of its copper production is located in extremely water-scarce areas. Similarly, about 40% of the Russia Federation's iron ore production is located in areas of high water stress (UNEP, 2024a).

Figure 11 Regions and areas with high water stress and intense mining activities



Source: (Laporte-Bisquit and Morgan, 2019).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Note: According to WWF's classification of water risk values, 1 is very low risk, 2 is low risk, 3 is moderate risk, 4 is high risk and 5 is very high risk.

While global material demand for solar PV will grow rapidly in the coming years, scaling up supply must be done in a way that considers impacts on the local environment and communities and minimises unwanted risks. Mitigating the unwanted impacts of mining activities requires the continuous engagement of local communities and leveraging third-party sustainability frameworks (Riedl *et al.*, 2026). Another key approach involves promoting the use of the circular economy to reduce the demand for virgin minerals, thereby partially avoiding the environmental impacts of new mining activities. The circular economy can strengthen the resilience of the critical material supply chain in the most affordable and sustainable way, along with its other social and economic benefits (see Chapter 4).

CHAPTER 2

PROJECTION OF END-OF-LIFE SOLAR PV IN THE ENERGY TRANSITION

Accelerated solar PV deployment requires more raw materials and will result in large amounts of solar PV panels that will be decommissioned in the future. This chapter provides an overview of potential waste streams associated with current and future solar PV panels in the energy transition. It examines global-level and selected markets that have deployed a large amount of solar PV capacity.

2.1 PROJECTION OF GLOBAL END-OF-LIFE SOLAR PV PANELS[5]

In 2016, IRENA and IEA-PVPS jointly developed the first projection of solar PV waste in the report *End of life management: Solar photovoltaic panels*. This analysis assessed the global cumulative weight of end-of-life solar PV panels for the first time (IRENA *et al.*, 2016). In 2026, IRENA updated the projection based on the 1.5°C Scenario. The projection assumes a 25- to 30-year lifespan for solar PV panels, with some projects failing or being decommissioned before reaching the end of their lifespan. It also considers the possibility that old solar panels may be replaced by new, more efficient solar PV technologies before they have reached the end of their lifespan.

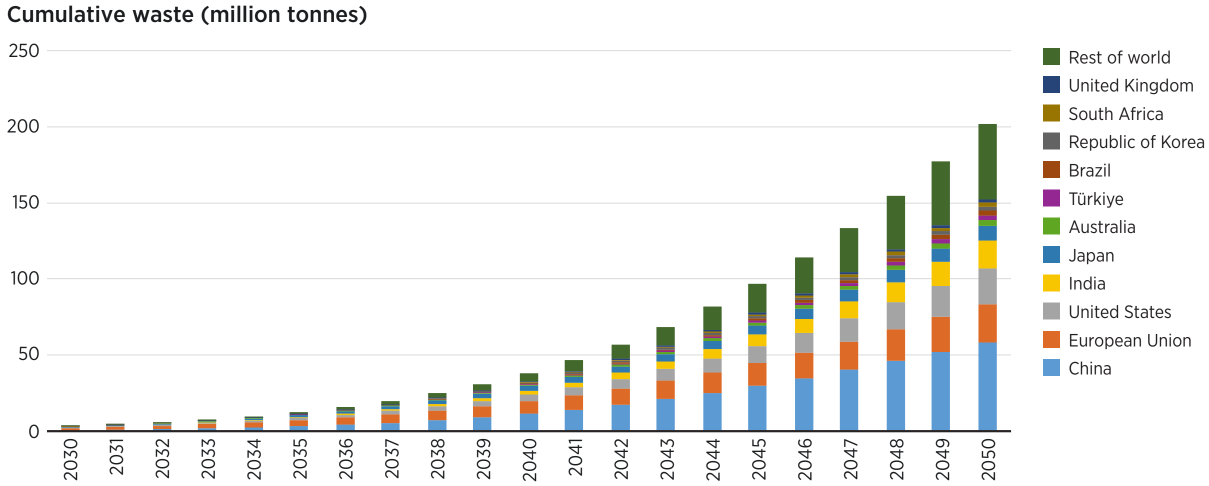
Based on the solar PV capacity needed in the IRENA 1.5°C Scenario, the global cumulative amount of end-of-life solar PV panels is projected to exceed 12 Mt by 2035, with G20 member countries and regions accounting for over 90% of this future waste stream. Because the European Union deployed large amounts of solar PV capacity during the 2000s, this region can anticipate having the highest volume of retired solar PV panels in the next decade. Other major markets with substantial amounts of end-of-life solar PV panels by 2035 include China, Japan and the United States, with each surpassing 1 Mt of cumulative end-of-life PV panels by 2035. Australia, India, the Republic of Korea and the United Kingdom will also have to manage a large number of end-of-life solar PV panels at the same time.

The 1.5°C Scenario projects that the cumulative weight of end-of-life solar PV panels will surpass 200 Mt globally by 2050. This is linked to the rapid expansion of solar PV capacity in the last decade (see Chapter 1). Based on IRENA's estimate, the cumulative weight of end-of-life solar PV panels will increase 16 times from 2035 to 2050 in the 1.5°C Scenario. China is projected to contribute the largest share (29%) to the global cumulative end-of-life solar PV panels. This aligns with the fact that this country has been driving global solar PV deployment over the last decade. Apart from China, the European Union (12%), the United States (11%) and India (9%) are expected to contribute major shares to the global cumulative amount of end-of-life solar PV panels by 2050 (see Figure 12). Collectively, these markets will account for over 60% of the total global cumulative end-of-life solar PV panels by mid-century. Other countries, such as Australia and Japan, will also face a significant number of end-of-life solar PV panels.

[5] The projection of end-of-life solar PV panels is based on Weibull functions. Weibull functions are frequently applied in the modelling of life data and failure analysis of solar PV module materials. The modelling of this study is based on shape factor(a) = 5.38, and average lifetime (T) = 25 years. Input data is based on IRENA's 1.5°C Scenario.

Notably, more than 80% of solar PV panels that reach end-of-life status by 2050 will have been generated between 2040 and 2050. The solar PV waste stream generated in the five years from 2045 to 2050 will be larger than that generated before 2045. The uneven pace of the solar panel waste stream in the future poses challenges for industrial players and policy makers. In China and the European Union, tens of thousands of tonnes of end-of-life solar PV panels are reported. Outside of these two markets, end-of-life solar PV panels have just emerged. However, the waste stream in some markets, such as in many G20 member countries, will likely increase by almost tenfold by 2040 compared to the 2030 level, posing significant challenges for these markets' regulatory frameworks and industrial capacity. To prepare for foreseen solar panel waste streams, countries and regions must establish proper policy frameworks to guide industries and investors (see Chapter 4). They also need to invest in necessary infrastructure for the collection, transportation and storage of end-of-life solar PV panels.

Figure 12 Cumulative end-of-life solar PV panels in selected markets and the rest of world, 1.5°C Scenario, 2030-2050



The annual volume of end-of-life solar PV panels globally is projected to exceed 3 Mt by 2035. It will further increase to over 7.8 Mt by 2040, and surge to over 25 Mt by 2050 (see Figure 13). Countries with substantial amounts of installed solar PV capacity in the last few decades will likely need to be ready to embrace waste streams in the 2040s. For example, China, the European Union, India and the United States will need to handle over 1 Mt of decommissioned solar PV panels in a single year starting in 2043. The weight of the annual solar PV waste stream in each of these markets will surpass 2 Mt by 2048. Other markets, even though not yet at the million-tonne level, will also have to manage a large number of end-of-life solar panels during the same period (see Figure 14). For example, Japan will contend with over 500 000 tonnes of end-of-life solar PV panels by 2041; this will further increase to more than 740 000 t annually by 2050.

Solar PV panel waste streams require transport infrastructure and dedicated treatment capacity. For example, by 2035, annual solar panel waste will require around 120 000 trips by heavy-duty trucks to transport it from solar plants to treatment facilities. In addition, at least 150 fully operational, medium-sized solar PV recycling facilities will be necessary. These facilities will need to have the capacity to treat and recycle 20 000 t of end-of-life solar panels per year. They will also need to promote innovation on technologies and business models to improve efficiency and reduce related costs.

Beyond the markets mentioned above, some developing markets are also poised to face a surge in end-of-life solar PV panels. By 2040, the annual waste stream from solar PV panels in Brazil, South Africa and Türkiye will range from 92 000 t to 106 000 t. The waste stream will further increase to between 370 000 t/year to 440 000 t/year in these countries by 2050.

Figure 13 Global annual end-of-life solar PV panels, 1.5°C Scenario, 2030-2050

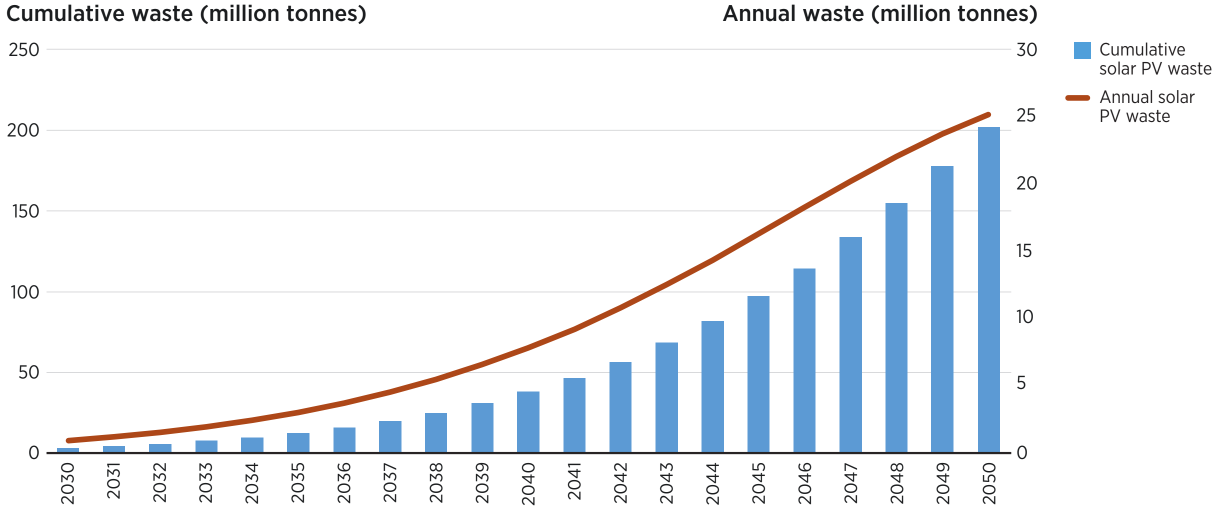
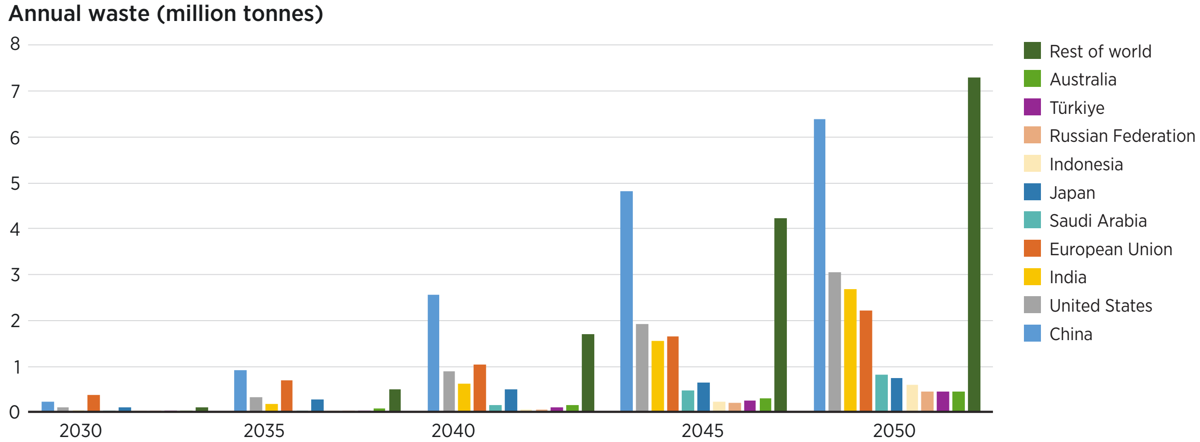
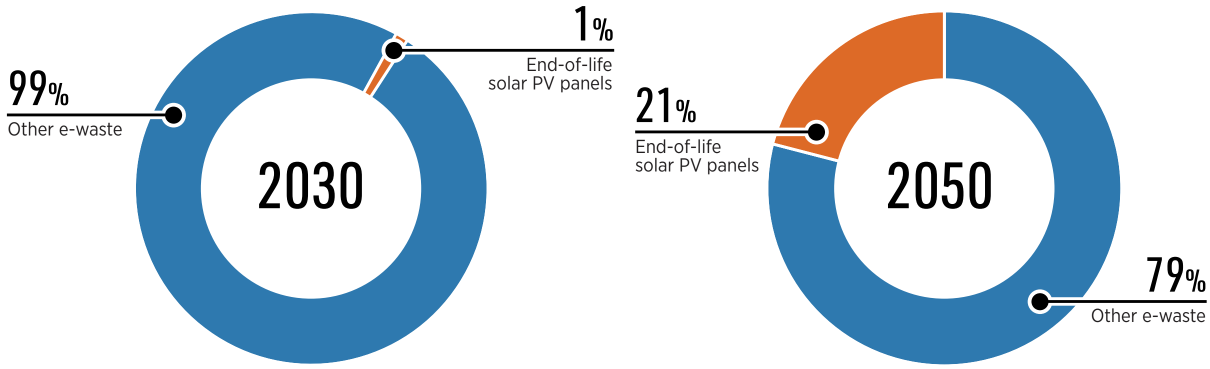


Figure 14 Annual end-of-life solar PV panels in selected markets, 1.5°C Scenario, 2030-2050



With the surging amount of solar PV waste, its share in total global e-waste will also increase. Currently, the estimated weight of end-of-life solar PV contributes a negligible share (<1%) of the global total weight of e-waste.[6] It will remain around 1% through 2030. However, the weight of end-of-life solar PV is projected to contribute over 21% to the global total weight of e-waste by 2050 (120 Mt annually by 2050) (see Figure 15) (ITU and UNITAR, 2024; UNEP, 2023). By 2050, waste streams from solar PV panels will be much larger than current e-waste from large equipment worldwide. This necessitates adaptive measures by policy makers and the e-waste collection and transportation industry to accommodate changes in the e-waste stream in the future (see chapters 4 and 5).

Figure 15 Share of end-of-life PV compared to total e-waste globally, 2030 and 2050



Based on: (ITU *et al.*, 2024).

Although the increase in solar PV waste is unavoidable, technological improvements have made positive contributions, including solar panels' increased efficiency and reduced material consumption (as shown in Chapter 1, Section 2). The increase in module efficiency means that the weight per MW of solar PV capacity in the future will be lower than that of the technology used in the past. For example, the efficiency of commercial mono-Si modules increased from about 16% to over 24% during 2014-2024, and silicon usage for cells declined significantly during the last two decades from around 16 g/watt peak (Wp) (in 2004) to about 2.0 g/Wp in 2024 (Fraunhofer ISE, 2025). Moreover, efforts are also being made to replace the valuable or hazardous materials in solar panels. For example, lead-free soldering for cell interconnections gained 5% of the market in 2024 and is expected to achieve 31% in 2035 (VDMA, 2025). If these advancements continue and accelerate, it will not only help reduce the weight of end-of-life PV panels required to generate the same amount of electricity, but also mitigate their negative environmental impacts and facilitate the circular management of PV waste.

2.2 PROJECTION OF END-OF-LIFE SOLAR PV PANELS IN SELECTED MARKETS

In the 1.5°C Scenario, several markets are expected to play a more active role than others in promoting solar PV deployment. These markets are likely to encounter a much larger volume of end-of-life solar PV panels in the future. This section will look at selected markets that may face a large number of end-of-life solar PV panels by 2050, including the G20, China, the European Union, India, Japan and the United States.

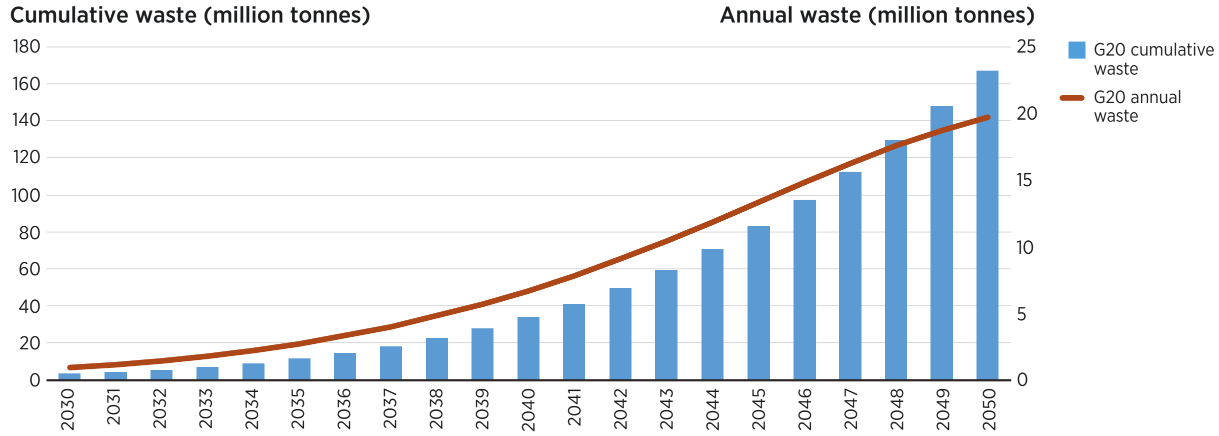
[6] E-waste includes temperature exchange equipment (*e.g.* air conditioning, refrigerators and heat pumps), screen and monitors (*e.g.* televisions, laptops), lamps, solar PV panels, other large equipment excluding solar PV panels (*e.g.* washing machines, dishwashers, large printers), small equipment (*e.g.* microwave ovens, radios, toys and others), and small information technology and telecommunications equipment (*e.g.* cell phones, global positioning systems, devices, routers) (ITU and UNITAR, 2024).

G20

G20 members accounted for over 80% of global installed solar PV capacity and more than 90% of new additions in 2025 (IRENA, 2026a). In all, G20 members accounted for more than 80% of global energy consumption and hosted more financial resources and industrial capacity than other countries and states. They are expected to take a leading role in driving the needed renewable energy capacity by 2030 and 2050 (IRENA, 2025e). According to IRENA's World energy transitions outlook, total installed solar PV capacity in G20 member markets would need to increase by about threefold to reach 4 500 GW by 2030, compared to the 2024 level, and almost ninefold by 2050(IRENA, 2024a). Achieving these targets requires an average annual capacity addition of around 450 GW from 2025 to 2050.

The cumulative volume of end-of-life solar PV panels across G20 members is estimated to reach 3 Mt by 2030, accounting for 95% of the global total. This figure will further increase tenfold within a decade and exceed 33 Mt by 2040. It will surpass 166 Mt by 2050 (see Figure 16). Meanwhile, the annual solar PV waste stream of G20 member markets will increase from about 1 Mt in 2030 to 6.6 Mt by 2040 and surpass 19 Mt by 2050.

Figure 16 Cumulative and annual end-of-life solar PV panels in G20 member markets, 1.5°C Scenario, 2030-2050

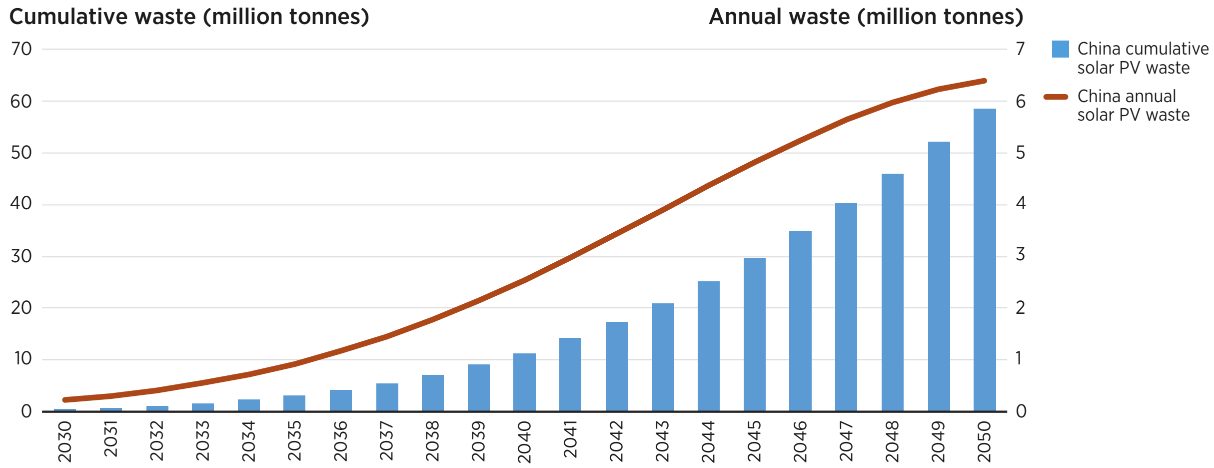


CHINA

China has deployed the largest solar PV capacity in the world. This country accounted for half of the global total installed solar PV capacity by the end of 2025 and around 62% of newly added solar PV capacity in the same year. From 2020 to 2025, China installed an average of 189 GW of solar PV capacity annually (IRENA, 2026a). By the end of 2025, China had added an additional 317 GW of solar PV capacity. Solar PV accounted for over 70% of newly added renewable capacity and 29% of total renewable electricity generation in 2025 (NEA, 2026).

In the 1.5°C Scenario, China will need to handle over 3 Mt (cumulative) of end-of-life solar PV panels by 2035. This will rise to 11 Mt by 2040 and exceed 58 Mt by 2050 (see Figure 17). The annual amount of end-of-life solar PV panels is anticipated to reach half a million tonnes by 2033 and cross the 1 Mt/year mark by 2036. This means at least 50 medium-size solar PV panel recycling and treatment facilities will be needed to treat these waste streams. It is estimated that China has around 20 dedicated solar PV recycling facilities with a total of 300 000 t of annual treatment capacity. The end-of-life solar PV panels in this country will further increase to over 2.5 Mt/year by 2040 and 6.4 Mt/year by 2050.

Figure 17 Cumulative and annual end-of-life solar PV panels in China, 1.5°C Scenario, 2030-2050

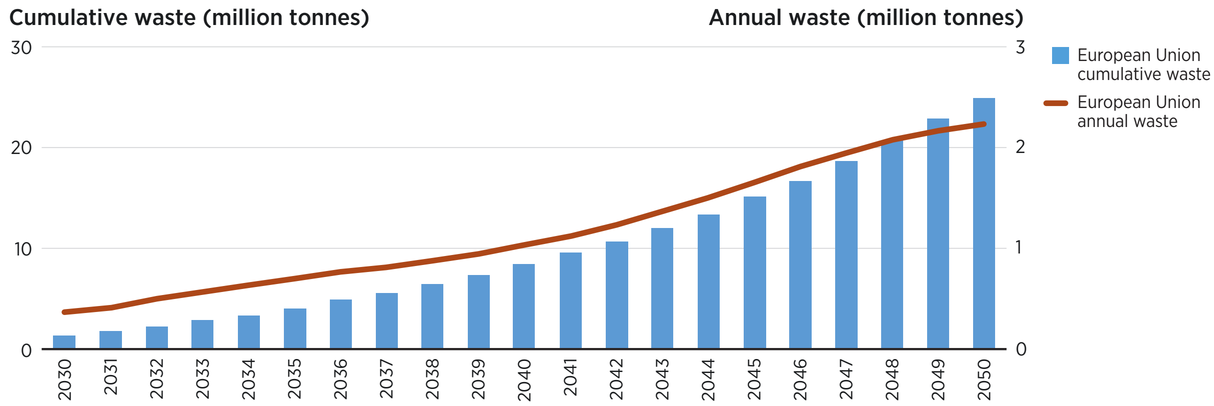


European Union

By the end of 2025, the European Union had installed over 364 GW of solar PV capacity, accounting for 47% of total installed renewable capacity in the bloc. In 2023, the European Union generated 247 319 GW hours of electricity from solar PV, accounting for 20% of all renewable electricity generation. From 2020 to 2025, an average of 46 GW of solar PV capacity was added annually in the European Union (IRENA, 2026a). The drive behind this achievement stems from renewable energy targets and an overarching policy framework supported by renewable energy directives and various policies and incentives.

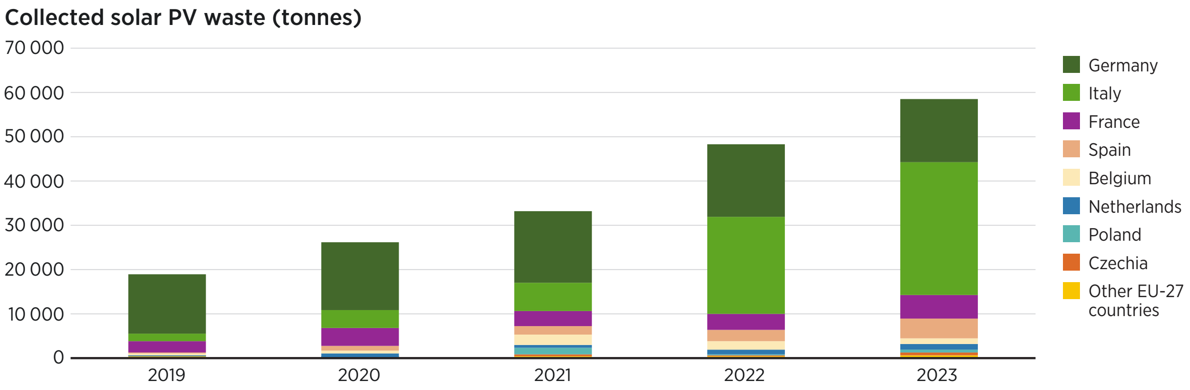
In the 1.5°C Scenario, cumulative end-of-life solar PV panels in this region will reach 1.5 Mt by 2030. This number will surge to over 4 Mt by 2035 and exceed 8 Mt by 2040. By 2050, the European Union is projected to face over 25 Mt of cumulative end-of-life solar PV panels. Annual end-of-life solar PV panels are expected to reach over 700 000 t by 2035, surpassing 1 Mt by 2040, and rising to over 2.2 Mt by 2050 (see Figure 18). In the next decade, it is estimated that around 40 medium-sized solar PV recycling and treatment facilities will be needed for the expected annual end-of-life solar PV panels in the European Union.

Figure 18 Cumulative and annual end-of-life solar PV panels in the European Union, 1.5°C Scenario, 2030-2050



The European Union stands out as one of the few jurisdictions with available data on the collection and treatment of end-of-life solar PV panels. The systematic collection of these materials in the region started in early 2010s, following the release of the Waste Electrical and Electronic Equipment (WEEE) guidelines in 2012. Based on the latest data, in 2023, European Union member countries collected 58 474 t of end-of-life solar PV panels, reflecting a tripling compared to the reported amount in 2019 (18 986 t). Countries with a significant amount of collected and disclosed end-of-life solar PV panels include Belgium, Czechia, France, Germany, Italy, the Netherlands, Poland and Spain (see Figure 19). Germany and Italy, in particular, accounted for 41% and 35% of the total number of end-of-life solar PV panels collected from 2019 to 2023, respectively. According to the reporting platform, over 86% of the total collected end-of-life solar PV panels during the same period were either recycled or prepared for reuse (Eurostat, 2025).

Figure 19 Reported collection of end-of-life solar PV panels in the European Union, 2019-2023



Source: (Eurostat, 2025).

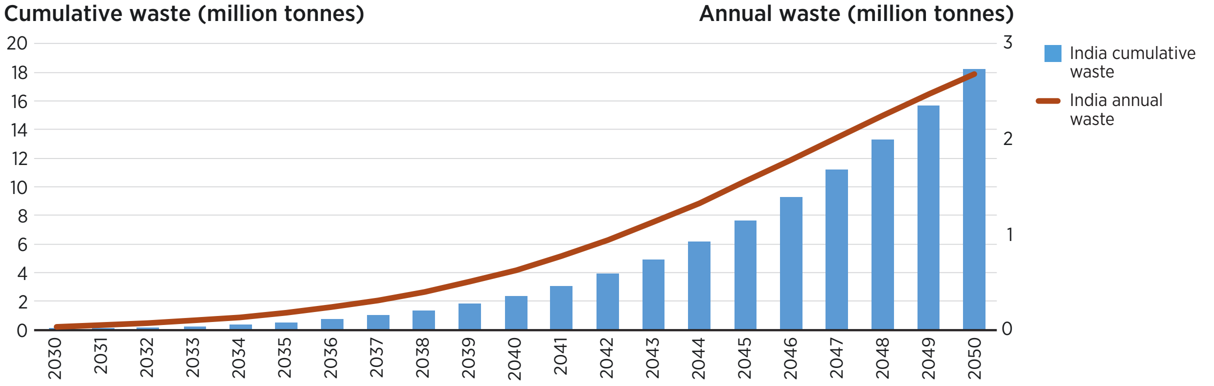
India

India has achieved significant growth in its total installed solar PV capacity, reaching 135 GW by the end of 2025. This marks a notable 3.4 times increase over five years compared to 2020 levels. Solar PV is now India's primary renewable power source, contributing more than half of the country's total renewable energy capacity by 2025 and 29% of total renewable electricity generation in 2023. In 2025, the annual installed solar PV capacity reached 37 GW, with an average of 19 GW installed annually from 2020 to 2025 (IRENA, 2025b, 2026a).

In the 1.5°C Scenario, India will encounter more than half a million tonnes of cumulative end-of-life solar PV panels by 2035. This figure is expected to rise to over 1 Mt by 2037 and to surpass 2.3 Mt by 2040. By 2050, India will likely face the fourth-largest number of end-of-life solar PV panels globally, following China, the European Union and the United States. However, around 85% of the total cumulative end-of-life solar PV panels by 2050 will be generated between 2041 and 2050.

The amount of annual end-of-life solar PV panels in India will reach half a million tonnes by 2039. It will then surpass 1 Mt by 2043 and reach over 2.6 Mt by 2050. From 2035 to 2050, India is expected to handle an average of 1.2 Mt of end-of-life solar PV panels every year, requiring around 60 medium-sized solar PV panel waste treatment facilities to be ready and operational during this period (see Figure 20). The waste stream in India will likely show a stronger surge in the 2040s compared to other markets. For example, the amount of India's annual end-of-life solar PV panels is estimated to be only one-third of Japan's level in 2030. A decade later, by 2040, solar panel waste in India will be 1.3 times higher than Japan's in 2040. By 2050, it will exceed Japan's waste stream by 3.6 times.

Figure 20 Cumulative and annual end-of-life solar PV panels in India, 1.5°C Scenario, 2030-2050

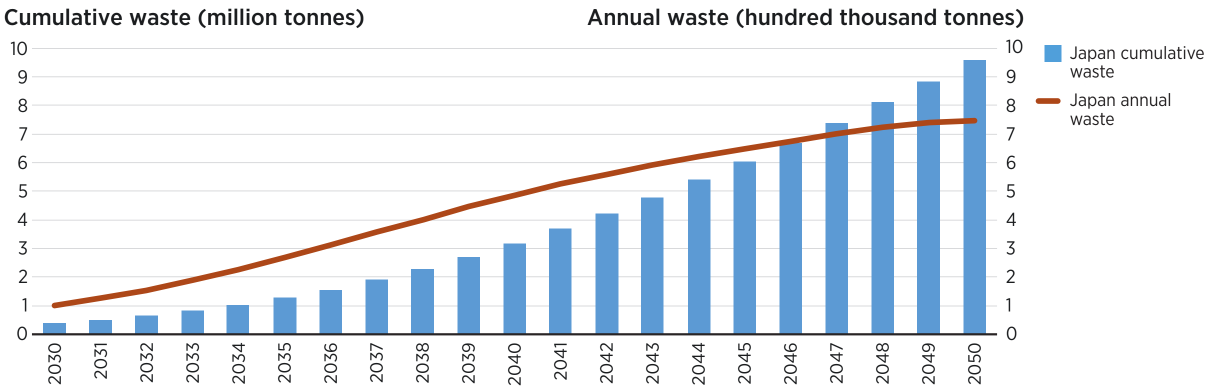


Japan

By the end of 2025, Japan had installed over 92 GW of solar PV capacity, accounting for more than 69% of the country's total installed renewable capacity. Solar PV provided 43% of Japan's renewable electricity generation in 2023. Currently, Japan has installed the third-largest solar PV capacity in Asia, following China and India, contributing 6% to Asia's overall installed solar PV capacity, which stood at 1528 GW by the end of 2025. The annual added solar PV capacity for 2025 in Japan was 2.6 GW. Japan maintained an average of approximately 4 GW of solar PV additions from 2020 to 2025 (IRENA, 2025b, 2026a).

In the 1.5°C Scenario, Japan is expected to encounter 1 Mt of cumulative end-of-life solar PV panels in 2034. The number will reach 3 Mt by 2040, and further expand to 9.5 Mt by 2050. In the single year of 2034, the amount of end-of-life solar PV panels in Japan is projected to exceed 200 000 t. The annual waste stream will reach over 500 000 t by 2041 and surpass 748 000 t by 2050 (see Figure 21).

Figure 21 Cumulative and annual end-of-life solar PV panels in Japan, 1.5°C Scenario, 2030-2050

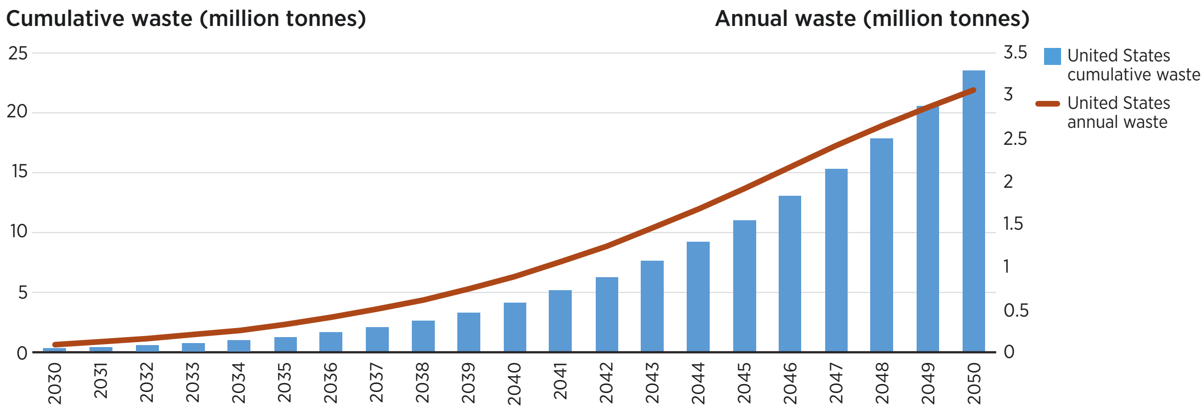


United States

By the end of 2025, the United States had installed 210 GW of solar PV capacity, accounting for 45% of the overall installed renewable energy capacity. Solar PV provided 22% of total renewable electricity generation in this country in 2023. Between 2020 and 2025, an average of 27 GW of solar PV capacity per year was installed in the United States. Even though political changes indicate a slowing of renewable installations in this country, the solar industry still deployed 34 GW of solar PV capacity in 2025 (IRENA, 2025b, 2026a).

In the 1.5°C Scenario, the cumulative amount of end-of-life solar PV panels in the United States will surpass 1 Mt by 2034. It will further exceed 5 Mt by 2041, and reach 23 Mt by 2050. On an annual basis, the country's end-of-life solar PV panels are projected to reach half a million tonnes by 2038. This amount will then double to 1 Mt within three years by 2041, and surpass 3 Mt by 2050 (see Figure 22).

Figure 22 Cumulative and annual end-of-life solar PV panels in the United States, 1.5°C Scenario, 2030-2050



In addition to the countries mentioned above, other markets will also face an increasing amount of waste streams from decommissioned solar PV projects. Policy makers and industrial players are urged to plan accordingly to improve policy frameworks to address future waste streams and invest in needed treatment facilities and infrastructure. To understand the scale of future waste streams and bridge the gap, countries must understand the current practices in different contexts as well as existing barriers and issues (see Chapter 3).

Meanwhile, taking into consideration the substantial scale of both existing and anticipated global solar PV installations, policy makers and industrial players should bear in mind that solar PV panel waste streams can also serve as important sources of raw materials to meet future material demand. This can be enabled by implementing a holistic framework supported by effective systems for collection, reduction, reuse and recycling. Such a framework is particularly important for countries with significant installations, which will likely face a surge in waste streams in the next decade (see chapters 4 and 5).

CHAPTER 3

CURRENT STATUS OF END-OF-LIFE SOLAR PV TREATMENT

While the amount of end-of-life solar PV panels will rise significantly in the near future, the current scale of decommissioned solar plants and the treatment of those panels remain unclear. Few regions and countries report end-of-life solar panel data in their markets, and most countries have not established systematic reporting and monitoring systems for end-of-life solar PV. Meanwhile, how these end-of-life solar PV panels are transported and treated varies significantly across markets, depending on local regulations and policies, as well as infrastructure readiness and industrial capacity. This chapter provides an overview of the current status of end-of-life solar panels in selected markets, how they are being collected and treated, and the potential environmental and public health impacts based on current practices.

3.1 CURRENT STATUS OF END-OF-LIFE SOLAR PANELS GLOBALLY AND IN SELECTED MARKETS

Scale of the waste stream

Currently, the amount of solar panels at the end of their service time is rarely reported at a global level. IRENA estimated that cumulative solar PV waste was around 700 000 t to 1 Mt by the end of 2025, with the majority of waste streams originating in Australia, China, the European Union, Japan and the United States (CRRA, 2026; Eurostat, 2025; Taylor *et al.*, 2025). Globally, the annual waste stream from solar PV panels generated in 2025 was around 400 000 t, accounting for nearly half of the cumulative weight.

Most deployed solar PV projects have not reached the end of their service time. It is estimated that solar PV panels deployed in the 2000s will be decommissioned soon, but the number of those panels is modest compared to current capacity. The majority (around 90%) of total installed solar PV panels globally were deployed within just ten years, from 2016 to 2025, and have not yet reached the end of their service time (25 to 30 years). However, solar PV waste will still be generated during the transporting and operation phases. For example, some solar panel components can be damaged during transportation and installation, and therefore would be considered to be waste streams. More frequent extreme weather can also cause solar panels to fail. In some cases, solar PV projects can be decommissioned (even though they have not reached the end of their service life) and replaced by more advanced solar PV technologies, a switch that is mainly driven by the desire for higher economic returns for investors. When solar radiation and land-use costs are both high, replacing old technologies with more efficient solar PV panels can maximise investors' economic return.

Overall, estimating the current waste stream from solar PV panels can be difficult due to limited high-quality data. The European Union is the only region with continuous reporting of solar PV waste collected from member states. Outside the European Union, the reporting methodology and data quality may not be aligned, even though multiple industrial organisations have reported estimates of solar PV waste streams in different markets. An enhanced data reporting platform and standardised methodology are urgently needed to inform the policy-making process (see Chapter 5, Section 3). Some international stakeholders have started to promote such efforts. For example, Global Energy Monitor, a US-based non-governmental organisation (NGO), has included trackers on solar PV projects in different regions. Even though this platform is not specifically designed for tracking PV waste, it recorded 536 MW of decommissioned and 755 MW of mothballed (disused but not dismantled) utility-scale solar PV plants as of February 2026. Most of these plants are in North America, Eastern Asia and Western Europe (Global Energy Monitor, 2026).

Current practices on collection and treatment in selected markets

Globally, current practices for the collection and treatment of end-of-life solar panels vary significantly, depending on regional or national regulatory frameworks (see Figure 23). In major solar markets, end-of-life management for solar PV can be separated into several patterns. In markets such as the European Union, India and the Republic of Korea, waste PV modules are categorised as e-waste and regulated by existing e-waste policies. Countries including China and Japan utilise their existing industrial waste management frameworks to regulate utility-scale end-of-life solar PV. In Australia and the United States, subnational-level governments have announced more dedicated policies and measures, although national policies and guidelines exist. However, in some developing markets, national efforts or capacity are limited and the collection and treatment of solar PV waste mainly rely on the informal sector. Notably, industries can play an active role in solar PV waste management, especially before governments announce formal regulations. In reality, a mix of different practices can be seen in the same market.

Figure 23 Different end-of-life management routes for solar PV panels

Some markets have initiated systems to encourage the collection and proper disposal of end-of-life solar panels, with efforts observed in Australia, China, Côte d'Ivoire, the European Union, Ghana, India, Japan, Kenya, the Republic of Korea, Rwanda and South Africa, as well as subnational jurisdictions in the United States (see Chapter 5). In the rest of the world, end-of-life solar panels make up a small amount of waste and likely follow common local e-waste treatment practices.

The European Union has been systematically disclosing data on the collection and treatment of end-of-life solar panels in its member states. This practice is based on the inclusion of solar PV into the regional WEEE regulation announced in 2012 (European Union, 2012). In the European Union, approximately 58 500 t of end-of-life solar panels were reported as collected in 2023. Over 84% of the collected solar PV panel waste (49 200 t) was either recycled or prepared for reuse within the region. A small share of the waste stream is treated in other ways or transported outside the European Union (Eurostat, 2025). The progress in collecting and treating solar panel waste in this region is also linked to the development of dedicated solar panel recycling facilities, with a capacity of approximately 170 000 t/year by 2024 (Espinosa *et al.*, 2026; Taylor *et al.*, 2025).

China is in the process of establishing its national framework for end-of-life solar PV. In China, many utility-scale solar PV projects are deployed and operated by state-owned companies. These developers are required to treat end-of-life solar PV panels in a timely way, mainly by contracting with certified waste treatment companies in accordance with national regulations. Due to the country's strong solar PV industry capacity, recycling facilities and pilot projects have been launched in recent years. It is estimated that dozens of facilities dedicated to the recycling of solar PV waste have been established, most of which are located in the Yangtze Delta area, where solar PV manufacturing capacity is concentrated and the local government has announced policy incentives (Jiang, 2023). In 2024, China established the state-owned China Resources Recycling Group, aiming to promote the research and application of recycling technologies for renewables. However, most large-scale solar PV plants are deployed in northwestern China, far from many recycling facilities, posing challenges with regard to transport costs and the economic viability of recycling.

In Japan, the collection and treatment of end-of-life solar panels are regulated by general waste management practices. Therefore, solar panel waste is not collected or reported separately. This country has strict regulations on e-waste treatment and widely established facilities for its treatment (JPEA, 2022). It is estimated that Japan generates tens of thousands of tonnes of solar panel waste each year (Jiji Press, 2025). A survey reported that more than 60% of solar power operators in Japan do not consider recycling decommissioned PV panels. Most waste panels end up in landfills due to the significant cost difference between landfill disposal and recycling (METI and MOE, 2026).

In India, solar PV waste is categorised as e-waste and regulated under the E-Waste (Management) Rules announced in 2022. While this rule mandates recycling obligations for electric and electronic equipment producers, solar PV modules are exempt from mandatory recycling targets. Instead, the regulation requires solar PV producers to safely store the generated PV waste until 2034, in accordance with the guidelines set by the Central Pollution Control Board (CPCB) (MoEFCC, 2022; CPCB, 2026). At the same time, PV recycling facilities are beginning to be planned and built in India. For example, Indian solar PV manufacturer Jakson Engineers Limited contracted with a European technology provider in December 2025 to establish a PV module recycling plant with the capacity to recycle 300 MW (or 13 500 t) of solar panels per year (Jakson, 2025).

In Australia, some subnational governments, including Victoria, South Australia, the Australian Capital Territory and Queensland, have announced dedicated regulations to prevent solar PV waste from being sent to landfill (see Chapter 5). At the national level, Australia has been developing a regulatory product stewardship scheme dedicated to solar PV systems and small equipment since 2022. However, the scheme has not yet been established. In January 2026, the Australian government announced AUD 24.7 million (Australian dollars; USD 16.5 million) to support a national solar panel recycling pilot project. The pilot is expected to start in mid-2026 and aims to collect up to 250 000 panels from 100 sites (DCCEEW, 2026).

In Canada, solar PV panels deployed in the 2000s may reach the end of their service life soon. Solar PV waste streams in Canada are not differentiated from other e-waste and are collected and treated as general e-waste streams. This means that most end-of-life solar panels are disposed of in landfills, with some reportedly exported for treatment at specialised PV recycling facilities in the United States (Lila, 2024).

In Brazil, solar panel recycling is in an early stage, with only 10% of panels currently being recycled (Amorim, 2025). Most recycling steps, including dismantling, recovery of aluminium and glass, and disposal of plastic and metal fractions, are handled through regular e-waste recyclers. Even though large-scale facilities dedicated to the treatment of end-of-life solar PV have not yet been established, some specialised companies have emerged with a focus on solar panel recycling, particularly in reverse logistics, collection and mechanical dismantling. The National Solid Waste Policy, Brazil's overall regulatory framework for waste management, requires the reverse logistics of electrical and electronic equipment, including solar PV (Neves, 2021).

In Sub-Saharan Africa, some countries have national schemes relevant to e-waste. These include Cameroon, Côte d'Ivoire, Ghana, Kenya, Madagascar, Mauritius, Nigeria, Rwanda, South Africa, the United Republic of Tanzania, Uganda and Zambia (GESP, n.d.). Kenya and South Africa have been moving forward with dedicated requirements (*e.g.* financial responsibilities for collection and treatment) for solar PV panel waste within existing regulations. In Africa, off-grid solar appliances play an important role in increasing electricity access, but the large stream of off-grid waste will also pose challenges in the near future (see Chapter 3, Section 2).

In the majority of countries, most end-of-life solar PV panels end up in landfills along with other e-waste. The European Union, China and major developed economies are the exceptions to this rule. In countries where unregulated e-waste recycling exists, a significant portion of end-of-life solar panels and other e-waste is likely to be directed to small-scale, unregulated facilities and recycled through methods that are polluting and threaten public health (see Chapter 3, Section 3). In least-developed countries, such as Sub-Saharan African countries, dysfunctional off-grid solar home appliances are usually repaired and reused in different ways, but these countries also face a shortage of technicians. Meanwhile, in countries where solar PV waste streams are regulated by existing policies, infrastructure such as collection channels and recycling facilities may still face challenges and need to be established.

The cross-border transport of decommissioned solar PV panels has been reported in many countries. For example, in the European Union, a study indicates that large amounts of solar panel waste are exported outside the European Union, with PV module export rates up to 90% for certain countries. High recycling costs (usually EUR 100-200/t [euros], equivalent to around USD 114-228/t of PV waste) are the main reason for this; in addition, multiple organisations offer to buy and export PV waste (Rayner, 2024). In Australia, until 2024, around 80% of decommissioned solar panels were exported to other markets for reuse (SEC, 2025). Solar PV waste can also be shipped to other markets where modern recycling facilities have been established.

Similar to other e-waste, the cross-border movement of decommissioned PV panels often moves from developed markets to developing countries. According to Global E-waste Monitor, 5.1 Mt of e-waste were shipped across borders in 2022, among which 3.3 Mt were estimated to flow from high-income to middle- and low-income countries in an uncontrolled and undocumented way (ITU *et al.*, 2024). It has been reported that many decommissioned solar panels in Australia, the European Union and the United States ended up overseas as donations to lower-income countries (Dias, 2024). For instance, a solar installation firm in Australia shipped containers of modules to rural areas in West Africa. The modules were replaced during an upgrade of solar power systems and were reported to be in working condition (Bloch, 2022). In regions such as Sub-Saharan Africa, used solar modules and other electrical and electronic equipment are more affordable than new equipment and are used to power local communities.

However, even though they are declared to be usable or repairable, these cross-border streams of decommissioned solar PV panels are likely to become defective within several years. They may also be unable to function properly because of a lack of technicians with the necessary technical skills. For example, there is evidence that a significant portion of used electrical and electronic equipment shipped from developed markets to Kenyan beneficiaries was not able to be used properly (Lebbie *et al.*, 2021). These imported second-hand solar PV panels will likely contribute significantly to e-waste in the near future, raising concerns about local capacity for collection and treatment. This also undermines public confidence in PV adoption due to a lack of transparency regarding the origin, quality and history of the hardware. In response, countries like Senegal are introducing rigorous quality standards and incentive schemes to curb the import of substandard equipment and elevate the general quality of solar technology deployed nationwide (GOGLA, 2024).

3.2 WASTE STREAMS FROM OFF-GRID SOLAR APPLIANCES

In most developing markets in Sub-Saharan Africa and Asia, the bulk of solar PV products are off-grid solar home appliances. The lifespans of these off-grid solar appliance vary: modern and quality-verified products can last more than eight years, while some low-quality products tend to have shorter lifespans (two to three years) than quality-verified products. Because these regions' financial capacity, knowledge and socio-economic context differ from those of developed markets, there are significant differences in how dysfunctional off-grid solar equipment is treated. This section aims to outline the current status of off-grid solar appliances in selected markets and the practices used to handle the waste streams.

Global status of off-grid solar equipment

Solar panel-based off-grid systems are usually used to power electrical and electronic equipment such as lights, televisions, radios, fans and refrigerators, as well as solar water pumps. They can be categorised into different types, including solar lights (<11 W), solar home systems (>11 W), solar mini-grids (>1 kW), solar pumps (around 0.4 kW or more), as well as others (IRENA, 2025c). These off-grid solar PV systems play a vital role in providing electricity access in developing regions and countries in Africa and Asia, with smaller-scale deployment in Latin America. For example, solar energy kits, including solar lanterns and small-scale solar home systems used to power lights and small electrical devices for individual families, have experienced a significant boom in Sub-Saharan Africa over the past decade.

A large number of off-grid solar PV systems have been deployed globally. In 2024, It was estimated that the total weight of solar panels used for off-grid solar lights and solar home systems was more than 22 700 t, excluding the electric appliances or cables attached to the panels. Some 77% (by weight) of these off-grid solar PV panels are deployed in Africa, and an additional 15% are in developing Asia. Moreover, solar mini-grids are estimated to involve over 52 000 t of PV panels, with 64% of these panels deployed in Indonesia. Additionally, over 92 000 t of solar PV panels are being deployed as solar pumps, with 92% of these in India (IRENA, 2025c).

Estimate of the waste stream from off-grid solar PV panels

Quality-verified off-grid solar PV usually have professional maintenance and 25 to 30 years of service time. Companies distributing these high-quality products often have reverse logistics, warranty and repair offerings for customers. In the off-grid context, most customers tend to have broken products repaired, rather than discard them, to get a longer service time. A Solar Aid study in 2024 found that 90% of companies surveyed offered some type of repair and refurbishment service for their customers (Keane *et al.*, 2024). However, off-grid solar products without verified quality can have relatively short working lives, ranging from two to three years.

In Sub-Saharan Africa, data show that over 110 million small solar PV off-grid appliances are likely no longer functional. In 2020, an estimated 10 000-12 000 t of end-of-life off-grid solar products were generated in Sub-Saharan Africa, primarily due to a lack of local technical expertise or limited access to maintenance services (SESA, 2024). In Kenya, it is estimated that thousands of tonnes of off-grid solar waste may have been generated in the early 2020s, with 65% of these unfunctional items being kept at home (Hansen *et al.*, 2022; Kinally *et al.*, 2022).

In most cases, off-grid solar appliances are not collected or treated by formal and centralised treatment facilities. This is linked to the local context and practices of e-waste management. It is estimated that, in Sub-Saharan Africa, less than 1% of these non-functioning solar products are being covered and collected by formal recycling practices (Munro *et al*., 2023). When these off-grid solar appliances are no longer functional and are cleared from households, they are usually collected and dismantled by informal e-waste recyclers. After dismantling the metals in the appliances, the remaining components with minimal market value are usually disposed of in open dumpsites or landfills. They are also sometimes incinerated without taking proper health and safety measures, causing significant environmental and public health impacts.

Ghana, Kenya and Rwanda are in the process of developing formal regulatory frameworks for end-of-life management of off-grid solar appliances (Hansen *et al*., 2022). An increasing number of formal recyclers have also developed partnerships with quality-verified off-grid solar companies to further explore solutions and business models to address the challenges linked with handling off-grid solar waste streams. Despite these positive developments, if sustainable practices are to be promoted, significant barriers need to be addressed. For example, more investment and international development funds are needed to support the development of a sustainable reuse and recycling ecosystem in Sub-Saharan Africa. Another barrier is related to the cost of recycling. The high recycling cost adds to other challenges related to high financing costs in this region.

3.3 ENVIRONMENTAL IMPACTS RELATED TO LANDFILLING AND UNREGULATED RECYCLING

The unsustainable disposal and treatment of end-of-life solar panels, such as direct landfilling or open-air burning, can result in unwanted environmental impacts, polluting water, soil and air and threatening public health. Some heavy metals contained in solar PV panels, such as lead and cadmium, can contaminate soil and groundwater. When landfills are regulated properly with the best available measures, contamination risks can be controlled and monitored in many cases (Sinha *et al*., 2020). However, environmental regulations can be less stringent in developing regions, such as South Asia and Sub-Saharan Africa. In these regions, environmental impacts can be high, and additional measures and solutions are required.

E-waste landfilling can cause significant contamination of soil and water. For example, lead and brominated flame retardants have been commonly used for solar PV panels as solders and junction boxes, respectively. These two materials are among the most hazardous substances in solar PV panel waste. An analysis of Sub-Saharan African countries showed that lead concentrations in soils near e-waste dumping sites can reach 14 000 milligrammes/kg, which is 35 times above the level considered safe, which is less than 400 milligrammes/kg (Ssebugere *et al*., 2025). Such a high level of lead pollution threatens public health. Exposure to lead can affect multiple body systems and is particularly harmful to young children and women of childbearing age (WHO, 2024a).

Informal treatment or recycling of end-of-life solar PV panels is common in most of developing markets. Informal recycling practices are usually not equipped with skilled workers or professional machines that can properly handle the solar panels in alignment with the requirements for environmental and human safety. In Nigeria, more than 30 000 individuals are involved in informal e-waste recycling. Informal recycling plays a significant role in the livelihoods of these families, as it provides the majority of their income. In Ghana, the Agbogbloshie e-waste dumpsite is estimated to have provided income for over 15 000 informal e-waste workers (Adetuyi and Williams, 2022). However, this informal process leads to pollution and poses health risks to the informal workers and individuals living nearby (UNEP, 2021).

In most cases, informal recycling aims to recover the metals with the highest market value, with minimal or no measures taken to ensure workers' safety or environmental compliance. Usually, informal recycling of e-waste, including solar PV panels, does not involve large recycling equipment. The focus is solely on recycling aluminium and copper, which are easy to dismantle with simple tools. The rest of the components, including hazardous solder and plastic components, are likely to be burned directly at the dumpsite. This open burning of e-waste can cause significant air pollution (*e.g.* airborne dust, nitrogen oxide). It can also release polycyclic aromatic hydrocarbons and dioxins, both of which are highly toxic (Finn *et al.*, 2025; Greenpeace and ACEF, 2022; ITU *et al.*, 2024; Tyagi and Kuldeep, 2021; WHO, 2024b). Currently, most deployed solar PV panels use fluorine-based backsheet materials to improve performance and outdoor durability. Burning these backsheets generates highly toxic hydrogen fluoride (HF) gas, which is extremely dangerous to human and animal health. This pollution can cause significant environmental impacts and negatively affect health in communities near informal recycling sites (Ssebugere *et al.*, 2025).

Unregulated recycling by small-scale facilities usually involves directly discarding the process waste and residues in the nearby environment without proper treatment. This can also pose significant environmental risks. Similar to informal recyclers, these unregulated recycling facilities usually involve unsustainable recycling practices, such as open burning, or the use of strong acids to recover metals with a high market value, such as silver and copper. Liquid waste generated from such unregulated recycling processes can have significant impacts on soil and fresh water if it is not treated properly.

Solar PV waste is emerging in more markets and is expected to surge in the coming decades. It is critically important to prevent and minimise unwanted impacts on the environment and local communities. Addressing these potential threats requires the urgent adoption of circular economy approaches in solar PV waste management practices, which are introduced in Chapter 4.

CHAPTER 4
A CIRCULAR ECONOMY FOR END-OF-LIFE MANAGEMENT OF SOLAR PV PANELS

4.1 DEFINITION OF A CIRCULAR ECONOMY

The current economic system is often described as a “linear economy”, built on constantly extracting raw materials, turning them into products and then discarding them as waste. This linear model poses threats to finite resources and causes damage to the environment. A transition to a different system, a “circular economy”, is increasingly being promoted and pursued globally. A circular economy aims to use resources and conduct economic activities in a more responsible and sustainable way by increasing resource use efficiency, minimising waste generation and related pollution, and circulating products and materials (at their highest value), as well as regenerating nature (Ellen MacArthur Foundation, n.d.; UNDP, 2023).

A circular economy is based on three simple principles: reduce, reuse and recycle. The ultimate goal of a circular economy is to prevent, minimise and reutilise waste streams as much as possible. The circular economy principles extend to waste management across all economic sectors, including the electric and electronic equipment industry (EUR-Lex, n.d.; UNEP, 2024b). This makes it an important and foundational approach to manage end-of-life solar PV panels sustainably.

In 2016, IRENA and IEA-PVPS published End-of life management: Solar photovoltaic panels, a report highlighting the significance of circular economy approaches in addressing future waste streams from end-of-life solar PV panels (see Box 1). Meanwhile, a number of research institutions from different markets, including Germany’s Fraunhofer Institute for Solar Energy Systems, Australia's University of Technology Sydney, China’s Chinese Academy of Sciences and the US National Laboratory of the Rockies, have also addressed this topic. Indeed, an increasing number of research institutes are investigating the concept of the circular economy as it pertains to solar PV panels, including looking at technology innovations, concept development, and sustainable practices and policy analysis.

Box 1 IRENA and IEA-PVPS joint report: *End-of-life management: Solar photovoltaic panels* (2016)

In 2016, IRENA and IEA-PVPS jointly published the first projection of solar PV panel waste volumes up to 2050. The initial projections for end-of-life solar panels were based on two scenarios: a regular-loss scenario (assuming a 30-year panel lifespan with no early attrition) and an early-loss scenario (considering some percentage of solar panel failures before reaching the 30-year lifespan). The report highlights that the circular economy, including recycling and repurposing end-of-life solar PV panels, can unlock a growing reservoir of raw materials and valuable components for the needs of the energy transition. Circularity-based end-of-life management of solar PV panels can unlock the potential to spawn new industry opportunities, generate substantial economic value from recovered materials, and further move towards aligned and sustainable development goals.

This report further explains key principles for end-of-life management of solar PV panels and the policy actions needed to promote their adoption. To fully realise the benefits of the circular economy for end-of-life solar PV management, countries should establish the necessary institutional frameworks and manage the anticipated surge in solar panel waste. Policy actions are needed to address upcoming challenges, but they must be tailored to each region or country's circumstances.

Source: (IRENA and IEA-PVPS, 2016).

Building on the previous analysis from 2016 and taking into account the latest discussions and industrial practices on the circular economy for solar PV panels,[7] this chapter aims to offer a comprehensive analysis and provide practicable options for policy makers and industrial players. It aims to support stakeholders in better understanding the various aspects of the circular economy for the solar PV industry and the available and feasible actions associated with each circular economy principle.

4.2 CIRCULAR ECONOMY FOR SOLAR PV DEVELOPMENT: PRINCIPLES AND MEASURES

Reduce

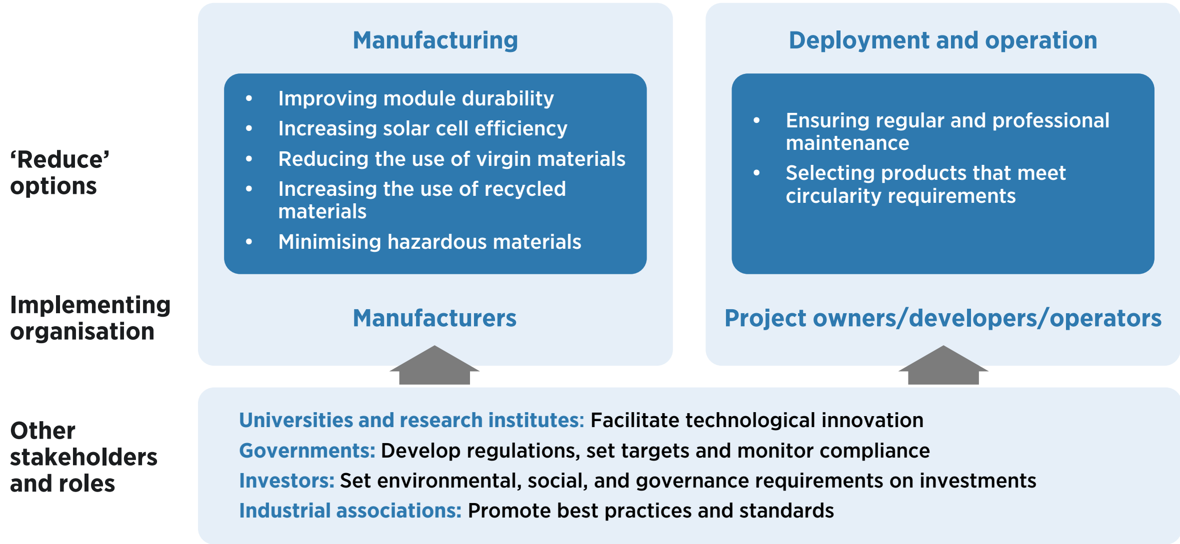
The “reduce” principle involves all measures taken to prevent waste generation and reduce the use of virgin and hazardous input materials in production (IRENA and IEA-PVPS, 2016). Adoption of the “reduce” principle should start as early as the product design and manufacturing phases. Producers should design and manufacture their solar PV panels by:

- Improving the design of industrial processes. This works to reduce material inputs and make disassembly and recycling easier (MIIT *et al*., 2026).
- Extending the lifespan of solar PV panels. Increasing their lifespan is critical for minimising waste generation and related environmental impacts (CISL *et al*., 2025; Paç and Gok, 2024).
- Reducing virgin material use. Minimising the use of virgin materials is key for a circular economy, including for the solar PV industry. Alternatively, industrial players should gradually increase the share of recycled materials in the manufacturing of solar panels. Such a transition should not compromise safety, efficiency or performance.
- Minimising hazardous material use. Design considerations should focus on reducing the use of hazardous materials, such as lead in solders, and limiting the use of fluorine in backsheets. In this way, the recyclability and resource recovery potential are improved (Ali, Islam *et al*., 2024; SEIA, 2025).

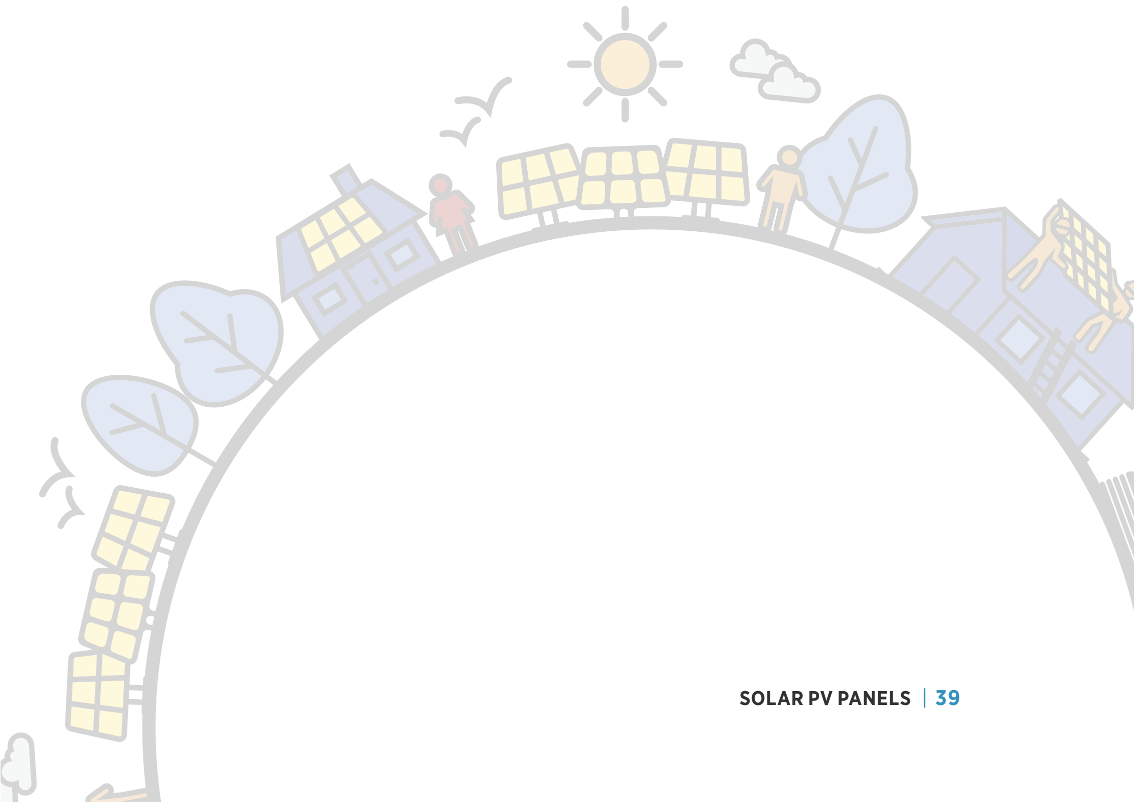
Adoption of these "reduce" options from the product design phase can avoid environmental costs efficiently (Ellen MacArthur Foundation, 2022). However, a circular product design usually means higher manufacturing costs, which in turn means that companies may lack the willingness to transition to a circular product design. Governments should therefore make relevant policies to encourage or mandate companies to adopt the circular economy principles during production. An example is the European Union’s Ecodesign policies, which set a series of “ecodesign requirements” for products that are to be placed on the EU market (see Box 2) (European Commission, 2026b).

[7] The discussion of “reduce”, ”reuse” and ”recycle” in this section is based on (Curtis *et al*., 2021; Ellen MacArthur Foundation, 2022; Greenpeace and ACEF, 2022; Heath *et al*., 2022; IEA-PVPS, 2022; IRENA and IEA-PVPS, 2016; Kirchherr *et al*., 2017; Tao *et al*., 2020; UNEP, 2023).

Figure 24 "Reduce" options and related stakeholders



One challenge in implementing the "reduce" principle could be the trade-off between manufacturing products that are easy to disassemble as a "reduce" measure and their durability (Bilbao *et al.*, 2021). For example, a circularity-based design for solar PV panels would require making solar panel systems easy to dismantle for repair and recycling, in which case durability might be compromised. However, solar PV plants are commonly faced with harsh weather conditions and require robust designs to make disassembly difficult without breaking components. Furthermore, solar cells usually use the strong adherence of EVA to ensure durability. When end-of-life solar PV panels are processed for reuse and recycling, it can be challenging to remove EVA without breaking the silicon cells, a high-value component that has the potential to be reused with promising economic returns for recycling facilities. Similarly, the use of fluorine-based backsheet materials can protect solar cells and improve a product's durability throughout its lifespan. However, highly toxic HF gas can be generated if fluorine-based backsheet materials are burned during the recycling process. If this occurs, it may also increase recycling costs because treatment facilities may need to invest in additional toxic gas capture and treatment equipment (Wei *et al.*, 2025).



Box 2 The European Union's Ecodesign policies

In July 2024, the Ecodesign for Sustainable Products Regulation entered into force in the European Union. It is an EU-wide legal framework that sets ecodesign requirements to ensure the sustainability and circularity of products. Under the Ecodesign framework, requirements include:

- improving product durability, reusability, upgradability and reparability
- enhancing the possibility of product maintenance and refurbishment
- making products more energy and resource efficient
- addressing the presence of substances that inhibit circularity
- increasing recycled content
- making products easier to remanufacture and recycle
- setting rules on carbon and environmental footprints
- limiting the generation of waste
- improving the availability of information on product sustainability.

The regulation sets two horizontal requirements: 1) repairability (including scoring) and 2) recycled content and recyclability. These are mainly intended for electrical and electronic equipment.

It also introduces the Digital Product Passport, a digital identity card for products, components and materials, aiming to promote the traceability of products.

Source: (European Commission, 2026b).

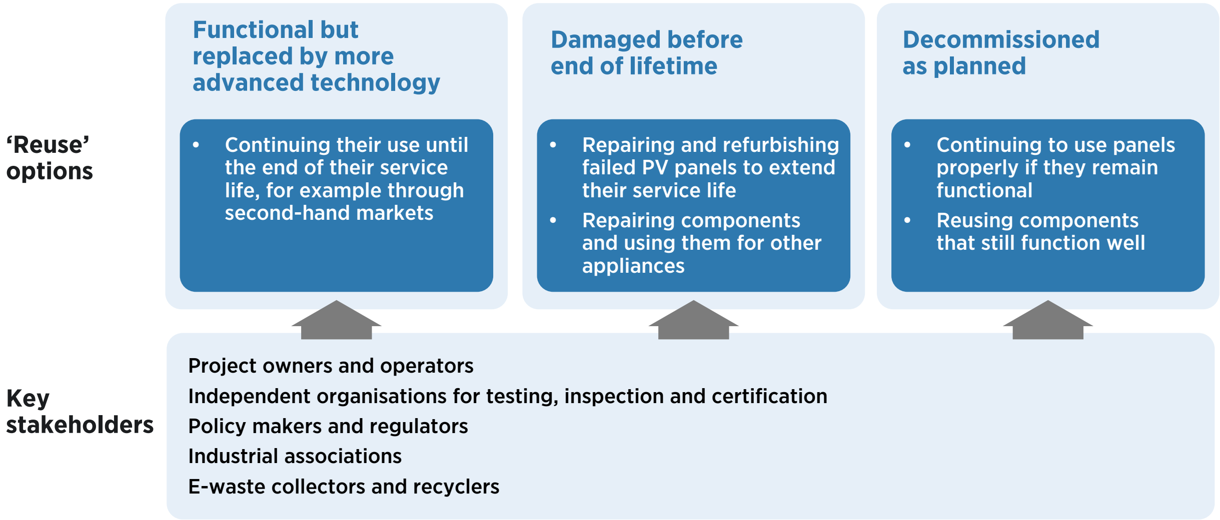
To improve the circularity-aligned product design and technology advancement, solar PV manufacturing companies, universities, technology research institutes, industrial associations, governments and other stakeholders all have critical roles to play. While efficiency improvement remains a common interest for industries, further targets, regulations and incentives will be needed to further drive the change in industrial practices by reducing hazardous materials and increasing the use of recycled raw materials (see Chapter 5).

Reuse

The "reuse" principle aims to extend the operational life of decommissioned solar PV panels and components (Basnet *et al.*, 2025). In the context of the end-of-life management of solar PV panels, the options to reuse include actions on:

- Reusing decommissioned solar panels. After decommissioning, some solar panels may have compromised performance but can still generate electricity. Reusing these decommissioned solar PV panels can prevent them from entering the waste stream (Bellini, 2026).
- Reusing components that are not damaged and can function properly. Many solar panel components, such as solar cells and junction boxes, remain in good working condition when solar PV panels are decommissioned. Based on a professional testing process, these components can be reused for second-hand products or other appliances.
- Repairing failed components or panels for second use. Some damaged or failed solar PV panels can be repaired and reused after undergoing a proper testing and certification process to ensure safety and continued service life.

Figure 25 "Reuse" options and related stakeholders



Decommissioned solar PV panels are not necessarily at the end of their service life because they often can still generate electricity. In many cases, project investors replace the older solar panels with newer, higher-power production models on the same site to improve profitability. Such replacements can result in a remarkable 50% increase in electricity production compared to older solar PV technologies and, therefore, be more attractive to investors (Greenpeace *et al.*, 2022). In this example, most of the decommissioned solar PV panels have not reached the end of their service time and can be reused for other purposes and sites.

The "reuse" approach offers huge potential for solar panels that have been decommissioned early, for which the remaining repairable and reusable solar PV capabilities represent a significant, but untapped, second-hand market. Studies indicate that c-Si solar PV panels typically experience power degradation rates ranging from 0.5% to 2.96% per year, depending on the local climate in which they are deployed. In that case, after two decades of service, these solar PV panels may still retain around 70% to 80% of their original nameplate capacity (Aboagye *et al.*, 2021; Atia *et al.*, 2023; Theristis *et al.*, 2023). However, the "reuse" approach should be underpinned by necessary testing and certification processes to enable a market for second-hand solar PV.

Reusing silicon cells offers significant economic potential. Silicon cells are estimated to account for more than half of total module manufacturing costs and a large share of total energy consumption in the entire solar PV value chain (VDMA, 2025). Theoretically, most solar cells in decommissioned solar projects remain undamaged and can be reused. Along with the technology advancement, since solar cells can deliver much higher profitability than recycled materials, they can play a vital role in enabling second-hand solar PV markets.

Currently, it is difficult to ensure that silicon cells remain undamaged during an industrial-scale recycling process. However, pilot projects have demonstrated that, through chemical etching and thermal processing or a mixed solution, recycling facilities can obtain solar cells with minimal damage. In China, a pilot facility – a collaboration among a PV company, a university and an institute – has developed a recycling process that can separate glass and cells without damaging them (CRRA, 2026). Research has shown that a significant share of separated solar cells from decommissioned solar panels showed excellent characteristics, efficiency and stability compared to newly produced cells. In other words, reusing silicon cells to produce solar panels may have comparable efficiency to using virgin materials (Dum *et al.*, 2023; Shin *et al.*, 2017).

Reusing components and panels from decommissioned solar panels can provide affordable options for markets with limited financial capacity. As a key part of ensuring quality infrastructure for these markets, proper testing and quality assurance are crucial to ensure market confidence in reused solar PV panels and their components. They are also necessary to determine the market value of second-hand solar PV panels and reused components. However, professional testing and certification processes require significant labour investment and proper training (Fong, 2023). Bridging these capacity gaps would require rigorous policy support and collaboration with industries.

Recycle

The "recycle" principle is a more commonly discussed topic for end-of-life management of solar PV than the other two principles. However, it is essential to remember that, in the waste management hierarchy, preventing waste streams by circularity-aligned design and reusing products and components should be the preferred priorities. Recycling end-of-life solar PV panels and recovering the materials should always be the last step after "reducing" and "reusing" (US EPA, 2025; Yazdi *et al.*, 2024).

Box 3 Current solutions and technologies for solar panel recycling

Currently, there are three major technology pathways for recycling end-of-life solar PV panels: mechanical treatment, chemical treatment and thermal treatment. Each of the solutions has specific advantages and disadvantages.

During mechanical treatment, end-of-life solar PV panels are treated through a process of crushing, shredding and/or pulverisation into smaller pieces or cullets. This involves machinery such as hammer mills, crushers and sorting equipment. During this process, glass, ferro and non-ferro metals, plastics, and other materials are separated. These separated materials can be sold to the secondary materials market for new production. Mechanical treatment usually has a lower cost compared to other waste treatment processes. However, this process cannot achieve 100% purity within the recovered materials, which may also affect the market value of recovered materials (Ali, Shahid *et al.*, 2024).

Chemical treatment involves treating the waste with chemicals. This includes hydrometallurgy, which is often used for the separation and recovery of valuable metals. During the leaching process, metals in the panels or cells are dissolved and transferred into the leaching solutions, from which high-purity metals can be further extracted. Chemical treatment can result in a higher purity of the recovered metals compared to other treatment methods. However, it is more expensive and has a higher environmental impact than *e.g.* mechanical treatment, because of the toxicity of chemical waste (Han *et al.*, 2023).

Through thermal treatment, solar PV panels are processed in a furnace to delaminate the materials of the waste. The remaining components can then be further processed through mechanical and chemical treatment. One of the thermal treatment options is a fluidised bed reactor that uses fine sand to burn EVA and the backsheet (serving the same role as the furnace). An additional thermal treatment process uses high temperatures (500°C or higher) to evaporate small plastic components and allow solar cells to be separated (Calero *et al.*, 2026; Kwon *et al.*, 2025).

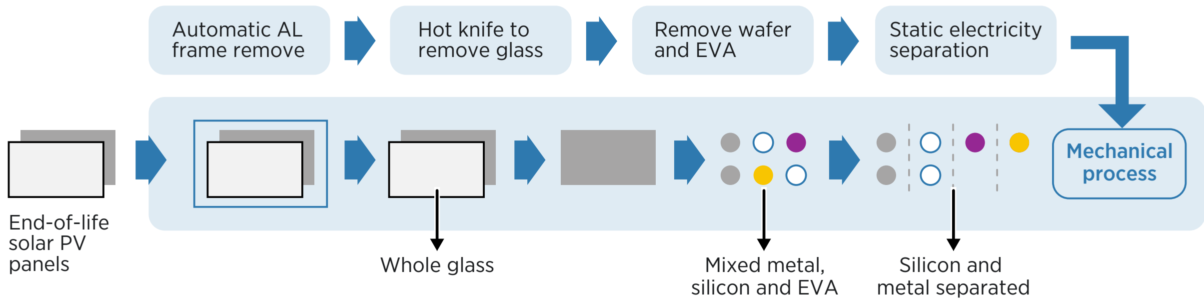
In reality, mechanical, chemical and thermal treatments are usually mixed in the recycling process to maximise the recycling rate and economic returns. The materials recovered during these treatments will usually be sent to dedicated facilities for further purifying or cleaning to obtain a higher grade of purity, ranging from 80% to 100%.

Source: (Ali, Shahid *et al.*, 2024; Calero *et al.*, 2026; Greenpeace *et al.*, 2022; Han *et al.*, 2023; Kwon *et al.*, 2025).

Recycling plays an important role in preventing landfilling and its relevant environmental impacts. It is estimated that more than one-third of the life-cycle emissions of solar PV panels can be avoided by using thermal decomposition recycling processes for end-of-life PV panels rather than sending them to landfills. Given the widespread deployment of solar PV plants, this approach has the potential to reduce carbon dioxide emissions by millions of tonnes per year (An and Sun, 2024).

Currently, the majority of reported efforts to recycle solar panels in line with circular economy principles rely on mechanical processes or a combination of mechanical and thermal treatment methods involving removal of the aluminium frame, the copper wires and the junction box manually or by using machinery (see Figure 26). Recycling facilities then carry out delamination and separation treatments according to different technical routes, sort the treated materials, and finally complete further material separation and extraction. This combination of technologies aims to reduce costs and recover purer components and materials.

Figure 26 Key steps for a mechanical treatment solution for end-of-life solar PV panels



Source: (Greenpeace *et al.*, 2022).
Notes: AL = aluminium; EVA = ethylene vinyl acetate; PV = photovoltaic.

Despite their availability, many of these solutions and processes remain in the early development and demonstration phases. Most solar PV panel recycling facilities are demonstrated in pilot facilities but not yet fully commercialised, except in China and the European Union. Technically, several existing technologies and processes can achieve recycling rates exceeding 90% of the overall weight of solar panels. For example, pilot projects combining thermal decomposition and chemical treatment can recycle around 90.2% of the total weight of end-of-life solar panels, according to data provided by the China National Resources Recycling Association. Metal recovery rates can reach 93.76% for silver, 96.27% for silicon and 99% for copper (CRRA, 2026). However, the economic returns of these pathways depend on the market prices of recovered metals. Additional regulations, incentives and infrastructure are necessary to enhance business profits, reduce costs and minimise energy consumption in the recycling process (see Chapter 5).

Treatment facilities and infrastructure

Dedicated end-of-life solar PV treatment facilities play an important role in promoting circular economy practices and exploring feasible business models. Currently, some dedicated facilities have realised commercial operations in various markets.

In the European Union, several specialised organisations have been in operation. PV CYCLE is a non-profit organisation that focuses on organising the collection and recycling of end-of-life solar PV. It mainly operates in the European Union and the United Kingdom, setting up legal entities in its target markets. By collaborating with waste treatment and recycling companies dedicated to recovering and recycling the materials from PV panels, PV CYCLE is able to organise the treatment of several thousands of tonnes of end-of-life solar PV panels annually. It is also represented in Japan (PV CYCLE Japan) and other regions through its partners in Brazil and Mauritius (PV CYCLE, 2026).

An increasing number of Chinese solar PV companies, including State Power Investment Corporation, Longi and Jinko, are currently developing and demonstrating advanced solar panel recycling processes (Greenpeace *et al.*, 2022; Jiang, 2023). For instance, State Power Investment Corporation has adopted a recycling system that includes a mechanical disassembly process, a thermal cutting process, a selective separation process, a pyrolysis process and a hydrometallurgical purification process. It can realise almost 100% recovery of module junction boxes, aluminium frames and intact glass. After EVA removal by pyrolysis, the comprehensive recovery rate can reach more than 92.5%. The silicon recovery rate can reach 99.99% (CRRA, 2026).

In Japan, solar PV recycling technologies are in a pilot phase, based on mixed mechanical and thermal technologies. Theoretically, this recycling solution can recover more than 99% of silicon cells, copper wires, aluminium and glass, or 82% of the overall weight of treated solar PV panels. This high recovery rate is achieved by burning EVA in a furnace for heat recovery, where the heat is utilised for EVA removal processes (Okinaga, 2023; Shinryo, 2022). In the Republic of Korea, the Korea Institute of Energy Research has developed a process based on thermal and chemical methods that can recycle the entire solar cell and extract high-purity metals. Currently, it has reached the commercialisation process (Lee and Jang, 2023).

In Southeast Asia, countries are at an early stage of addressing end-of-life management of solar PV systems. Indonesia is exploring research partnerships and pilot initiatives designed to develop scalable recycling solutions, while Viet Nam is advancing through the adoption of recycling technologies to build domestic processing capacity. In Malaysia, a dedicated solar panel recycler has started to collect and recycle decommissioned solar panels, aiming to recover materials for reuse. As solar deployment continues to expand rapidly across Southeast Asia, demand for effective and sustainable PV recycling solutions is expected to rise. This represents opportunities to foster industrial innovation, strengthen circular economy value chains, and establish policy and regulatory frameworks to ensure the environmentally sound management of solar module waste.

The minimum feedstock threshold for recycling facilities remains a key factor in determining profitability. Similar to other industrial plants, solar PV recycling facilities may incur high operating costs when treatment volumes fall below the threshold, typically set between 5 000 t and 10 000 t, depending on market context. In New South Wales, Australia, a recycling facility using advanced technology is estimated to need to treat 4 500 t of feedstock per year to cover capital costs and achieve a return on investment within 2.5 years. Similarly, a Canadian study estimated that an annual volume of 10 000 t of end-of-life solar panels is needed to establish a dedicated solar recycling facility (SPI, 2021a). In many markets, existing solar PV projects have not reached their end-of-service life and therefore feedstock can be limited. Recycling facilities may have insufficient information on decommissioned projects, or face incomplete transport or storage infrastructure. In some cases, a large number of end-of-life solar PV panels are directed to unregulated recycling facilities, while dedicated, environmentally aligned facilities do not have enough feedstock (see Chapter 4, Section 5).

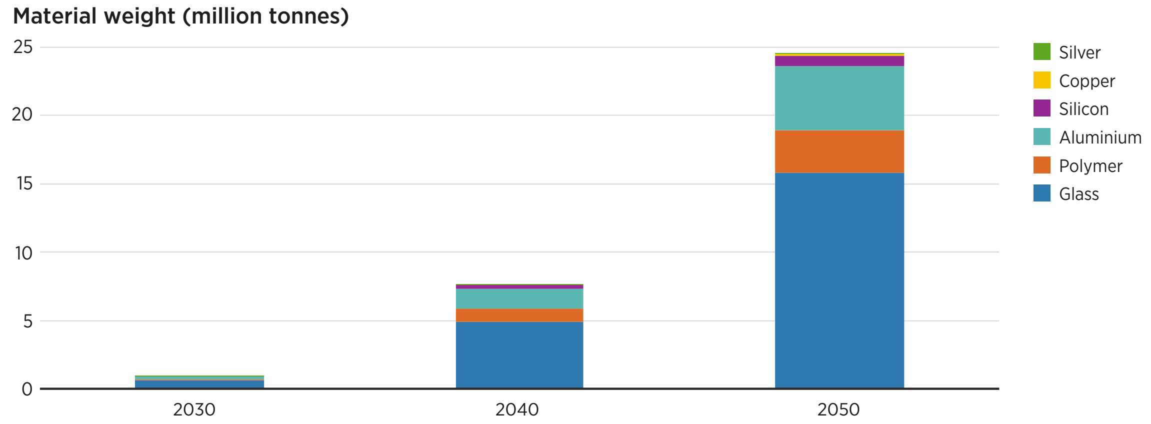
4.3 POTENTIAL ECONOMIC BENEFITS FROM RECOVERED MATERIALS

A significant share of recovered materials from end-of-life solar PV panels can bring economic benefits. Recovered copper, aluminium, silicon, silver, glass and others can be traded in existing material markets and used to manufacture new industrial products.

Current technology can achieve recovery rates of over 90% for c-Si panels. Available technologies in Europe and China can recover 100% (in weight) of insulated cable, 99% of aluminium, 98% of glass, over 96% of silicon and copper, and 93% of silver (CRRA, 2026; EPRI, 2021; IEA, 2022). With technological advancements, it is estimated that nearly 100% of these valuable materials technically can be recovered, but some of the processes can be costly. Therefore, cost-effectiveness at commercialised operations has become one of the major barriers.

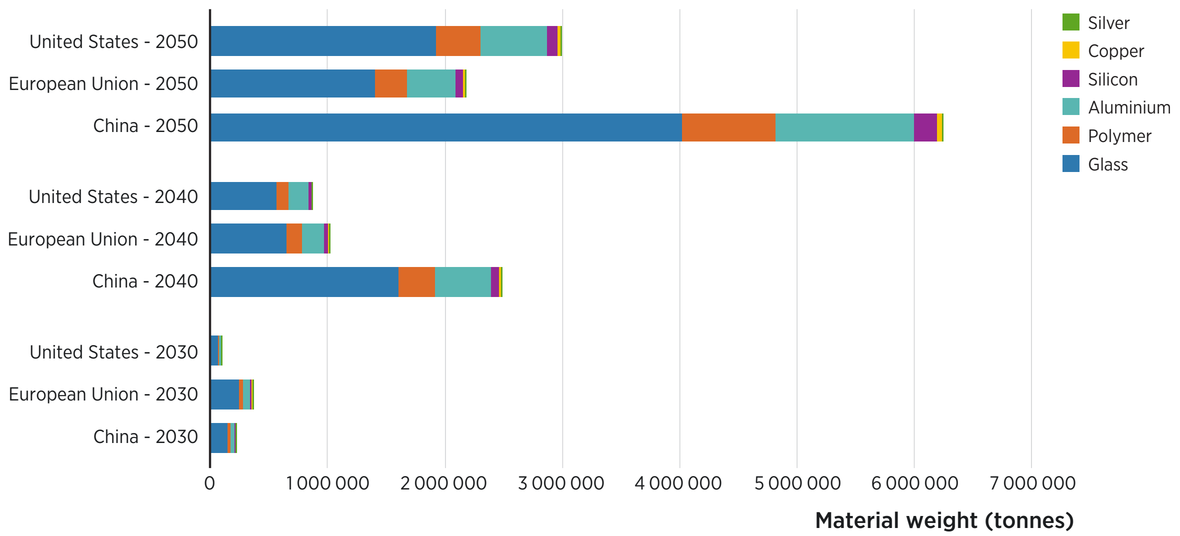
Based on IRENA's 1.5°C Scenario, technically, it is estimated that over 920 000 t of materials (*e.g.* glass, aluminium, silicon, copper and silver) can be recovered annually by 2030 through recycling end-of-life solar PV panels. The annual potential of material recovery will increase to 7.6 Mt by 2040 and 24 Mt by 2050 (see Figure 27). The majority of recovered materials include glass (64% of the total weight of recovered materials), polymer (13%) and aluminium (9%). Other materials, including silicon, copper and silver, will contribute to less than 4% of the total weight of recovered materials. For instance, the recovery potential of silver from end-of-life solar PV panels is estimated to be around 390 t (annually) in 2030. It will increase to 2 500 t by 2040 and exceed 8 200 t by 2050. Notably, China, the European Union and the United States are expected to account for almost half of the global total material recovery potential by 2050 (see Figure 28).

Figure 27 Global annual material recovery potentials from end-of-life solar PV panels, 1.5°C Scenario, 2030, 2040 and 2050



Notes: 1) The estimate is based on the technical recycling potential, assuming an overall recycling rate of approximately 97% of the PV module weight. 2) The weight of the polymer represents the combined amount of the encapsulant and backsheet.

Figure 28 Annual material recovery potential from end-of-life solar PV in China, the European Union and the United States, 1.5°C Scenario, 2030, 2040, and 2050

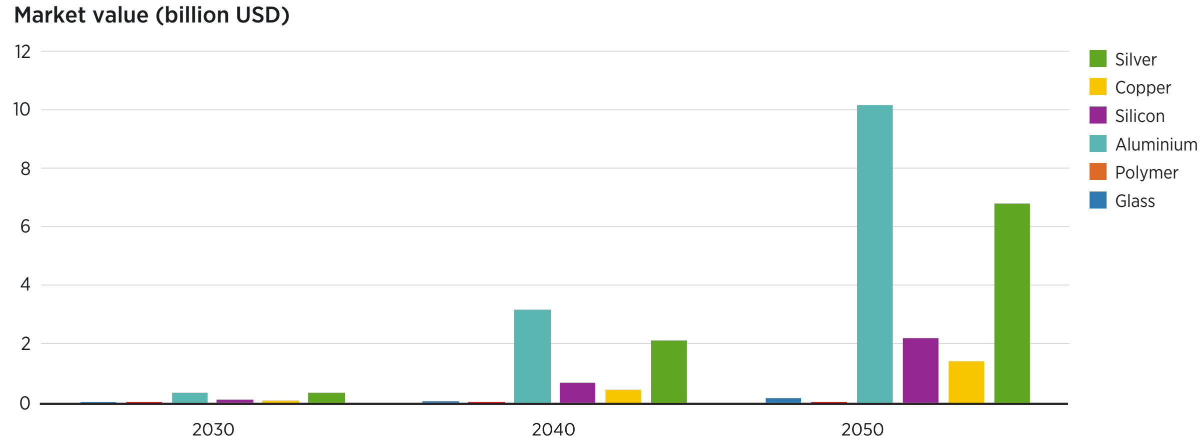


Note: Estimate is based on the technical potential of material recovery.

Recovered materials from end-of-life solar PV panels can provide additional raw materials to meet the growing demand for solar PV manufacturing. After a purifying process, most recovered materials and metals can provide additional feedstock for solar PV production. It is estimated that recovered materials from systematically collected end-of-life solar panels could meet 70% of the silver demand and 20% of the demand for aluminium, copper, glass and silicon needed by the solar PV industry (IEA, 2022). In Australia, recovered materials could meet 50% of silver and aluminium demand for solar PV deployment by 2038. The supply rate could even increase to 100% by 2045, which would signal a significant reduction in demand for virgin materials and associated environmental impacts (Tan *et al.*, 2024).

Trade in recovered materials can create market value and generate economic returns. Based on IRENA's 1.5°C Scenario, the market value of annually recovered materials from end-of-life solar PV panels is projected to surpass USD 810 million by 2030, reach USD 6 billion by 2040 and exceed USD 20 billion by 2050 (see Figure 29). The majority of this market value will be contributed by valuable metals. By 2050, nearly half of the value will be derived from recovered aluminium, followed by silver (33%), silicon (11%) and copper (7%). However, glass and polymer represent the largest share of the weight of globally recovered materials from end-of-life solar PV panels (over 75%). Their market value is relatively lower than that of metals, contributing a minimal share of the total market value of recovered materials. Even though the prices of secondary raw materials are influenced by various factors, future prices of recovered metals will likely increase when geopolitical dynamics and reduced natural reserves are taken into consideration.

Figure 29 Estimate of the market value of annual recovered materials, 1.5°C Scenario, 2030, 2040 and 2050



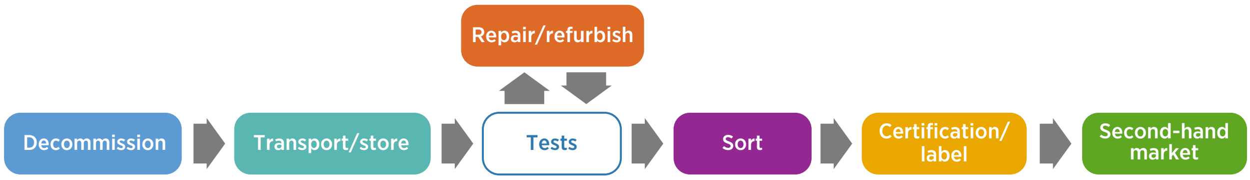
Note: All material prices are based on 2022-2024 average market prices.

4.4 ENABLING THE SECOND-HAND MARKET

Among all circular economy principles for solar PV panels, the "reuse" principle has been the most challenging. This is due to missing enablers, such as technologies, testing and certification systems; market confidence; and demand for second-hand solar PV panels (CISL *et al.*, 2025). Even though a few online marketplaces that test, repair and refurbish PV systems can be found in Europe and North America, they are far from a mature business or industry. In Europe, it is estimated that around 300 MW of solar PV panels are traded for reuse per year. In Australia, there are around 15 companies active in the reuse of solar PV panels (Salim *et al.*, 2023).

Any market for reusing solar PV panels and components urgently requires the establishment of standards, as well as testing and certification systems. Without these preconditions, a second-hand market for solar PV panels would not exist. Currently, there is no agreed-upon definition of or criteria for reusable PV systems. New solar PV modules must be tested against international certification standards (IEC 61215 and IEC 61730) to ensure quality and safety. Similar standards and certification systems need to be improved for second-hand solar PV panels and reusable components. These standards can be either promoted by governments or established as voluntary industry standards by industrial associations (Basnet *et al.*, 2025).

Figure 30 Key steps for reusing solar PV panels



Source: (Basnet *et al.*, 2025).

In Europe, an EU-funded project called Circusol has published guidelines for testing decommissioned modules for reuse. The guidelines suggest that reused PV modules can have lower safety and performance requirements, which may not meet the expectations of potential buyers. In Japan, similar guidelines have highlighted the need for an inspection and testing framework to promote the reuse of decommissioned solar PV panels, aiming to export second-hand solar PV modules to overseas markets (Basnet *et al.*, 2025). In most other markets, established standards for the quality and credibility of second-hand solar PV components and panels are still missing. A robust quality infrastructure system across markets is urgently required to bridge the gap.

Figure 31 Key enablers for reusing solar PV panels and components

Technical guidelines can provide industries with detailed procedures to assess and maximise reusability. The reusability of PV modules should account for factors such as panel age, geographic location, panel technology and the specific test protocols used. However, many of these factors are not accessible for industrial players, discouraging potential buyers and damaging market confidence. Therefore, standardised criteria and procedures to assess and certify the reusability of second-hand solar PV modules need to be established.

Certification of reusable solar PV modules and components remains a cornerstone for the development of a second-hand market. Currently, there are no widely accepted certification standards specific to reused solar PV panels, nor are there dedicated certification organisations or professional experts. To improve market acceptance, industrial players and policy makers need to collaborate to establish standardised labelling schemes showing certified performance characteristics and testing results, together with limited warranties for second-hand panel customers (Basnet et al., 2025; SolarPower Europe, 2024).

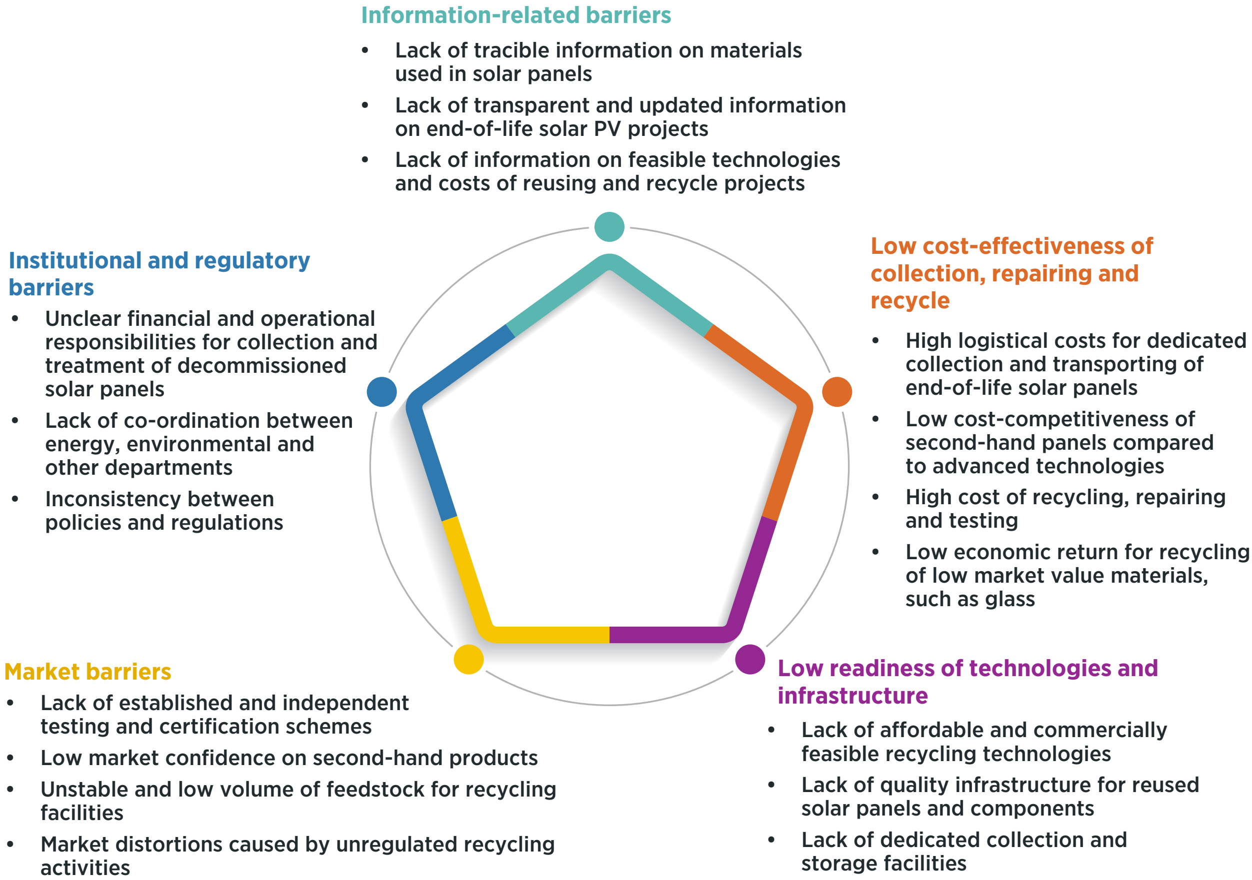
In addition to standardised guidelines, testing and certification systems, and quality warranties for second-hand solar PV panels, the engagement of key stakeholders across all these segments is crucial. Key stakeholder engagement can foster business models that demonstrate the profitability of the market and ensure it will be sustainable in the medium and long term. Further, quality infrastructure needs to be included in policies and technical regulations to ensure market players are required to comply with international best practices.

The reused solar PV panel market remains niche. Currently, the cost of reused solar PV products tends to be much higher than that of new solar PV products. Achieving a preferential business model for reusable components will be challenging. Finally, further training and investment will be needed to enhance workers' knowledge and skills in this industry.

4.5 EXISTING BARRIERS TO PROMOTING THE CIRCULAR ECONOMY

Even though circular economy approaches, including reduce, reuse and recycle, can tap into significant potential to promote solar PV deployment with minimised material demand and environmental impacts, their adoption and implementation remain staggered in most markets due to existing barriers. Many of these barriers are relevant to limited financial resources, high costs, lack of infrastructure, a lack of reliable and commercialised technology, a lack of standards and information, and other market or institutional barriers (see Figure 32).

Figure 32 Main barriers to the adoption of the circular economy for solar PV panels



High transportation costs constitute a major economic barrier for recyclers and the potential reuse market (CISL *et al.*, 2025; IEA-PVPS, 2022). In many cases, utility-scale solar PV plants are located in remote regions, far from formal waste treatment facilities. The transportation of end-of-life panels to treatment facilities can be much higher than the economic return from recovered material or landfilling costs. In Australia and Canada, the collection and takeback of end-of-life panels from power plants to treatment facilities can be expensive due to geographic dispersion (SPI, 2021a; Tan *et al.*, 2024). In China, many large-scale solar PV panels (in the northeast) are located over 1 000 kilometres from large-scale recycling facilities (close to the Yangtze Delta area). It is estimated that solar PV recycling is considered economically viable only when the transport distance is within a radius of 200 kilometres. Transport costs will add to operation costs. For example, recycling companies in China usually need to pay an additional transportation cost of about CNY 25 (Chinese Yuan; USD 3.5) for each panel they are collecting, which adds to the recycling cost of CNY 55 (USD 7.6) per end-of-life solar panel (Jiang, 2023). Similarly, in many other developing countries, recycling solar PV panels is challenging because of high logistical costs and a lack of infrastructure (Munro *et al.*, 2022).

Processing costs for end-of-life solar PV panels can exceed expected economic returns and therefore discourage industrial players. This is especially the case for countries with high labour costs and stringent environmental requirements for treatment facilities. For example, in New South Wales, Australia, the value of the recovered materials from PV panels is lower than the treatment costs. It is estimated that, in Australia, establishing facilities with high material recovery capabilities (*e.g.* 90% or more recovery rate) requires a capital cost of AUD 7 million (around USD 4.9 million) for a small- to medium-scale treatment facility that can treat 4 500 t of solar PV panels every year. Operational costs can be around AUD 1 120/t (around USD 790/t). This means that the treatment facility still needs AUD 14-17 (around USD 10-12) to achieve profitability for each unit of solar PV panel it treats (Florin *et al.*, 2020). In Victoria, Australia, the treatment cost of end-of-life solar panels ranges from AUD 10-20 (around USD 7-14) per panel. This is much higher than the value of the recovered materials from each panel and therefore a disincentive for the waste treatment and recycling businesses (Thou, 2024).

A lack of feedstock is a major barrier to the development of dedicated and circularity-aligned solar PV recycling facilities. Reports from China, Europe and Japan show that existing solar PV treatment facilities face difficulties in receiving a stable and sufficient quantity of solar PV panel waste streams, leading to operational costs that are significantly higher than their full treatment capacity (IEA-PVPS, 2022). For example, in China, a well-established formal solar PV recycling facility can process 20 000 t of end-of-life PV panels annually, but it only collected 5 000 t of feedstock in 2023 (Jiang, 2023).

Market distortion caused by unregulated recycling practices further exacerbates this challenge. While formal treatment and recycling facilities charge a fee to project owners, the informal sector may offer to buy those end-of-life solar PV panels. They compete for feedstocks with formal treatment facilities and have collected a large share of decommissioned solar panels. However, unregulated recyclers usually break down the equipment into marketable components, which can involve burning, leaching and melting techniques without proper treatment standards (ITU *et al.*, 2024; Jiang, 2023). These unregulated recycling practices are inefficient and lead to high environmental pollution and social impacts (see Box 4).

Box 4 Unregulated recycling facilities and their impact on the circular economy

Unlike circular economy-aligned recycling practices, unregulated waste treatment typically involves simple processes performed in small plants that recover only a portion (specifically, the aluminium frame and the cables) of the materials from end-of-life PV panels. These facilities usually burn these panels and then employ a leaching process to recover high-value metals. These practices release significant amounts of hazardous gases or liquids into the environment and threaten the health of nearby communities, especially in rural areas. This issue is a common and complex challenge for the e-waste industry in most developing countries.

When burning solar PV panels without proper treatment, the process generates toxic waste containing pollutants hydrogen fluoride, volatile organic compounds, and heavy metal particulates. Exposure to these gases can pose severe health risks, including poisoning, cancer, and damage to the liver and heart (Greenpeace *et al.*, 2022). Chemical processes to recover silver can generate highly toxic liquid residues that can contaminate soil and groundwater if not properly treated. In other words, while unregulated recyclers receive economic returns, the negative environmental and social externalities are borne by vulnerable groups and the general public.

These unregulated recycling facilities and practices can significantly undermine the circular economy market. While these facilities focus only on economic returns, their material recovery rates can be very low. Meanwhile, these facilities usually offer higher prices for collecting end-of-life solar panels from power plants. They still profit from the unregulated recycling business because they invest neither in pollution-control equipment nor in high-efficiency technologies. Consequently, circularity-aligned recycling facilities face challenges associated with a distorted market.

Source: (ITU *et al.*, 2024; Jiang, 2023)..

The cross-border trade of second-hand solar PV may also face challenges. Usually such trade flows from developed markets to developing countries, which likely have limited financial resources and less restrictive environmental regulations (Gebremariam and Beall, 2022). After several years of operation, these second-hand solar PV panels will enter the waste stream in importing countries. These developing countries are unlikely to have the needed local industry capacity, knowledge or technologies to treat end-of-life solar PV panels. This can pose environmental and social risks to developing countries (ESMAP, 2024; Kinally *et al.*, 2022).

Additional barriers include those related to repair and reuse, transport, a lack of data and co-ordination, and low public awareness of e-waste impacts. Local technicians in developing markets may lack access to repair manuals, spare parts and tools, while customers have limited access to trustworthy, trained repair technicians. In Kenya, a lack of waste transport infrastructure has been identified as a major barrier, compounded by the dispersed locations of off-grid solar product users. In Nigeria, a major challenge faced by stakeholders is the lack of data on the total number of solar products currently in use in the country and the scale of e-waste generated. Other challenges include the lack of co-ordination between different sectoral stakeholders and low public awareness of the environmental and health impact of e-waste (ACE TAF and NESREA, 2021; EEP Africa *et al.*, 2020).

There are many other barriers, such as a lack of clear information on materials and a lack of tracking platforms. For example, the reporting mechanism (often linked to a registration system) is the foundation for the solar waste (and e-waste) management system. Industrial players need such a platform for monitoring and sharing data with recyclers, forecasting the decommissioning of solar PV panels, and connecting potential buyers and providers for the second-hand market. However, in most markets, platforms for data and information are not available. Addressing these barriers requires the presence of regulations, policies and incentives, as well as international collaboration between markets.

CHAPTER 5

ENABLING A CIRCULAR ECONOMY FRAMEWORK FOR SOLAR PV

Integrating circular economy strategies into end-of-life management of solar PV panels helps to secure the potential of the long-term energy transition and benefits for the environment and local communities. Enabling systemic changes in the sector requires the adoption of different measures and tools. It necessitates a comprehensive and integrated policy framework to provide clear signals to the market (UNEN, 2023). This chapter outlines a holistic policy framework for integrating the circular economy into end-of-life management of solar PV, highlighting key policies and measures to enable infrastructure and encourage sustainable practices.

5.1 A POLICY FRAMEWORK FOR END-OF-LIFE SOLAR PV PANELS

A policy framework for enabling and integrating the circular economy for end-of-life management of solar PV panels in the energy transition should include the following key components:

- **Clear environmental regulations** to prevent unsustainable and unregulated collection and treatment of end-of-life solar PV panels. These regulations may include measures to prevent the landfilling of end-of-life solar PV panels, treatment by unregulated facilities, or shipment to developing markets without appropriate environmental and safety measures.
- **Mandatory and clearly defined financial and implementing responsibilities** for the collection, treatment and reporting/monitoring of end-of-life solar PV panels. An example is the extended producer responsibility (EPR) or similar schemes. These schemes should clearly define who should collect and treat end-of-life solar PV panels and who should pay for the costs.
- **A harmonised mechanism and platform for data collection, reporting and verification.** Data and information are the basis for circular economy policy-making and industrial actions. They should be traceable, consistent, transparent and accessible to all stakeholders.
- **Standardisation and certification systems supported by labelling schemes.** This includes the standardised criteria and certification systems for circularity-aligned design, reusable panels and components, and treatment facilities and workers. These requirements should also be included in solar PV-related industrial policies and technical mandates.
- **Industrial guidelines** should be developed and disseminated to support sustainable practices along the whole value chain. These voluntary guidelines can be combined with training, capacity building and technical assistance to bridge knowledge and skill gaps in developing markets.
- **Financial support and fiscal incentives for research and development (R&D) and market participation.** Since circular economy-aligned businesses for end-of-life solar PV panels are at an early development stage, financial support and fiscal incentives are needed to foster advanced technology development. Public finance can play an active role in accelerating technological advancement and supporting innovative business model development.
- **International co-operation for aligned actions, an integrated reporting system and harmonised standards.** The nature of global solar PV supply chains requires international collaboration between manufacturing countries and consumers to harmonise data and standards, and to align circular economy strategic priorities and policy directions. Additional support should also be directed to emerging and developing markets to improve their participation.

- **A just and inclusive framework based on the engagement of vulnerable groups and impacted communities.** The process of integrating a circular economy must take into consideration the impacts on youth, women, local communities and informal recyclers to ensure an inclusive transition process (see Figure 33).

Figure 33 Overall policy framework of a circular economy for solar PV, stakeholders and policy measures

Clear environmental regulations	Mandatory requirements for financial and implementing responsibilities	Mechanism and platform for data collecting, reporting and monitoring	Standardisation and certification systems supported by labelling schemes
Industrial guidelines	Financial and fiscal incentives for R&D and market participation	International co-operation for aligned actions, integ-rated reporting systems and harmonised standards	Engagement of stakeholders, including vulnerable groups
Cross-sector collaboration	Collaborations among the solar PV industry, government departments, investors, multilateral development banks, research institutes, environmental NGOs and recyclers		

5.2 KEY STAKEHOLDERS AND THEIR ROLES

Enabling the circular economy for end-of-life management of solar PV panels must include the engagement of various stakeholders across sectors. Stakeholders have unique roles and responsibilities to carry out for the successful establishment of the framework and the effective implementation of policy schemes (see Figure 34).

Industrial manufacturers, including both upstream and downstream, should be involved and encouraged to gradually increase the share of recycled materials used in manufacturing when technically feasible ("reduce"). They should also be guided to improve the design of solar panel products so that reuse, dismantling, treatment and recycling are easier, under the condition that solar panels' energy performance and durability are not compromised. Further, differentiated compliance approaches should also be offered to industrial players to ensure the participation of stakeholders operating in different contexts and with different capacities.

Figure 34 Key stakeholders and their roles in promoting the circular economy for solar PV panels

	Reduce	Reuse	Recycle
Manufacturers	• Designing and manufacturing circularity-based products	• Conducting own takeback and recycling schemes or joining an industry compliance scheme • Providing transparent and traceable product information	
Solar PV project owners	• Selecting eco-friendly products	• Proper operation and regular maintenance	• Delivering end-of-life panels to certified recyclers
Governments	• Developing policies and incentives to promote circularity-based design of solar PV panels	• Clearly defining and mandating financial and operational responsibilities • Setting standards and enforcing compliance • Directing data collection and reporting work • Setting long-term targets and roadmaps	
Recycling industry	• Providing feedback to manufacturers and designers	• Participating in second-hand markets	• Sustainable recycling that aligns with environmental and social regulations
Other stakeholders	Investors, universities, research institutes, NGOs, international organisations, *etc.* • Providing knowledge, experience and other support • Promoting and sharing best practices		

Owners and operators of solar PV systems and projects usually and ultimately determine how, when and where PV panels will be decommissioned. If qualified products are available and the necessary testing and certification infrastructure is in position, these owners and operators become potential consumers in the second-hand solar PV panel market. In some contexts, the operators of solar power plants, as the waste generators/emitters, have a responsibility to ensure their decommissioned panels receive proper treatment.

Governments have critical roles to play in enabling the circular economy and preventing unsustainable practices. Through a range of policy measures, governments can internalise environmental costs and enable circularity-aligned practices. Governments can develop new policies and adjust existing ones to integrate the circular economy for solar PV panels (CISL *et al.*, 2025; Ellen MacArthur Foundation, 2021). Governments can also direct data collection and information sharing, enable quality infrastructure, set targets and mandates, and facilitate public financing opportunities.

The lack of professional treatment and recycling facilities for end-of-life solar PV panels may impede the adoption of circular economy strategies. In Australia, current waste treatment and recycling providers can only recycle approximately 17% of a panel's weight, primarily the aluminium frame and junction box. The majority of a solar panel's materials, including glass, silicon and polymer backsheet, are currently not recycled in the country due to a lack of professional recycling facilities (Baumgurtel and Merwe, 2024). In Canada, some end-of-life solar panels are collected voluntarily and shipped to specialised recycling facilities in the United States. For example, the non-profit Alberta Recycling Management Authority collected around 1 900 solar panels during a pilot project begun in 2020, during which around 1 200 were transported to Ohio, United States for recycling (Ma, 2023; SPI, 2021b). In Kenya, a substantial number of the solar panels collected are reportedly shipped to the Middle East for further processing (Munro *et al.*, 2022).

Under the EPR framework, producer responsibility organisations can fulfil responsibilities on behalf of solar PV producers. Such organisations have been established to promote sustainable practices. In the European Union, producer responsibility organisations (*e.g.* PV CYCLE) have been established to offer EPR-compliance services, including the organisation of collection, treatment and recycling of end-of-life solar PV panels. In South Africa, producer responsibility organisations have also been established to help companies comply with EPR obligations (South Africa, 2020). In Japan, the PV Reborn Association was established in 2022, comprising approximately 120 member businesses and individuals dedicated to solar panel recycling and renewable research. It aims to recycle all materials from end-of-life panels to produce new solar panels and bring the products to market by 2028 (Ozawa, 2023).

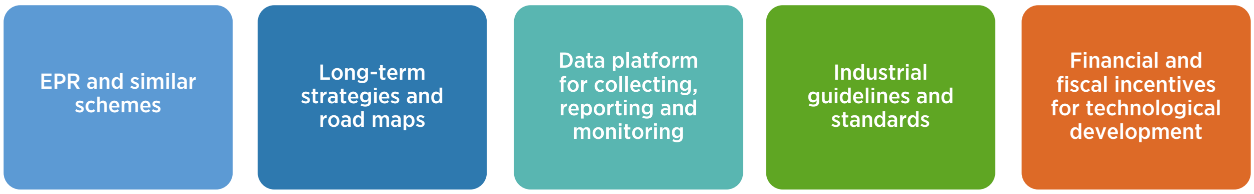
Industrial associations can establish voluntary programmes and complement them with government policies. In China, the Photovoltaics Committee of China Green Supply Chain Alliance (China ECOPV Alliance) was established in 2020. This platform brings together over 150 solar PV manufacturers, developers and institutes, including industry leaders such as Jinko Solar, Trina Solar, the State Power Investment Corporation and the Chinese Academy of Sciences. The alliance primarily focuses on organising events related to the solar PV recycling industry and facilitating information exchange among its members (ECOPV, 2020). Another national association, China National Resources Recycling Association has a dedicated team (Committee for Wind and Solar Equipment Recycling, CRRA-CWSER) for promoting a circular economy for wind and solar. Such national and regional-level industrial associations have unique roles in disseminating best practices and sharing existing experience.

Various stakeholders have positive roles to play in promoting circular economy practices in the solar PV industry and further ensuring the realisation of socio-economic benefits. Collaborating with governments and industrial players, civil society organisations (CSOs), NGOs, think tanks, universities and institutes can be involved in knowledge generation and technical support for communities and developing markets. Financial institutions and investors can enable sustainable finance practices. International collaboration is key to driving technology innovation. For example, a solar PV manufacturer from the Republic of Korea, Qcells, has partnered with a US-based solar panel recycler to recycle all of its products in the US market (SOLARCYCLE, 2024).

5.3 POLICIES AND MEASURES FOR ENABLING SUSTAINABLE PRACTICES

To enable the circular economy for end-of-life solar PV panels, policies and measures are needed to incentivise sustainable practices and scale up innovative business models (see Figure 35). They can inform industries, enable the market, address persistent barriers, minimise negative social and environmental impacts, and ensure a just and inclusive transition. Clearly defined strategies and targets are essential to guide appropriate investments in technology and infrastructure development, which may take decades to reach the necessary level of maturity. While many technologies are not yet commercialised or profitable, mandates and regulations are urgently needed to level the playing field and secure a healthy and sustainable market.

Figure 35 Examples of policy tools and measures for promoting the circular economy for solar PV panels

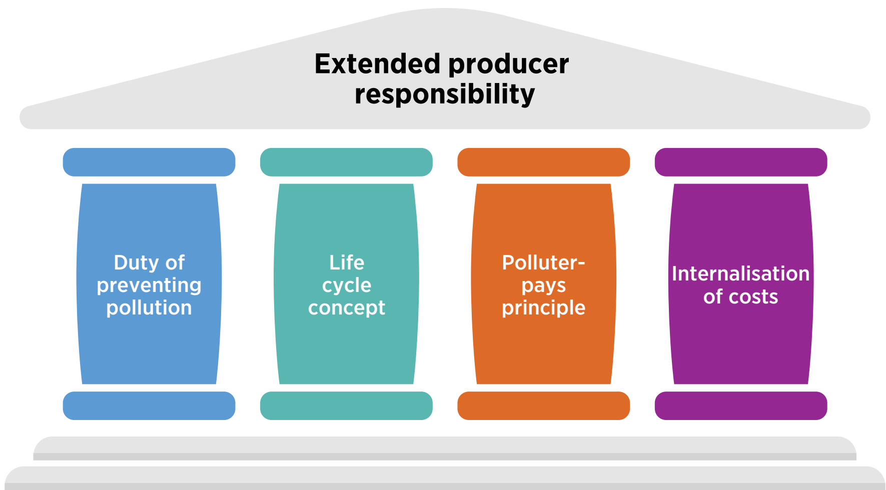


Note: Examples in this figure are not intended to include all existing policies.

EPR and similar schemes

EPR is the most common policy tool for enabling the circular economy for e-waste management, including solar PV panels (ITU *et al.*, 2024). EPR is an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of its life cycle (see Figure 36). This specially designed environmental policy approach shifts the burden of managing certain end-of-life products from municipalities and taxpayers to producers who place them on the market. Beyond the end-of-life management stage, EPR also has the capacity to stimulate greater producer engagement in the overall redesign of products, with the ultimate aim of reducing waste and mitigating environmental and health impacts (UNEP, 2024c).

Figure 36 Key pillars of the EPR scheme



Source: (UNEP, 2024c).

EPR has been adopted and implemented by many markets for end-of-life management of solar PV panels. The European Union has included solar PV for the EPR scheme since 2012 (IRENA *et al.*, 2016). In the United States, EPR has been adopted by several state-level programmes, such as Washington State's PV module Stewardship and Takeback Program, to regulate end-of-life solar PV management (Gangwar *et al.*, 2025). Other countries, such as India, the Republic of Korea, Singapore and South Africa, have adopted the same policy direction based on the EPR scheme.

According to the experience of the European Union, EPR can comprise several key components for effective implementation. These include establishing clear legal definitions for the waste of regulated and hazardous components, enforcing producers' responsibility to finance end-of-life management and relevant implementation, setting mandatory requirements for standardised waste treatment facilities, prohibiting landfilling and open dumping, as well as establishing a national monitoring system for data collection, reporting and tracking (European Union, 2012; IRENA and IEA-PVPS, 2016; SolarPower Europe, 2024).

Financial responsibility for the collection, transport and treatment of end-of-life solar panels is a key component of EPR and similar policies. Specific players in the solar PV segment need to cover the costs of collection and takeback of decommissioned panels. In the European Union, solar panel producers (manufacturers or importers) bear the costs of collecting and transporting decommissioned panels from the site to recycling or treatment facilities. In Japan, end-of-life solar panels are regulated under the general waste management framework. Since 2022, under the feed-in tariff (FIT) scheme, PV system and plant owners (excluding residential projects under 10 kW) have been required to set aside money as a decommissioning reserve fund to cover related costs (IEA-PVPS, 2022). In China, end-of-life solar PV panels are managed as industrial waste, and solar PV plant owners are responsible for managing the waste. A policy announced by the national government in August 2023 also stated that owners of utility-scale solar PV plants must take responsibility for the treatment of decommissioned panels (NDRC *et al.*, 2023).

In India, the EPR policy involves three key stakeholders: manufacturers and producers, recyclers, and a public organisation, CPCB. In 2022, the Ministry of Environment, Forest and Climate Change of India updated the national e-waste management rules to include solar PV waste. According to its national policy, solar PV manufacturers and producers are required to register on a designated portal, store PV waste, submit annual reports online, maintain a PV inventory, and adhere to standard operating procedures and guidelines (MoEFCC, 2022). Recyclers are required to recover materials in accordance with the rules, and the CPCB is responsible for developing an online system to support policy implementation and for establishing guidelines for PV waste storage and recycling requirements.

The Republic of Korea began implementing an updated EPR policy in early 2023 that includes end-of-life solar PV. The policy mandates solar panel manufacturers and importers to achieve the annual recycling target published by the government every year. The targets for solar panels are calculated and published separately from those for general e-waste. In 2026, 2 382 t of the total amount of solar PV panels are targeted to be recycled under this policy (MCEE, 2026a). Producers are required to provide funding for the needed infrastructure, as well as collection and treatment services. Fees are charged based on the weight of the solar panels, around KRW 1 200/kg (Republic of Korea won; USD 1/kg) .

In South Africa, the national EPR regulation began to cover solar panels in May 2021. The policy allows producers to establish non-profit "producer responsibility organisations" to fulfil their EPR responsibilities. These organisations handle EPR fees; register members; conduct audits; upload information; and collect, record, and submit data to the South African Waste Information System, known as SAWIS (Adetuyi *et al.*, 2022). Similarly, in 2022, Kenya incorporated EPR into its national Sustainable Waste Management Act, with specified measures and responsibilities for end-of-life management of solar panels (ACE TAF *et al.*, 2021; Lighting Global/ESMAP *et al.*, 2022).

In 2021, Singapore unveiled its national e-waste management system, with solar PV panels covered. This EPR-based framework requires all producers supplying solar panel products exceeding a specified threshold to consumers to participate in and fund the EPR scheme. The national environmental agency has licensed four producer responsibility scheme operators, including ALBA E-waste Smart Recycling, a German company, to oversee the collection and proper treatment of solar panels on the behalf of producers. Additionally, certain retailers of a specific scale are obligated to establish in-store collection services. Producers are also required to offer free takeback services to customers, including picking up old products on the delivery of new ones, irrespective of the brand or purchase location (MSE, 2022; NEA, 2021).

Similar to EPR, banning solar PV from landfills is another mandatory policy that can be used for enabling circular economy practices. In Australia, several governments have adopted bans on solar panels in landfills. For instance, Victoria State, Australia, banned all e-waste from landfills in July 2019, and Queensland, Australia, implemented a similar ban in 2023 (WA Government, 2025). South Africa banned e-waste from landfills in 2021. Through these landfill bans, options for collection, treatment, recycling and repair need to be provided to consumers and industries. The capacity for these services must be established, although policy enforcement or implementation may take months or even years.

Long-term strategies and road maps

Strategies and action plans play a crucial role in aligning the efforts of policy makers and stakeholders at various levels. They can guide business investments and boost market confidence by sending clear signals.

In March 2022, the US Department of Energy announced an action plan aiming to facilitate the safe and responsible handling of end-of-life materials from solar PV panels. It focuses on outreach activities with stakeholders, data collection, research and analysis. It also seeks to support research on hardware to reduce environmental impacts and reduce half of the module recycling costs by 2030 (US DOE, 2022).

In China, the state government unveiled strategies for circular economy practices in solar PV and other renewable technologies in 2023. This strategy prioritises technology advancements in the recycling of decommissioned solar PV panels, the establishment of industrial standards, and outlines a timeline for policies to regulate collection responsibilities (NDRC *et al.*, 2023). This strategy has been seen as a key enabler of the renewable recycling market in China. More action plans and dedicated policies are expected in the coming years to provide detailed guidance and incentives.

To ensure effectiveness, strategies and road maps need to consider the local context and capacity to identify the most suitable measures. For example, in Australia, the majority of solar panels are installed on residential rooftops, which may affect service time and collection factors (Thou, 2024). Such conditions require producer responsibility organisations to design proper business solutions. Strategies and targets may also be complemented by additional financial support for technology or value chain development to increase feasibility and drive market momentum.

Data platform for collecting, reporting and monitoring

A harmonised data and information platform can provide the information necessary for industrial stakeholders to fulfil their responsibilities and transform them into action. Currently, a lack of information is a major barrier to circular economy practices. The necessary data and information include the components and materials used for solar panel products, the location and owner of solar PV projects that are expected to reach their end-of-service life, available producer responsibility organisations, circularity-aligned treatment facilities and their locations, and other information related to the circular economy of solar PV. These data and information are usually needed from different industrial stakeholders, such as PV manufacturers, plant developers and operators, recyclers, and industrial associations. In most cases, solar panel owners or installers do not know where the solar panels can be treated in line with circular economy principles, even though solar recycling facilities are available in several countries (Nain and Kumar, 2023). In Western Australia, a study found a shortage of information on when solar PV systems will reach end-of-life status (Shrestha and Zaman, 2024).

Creating an accessible database for both upstream and downstream stakeholders is essential. Such a database would allow reuse and recycling companies to access information about PV plants that are either planned for decommissioning or approaching it. Companies can gather details on the location, timing, quantity and technical specifications of PV panels slated for collection. Stakeholders can also obtain information on associated costs and discover suppliers offering relevant technologies or services.

This data platform should include: 1) product information, material composition, risk factors (*e.g.* lead content, fluorinated layers), dismantlability and maintenance manuals; 2) asset and life cycle information, including installation date, capacity, geographic location, owner, failure or retirement reason, and projected decommissioning timeline; and 3) flow and performance information, covering collected volumes and end destinations (reuse, refurbishment, recycling, disposal), qualifications of processing facilities, recovery rates, pollution control metrics, and compliance records. This information can be integrated into a digital product passport to ensure traceability (Bern University of Applied Sciences, 2025; CISL *et al.*, 2025). In the United States, experts at Arizona State University are developing a similar digital tool based on quick-response (QR) codes and radio frequency identification (RFID) tags. The tool aims to help establish standardised information to assist recyclers in tracking and treating end-of-life solar panels (Triolo, 2024).

In the Republic of Korea, an online waste disposal verification system was implemented in 2022 to monitor and manage all waste-related processes and data, including end-of-life solar PV. This system, involving national and local environmental government departments and agencies, utilises RFID to cover and monitor most of the waste generated in the Republic of Korea. Annual analyses based on statistics from this platform provide valuable insights to the government for its policy making (K-eco, 2024; Lee *et al.*, 2023; OECD, 2017). In Japan, the Japan Photovoltaic Energy Association hosts and regularly updates a list of companies that can provide services for the removal and disposal of PV panels (JPEA, 2022). South Africa's EPR requires all producers and producer responsibility organisations to register with the SAWIC platform, which aims to ensure compliance with waste management regulations and facilitates the monitoring of waste-related activities (DFFE, 2021; SAWIC, 2026).

Industrial guidelines and standards

Clearly defined standards and guidelines for end-of-life solar PV products are necessary to guide industry players (SolarPower Europe, 2024). For example, an internationally standardised practice for the use of toxic materials in module components is urgently needed. In the context of solar panel repair and reuse, standards are needed regarding performance, safety and lifetime that second-hand components or products must meet before they are allowed to go to market. Those standards would be a significant enabler for a second-hand solar PV market (Chhillar *et al.*, 2025). In the recycling stage, solar panel recyclers would benefit from handling standards for different processes and for the emission of gases, wastewater, or solid waste.

In the European Union, SolarPower Europe, an industrial association, released guidelines for end-of-life management of solar PV in 2024. The guidelines analyse the regional legal framework and provide examples of and recommendations for enhancing the circularity of solar PV within the European Union (see Figure 37) (SolarPower Europe, 2024).

Figure 37 Industrial guidelines and key steps for end-of-life solar PV in the European Union

Activities	Agreement on service/ offer and contract	Selection of waste operator	Dismounting and storage on-site	Collection and transportation	Disposal and recycling	Managment of EoL documentation
Stakeholders involved	O&M service provider and plant owner	O&M service provider and plant owner	O&M service provider	Waste operator	Waste operator	O&M service provider, waste operator and local authorities
Documentation exchange	• Service contract • Declaration by PV plant owner that decommissioned components are waste	• Acceptance order from C&M service provider or PV plant owner • Invoice issued by the PV waste operator	• SN number list	• Shipment order • H&SA clearance	• Transfer of ownership	• Certificate or proper disposal

Source: (SolarPower Europe, 2024).
Note: EoL = end-of-life; H&SA = health and safety authority; O&M = operation and maintenance; SN = serial number.

In China, the China Photovoltaic Industry Association, which represents over 95% of China's manufacturing capacity in silicon wafers, panels and backsheet, has established a dedicated working group focused on PV module recycling. It has issued several industrial standards and guidelines for the recycling and reuse of c-Si solar PV panels since 2017 (CPIA, 2017). In India, the Ministry of New and Renewable Energy and CPCB are developing guidelines to guide solar PV recycling standards and procedures for local industrial stakeholders. In Japan, the Agency for Natural Resources and Energy, a public agency, released guidelines on business planning for the solar industry that cover proper dismantling and treatment of PV panels, including reuse and recycling. The guidelines have been updated annually since 2017 (METI, 2026).

In the Republic of Korea, the Ministry of Industry, Trade and Energy approved a solar panel recycling programme. This programme aims to establish a standardised collection system in major regions, seeking to recycle or reuse over 80% of end-of-life solar panels. It also plans to introduce a certification under the framework in the near future (MCEE, 2026b). In emerging and developing markets, the global association for off-grid solar industry, GOGLA, has also developed guidelines and standards, such as an e-waste toolkit and circularity blueprints. It aims to provide standardised guidance and tools to companies for the sustainable end-of-life management of off-grid solar PV products in developing countries.

Quality assurance is one of the potential tools that can be adapted to assist in creating a sustainable solar panel market. Quality assurance is relevant to three factors, including quality standards, operating facilities and technicians, and the cost of testing and/or certification for the used solar panels. For example, a certification scheme called VeraSol has been supported by the World Bank and operated by CLASP since 2020. This scheme provides services, such as testing, certification, quality standards and product data sharing. It has been adopted by an increasing number of developing countries (Verasol, n.d.).

Box 5 Quality infrastructure and the reuse of solar panels

The reuse and sale of repaired solar PV panels are integral components of the circular economy for solar PV. However, the lack of market confidence poses a significant obstacle to the creation of a second-hand solar PV market. Currently, there is not yet a globally standardised process for testing second-hand (reused, refurbished) solar PV panels, leading to inadequate quality checks of their functionality and safety.

The establishment of quality infrastructure can play a pivotal role in benefiting solar PV systems by reducing risks and enhancing market confidence. This is particularly crucial for the reuse of repaired or refurbished solar PV panels. Quality infrastructure in the context of solar PV entails a mechanism that ensures the quality of solar PV products and services, thereby mitigating technical risks and establishing market trust. Implementing this mechanism necessitates the development of quality infrastructure as the initial step.

At the national level, a comprehensive quality infrastructure typically encompasses standards (defining methods and specifications), certification (ensuring compliance with standards), testing processes (verifying conformity through testing), accreditation (evaluating conformity-assessment bodies), inspection (ensuring conformance with requirements), metrology (determining conformance through measurement), and market surveillance (monitoring market status). While quality assurance measures may incur short-term costs and effort, the long-term benefits, including reduced costs enabled by quality infrastructure services, outweigh the initial development and implementation costs.

Source: (IRENA, 2017).

Financial and fiscal incentives for technology development

Financial and fiscal incentives provided by governments are key to fostering technology development and research in the early development stage. In the solar PV industry, business-driven technology initiatives usually focus on enhancing the durability and energy efficiency of solar panels. These initiatives may not prioritise circularity in product design. Further, the limited scale of reuse and recycling of end-of-life solar PV panels indicates a scenario of high upfront investments and low economic returns. Technologies for circularity-aligned treatment and recycling remain at an early stage of development and need further support to enable their commercialisation and scale-up. Financial and fiscal incentives can provide additional support to accelerate the development of technologies and business models.

In 2023, the European Union and Switzerland allocated approximately EUR 18 million (USD 20.5 million) to support a three-year project, PILATUS. This project aims to foster technology innovations developed and owned by the European Union, while also establishing a solar PV supply chain in this region. One of the primary objectives of the project is to promote eco-designed, high-circularity solar PV technology. This includes incorporating bio-sourced and recycled encapsulant layers, reducing the use of silver, enhancing the panels' durability for a longer (more than 40-year) lifetime, and increasing their power production capacity (PILATUS, 2024).

In 2023, the US government allocated USD 9.8 million to eight projects focused on reducing costs and increasing the efficiency of panel recycling processes (US DOE, 2023a). An additional USD 20 million was added to support reducing material use in solar energy systems. This funding aims to enhance installation quality, improve the resilience of PV systems, and streamline the reuse and recyclability of solar panels. For instance, a US-based PV recycling centre received a USD 1.5 million research grant from the Department of Energy to develop processes for recovering higher-quality metals and materials from end-of-life solar panels (US DOE, 2023b). It also aims to set up an industrial partnership with the purpose of promoting the development of circular economy technologies for solar panels. However, these funds were awarded before 2025, under a previous administration, and the current status of these funds is unclear.

In 2023, the Australian government announced funding of AUD 11 million (USD 7.6 million) to an Australian solar technology company. This company had developed a solar cell metallisation technology that utilises copper instead of silver in manufacturing. The government funding aims to support the company in scaling up its production line to manufacture copper-metallised solar panels for approximately 15 000 household solar systems each year (DCCEEW, 2023).

In China, the Ministry of Finance and other entities released the 2021 national Catalogue of Income Tax Preferences for Enterprises Comprehensive Utilisation of Resources, which includes tax benefits for eligible PV recycling companies (MOF *et al.*, 2021). In 2024, the National Development and Reform Commission issued a funding programme to support energy transition and climate actions, which includes solar PV module recycling and utilisation projects. Projects for solar PV recycling and related technological development are eligible to receive funding of up to 15% of the total project investment (NDRC, 2024).

Government funds and grants may be provided to promote innovation from the laboratory stage to pilot plant implementation. In 2022, the Australian government allocated a fund of AUD 10 million (USD 7.1 million) to reduce the landfilling of solar panels and batteries. This funding included AUD 1 million (USD 0.7 million) for the University of New South Wales, with the aim of developing a highly efficient, mobile and flexible solar panel recycling technology to recover metals, glass and silicon. The expected outcomes include lab-scale prototypes capable of recycling 95% of silver, copper, silicon and glass, with energy consumption of less than 30 kWh for recycling each kW of solar panels (NSW EPA, 2023).

Decent jobs for solar PV recycling and reusing

Circular economy strategies, such as reducing, reusing and recycling, have the potential to deliver social and economic benefits, including the creation of new employment opportunities (Heath *et al.*, 2022). In France, a producer responsibility organisation called Soren announced a tendering process in 2022. It shows that a waste treatment plant can employ 25 staff members and process 4 000 t of end-of-life PV panels annually (Deboutte, 2022). In Europe, with proper workforce training, it is estimated that the reuse of e-waste could generate 60 to 140 jobs per 1 000 t of materials collected (RREUSE, 2021).

The involvement of the informal economy in circular economy practices for solar PV is also noteworthy. The International Labour Organization's (ILO's) analysis indicates that circular economy practices, including waste collection, repair, reuse and recycling, largely operate in the informal economy for developing markets (ILO *et al.*, 2023). In Nigeria, the ILO estimates that over 100 000 people work in the informal sector for e-waste collection and treatment. In India, a study suggests that 76% of end-of-life solar PV panels are not recycled in a regulated and formal manner, and the waste is often passed on to the informal sector. Formalising and involving the informal sector in managing end-of-life PV module materials could effectively leverage the sector's capabilities for waste collection and recycling, leading to various social benefits and an improved quality of life for informal workers (Tyagi *et al.*, 2021). Meanwhile, it is crucial to consider potential impacts on human health, especially in informal waste collection and treatment practices in developing countries, within the policy framework for circular economy practices for solar PV.

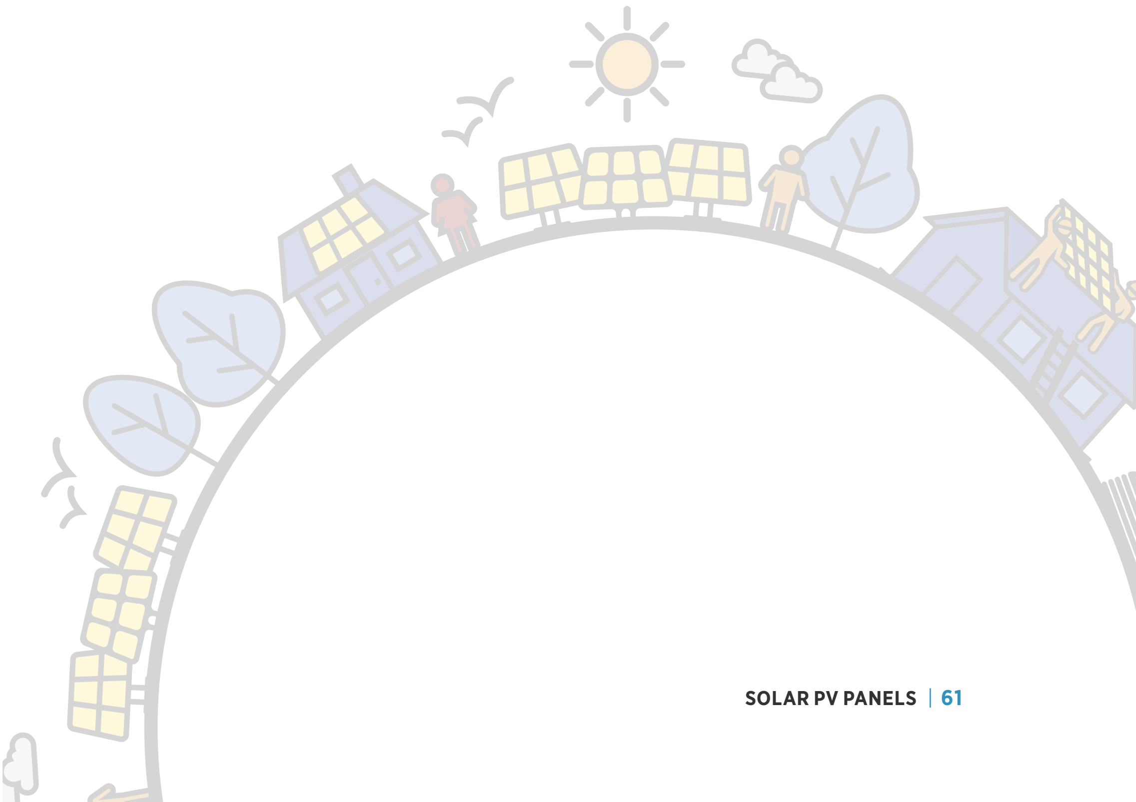
A just and inclusive framework for the circular economy in solar PV should include labour policies, safety standards and environmental protection measures to ensure workers' health and safety. In addition to infrastructure, regulations, incentives, policies and processes, and specialised equipment and procedures can help mitigate risks. Information campaigns can raise awareness among workers about the hazards they face. Learning and training tools and methodologies designed for e-waste workers can be adapted for workers in the PV sector, including those in the informal economy (Goel and ILO, 2019).

Enhanced awareness of circular economy approaches and solutions

In many cases, awareness regarding the management of end-of-life solar panels and their potential environmental, biodiversity and public health impacts may be lacking among policy makers, industry stakeholders and solar power system owners. Policy makers may not be fully aware of the current and future challenges posed by end-of-life solar panels, nor of the potential solutions and policy measures needed to address them. Additionally, the public may hold misconceptions about the safety and performance of second-hand solar panels and therefore lack confidence in the market. Public awareness activities, such as training sessions and public campaigns, may be necessary to educate the general public and targeted groups (Vijayakumar Nair *et al.*, 2024).

The limited presence of end-of-life solar panels in most markets can lead to insufficient awareness of the importance and urgency of addressing this issue. An example from Queensland, Australia, highlights this awareness gap. End-of-life solar PV and battery systems only accounted for less than 1% of reported e-waste by weight in the past. However, half of the electronic products (by weight) entering the state currently are solar PV and battery storage equipment, totalling around 114 000 t (DES, 2023). The dominance of solar PV and related equipment indicates its significant share in future e-waste streams.

A lack of consumer and manufacturer awareness of circular economy principles for solar PV remains one of the barriers to the mainstreaming of circular economy practices. A survey covering over 300 customers and manufacturers from China, Europe, India and the United States revealed that while over half of the survey respondents had considered selling used panels, over 80% had never considered the fate of end-of-life solar panels (Nain *et al.*, 2023). To address this barrier, some countries have announced programmes to improve public awareness. In South Africa, the government has launched public campaigns as initial steps to raise public awareness and ease implementation. This approach is seen as crucial for the effective implementation of policies in both developed and developing markets.



CHAPTER 6

THE WAY FORWARD

Understanding the urgency and adopting contextualised solutions

The transition to renewable energy has emerged as a crucial pillar in combating climate change and fostering socio-economic advancement, with solar PV playing a central role. The management of end-of-life solar panels, aligned with the Paris climate targets, anticipates a cumulative volume of over 200 Mt by 2050. This projected volume has raised concerns about how these panels should be handled and the potential costs and benefits of doing so.

The first wave of end-of-life solar PV panels is coming in the near future, and governments need to prepare by developing and implementing appropriate policies for their management. However, each country must identify the most suitable policies and measures for its market based on a clear assessment of its context, institutional capabilities and financial resources. For instance, EPR and similar policies are increasingly adopted by markets with extensive solar PV deployment, including Australia, Canada, China, the European Union, India, Japan, the Republic of Korea, South Africa and the United States. Financial support for technology development and recycling process innovations remains the focus for regions and countries that intend to take advantage of local value chains. For many developing markets, properly addressing the issues related to unregulated recycling and informal recyclers may be the most complex topic to address.

Policy designs vary among these markets. For example, financial responsibility for collection and treatment is a key aspect of end-of-life solar PV policies. While the European Union and South Africa require PV manufacturers and producers to assume this responsibility, Japan earmarks funds from its FIT scheme for the same purpose. In China, the responsibility is allocated to solar power plant owners, reflecting the country's economic structure. However, EPR and similar policies underscore the importance of digital-based reporting and data collection portals to ensure consistent recordkeeping by industry players.

An urgently needed step is creating demand from the solar PV industry and manufacturers for recovered materials and components. While research and technology development are progressing, the largest bottleneck might be the reality that the industry has no motivation to buy recycled or reusable products, even when they are tested and properly certified. Newer solar PV technologies will likely offer better economic returns for investors. Creating market demand through public procurement, mandates or industrial initiatives is an important step to set the cornerstone of such a market.

In the least-developed countries, such as those in Sub-Saharan Africa, solar panels mainly serve off-grid solar appliances, with reuse as the dominant principle. However, these countries face challenges due to a lack of financial and training support for local value chains and technicians. Investment has a central role to play in the development of a circular economy value chain in developing markets. For least-developed markets and in the off-grid solar context, international development funding can provide additional support for local stakeholders and circular economy business practitioners. It can also enhance their capacity before their business model becomes profitable and self-sustaining.

Adopting a holistic policy framework based on regulations and guidelines

Essentially, there is an urgent need for a comprehensive policy framework to guide the management of end-of-life solar panels and promote circular economy practices. This framework should inform policy makers, advocate for circular economy principles, and ensure the sustainable development of the solar PV component reuse and recycling market.

A robust circular economy framework for solar PV should encompass regulations that divert end-of-life solar panels away from landfills and towards circular economy practices, while also enhancing the economic viability of these practices. While EPR has received the majority of attention as the main policy tool to promote a circular economy for e-waste management, a mix of targets, strategies, regulations and guidelines can bridge the policy gaps and complement existing environmental regulations or e-waste frameworks. Where policies are not in place, industrial guidelines and voluntary initiatives can always play a proactive role in fostering sustainable practices.

National strategies and long-term targets are essential policy measures that provide clear signals to institutions, investors and industry stakeholders. Aligning these stakeholders' efforts can effectively address significant barriers. Once policy signals are established, markets for the reuse of second-hand panels and their components, as well as recycling markets, need to be enabled. This can be achieved by providing information and data related to products within these markets; sharing standards and guidelines to assist recyclers, technicians, producers and manufacturers; engaging key industrial players to participate in recycling and reuse activities and promoting their profitability; and mandating policies to ensure the sustainability of the market.

Establishing a circular economy framework for end-of-life solar PV should be just and inclusive. Governments should adopt measures to secure occupational health and safety, skills training, and regulatory governance to prevent externalised pollution and health risks from being shifted onto vulnerable groups, ensuring a safe and equitable transition in PV recycling practices. Meanwhile, the transition process should integrate with prudent consideration for communities that rely on the informal collection and recycling of e-waste, particularly in developing markets.

Intensified geopolitical dynamics and discussions on critical minerals have further made the policy making for end-of-life solar PV panels more complex in some markets. While it is sensible for countries to take necessary measures for improved resilience and maximised domestic benefits, international collaboration should always be prioritised to support the transitioning of developing markets. Collaboration is the most effective way to address existing barriers that impede the establishment of infrastructure.

Maximising benefits to developing markets

In the near and medium term, some developing and least-developed countries may lack the necessary financial capacity to purchase new solar PV panels and instead begin to rely on second-hand PV panels received through donations, trade or illegal transportation. These second-hand solar PV panels may be the only affordable option for developing communities to access renewable electricity. These refurbished PV panels have the potential to bring numerous benefits to populations in Sub-Saharan Africa, Central Asia, Southern Asia and Southeastern Asia (IEA *et al.*, 2023).

However, additional measures are required to ensure equity when second-hand products are transported from developed markets to developing countries, a practice that is often linked with a potential risk of e-waste dumping. International agreements and collaborations between developed and developing countries could potentially prevent improper exports of PV panels that may bring unwanted negative impacts due to limited financial or institutional capacity.

In developing markets, such as Sub-Saharan Africa and developing Asia, off-grid solar appliances account for a large segment of the market. The end-of-life management of solar PV panels in these markets may follow a different process because, due to financial considerations, most defective second-hand off-grid solar appliances are repaired and reused by households. In this context, additional financial investment and technical support are necessary to establish local value chains and train more technicians. Small-scale businesses and innovative business models for the solar PV circular economy may further provide industrial development opportunities for developing markets. Stakeholders such as NGOs, institutes and universities can also share knowledge, expertise and best practices globally to address these technical, economic and regulatory challenges.

REFERENCES

Aboagye, B., *et al.* (2021), "Degradation analysis of installed solar photovoltaic (PV) modules under outdoor conditions in Ghana", *Energy Reports*, vol. 7, pp. 6921–31, https://doi.org/https://doi.org/10.1016/j.egyr.2021.10.046

ACE TAF and NESREA (2021), *E-Waste Guide for Stand-Alone Solar in Nigeria*, Africa Clean Energy Technical Assistance Facility and National Environmental Standards and Regulations Enforcement Agency of Nigeria, www.ace-taf.org/kb/e-waste-guide-for-stand-alone-solar-in-nigeria

Adetuyi, A., and Williams, N. (2022), "E-waste management in Africa: Overview and policy", illuminem, https://illuminem.com/illuminemvoices/e-waste-management-in-africa-overview-and-policy (accessed 23 April 2026).

Ali, A., Islam, M. T., *et al.* (2024), "Solar Photovoltaic Module End-of-Life Waste Management Regulations: International Practices and Implications for the Kingdom of Saudi Arabia", *Sustainability*, vol. 16/16, https://doi.org/10.3390/su16167215

Ali, A., Shahid, M., *et al.* (2024), "Solar PV End-of-Life Waste Recycling: An Assessment of Mechanical Recycling Methods and Proposed Hybrid Laser and High Voltage Pulse Crushing Method", *Resources*, vol. 13/12, https://doi.org/10.3390/resources13120169

Amorim, C. (2025), "The challenge of the end of life of solar modules.", Canal Solar, https://canalsolar.com.br/en/End-of-life-recycling-of-solar-modules (accessed 19 May 2026).

An, M., and Sun, X. (2024), "Carbon footprints of solar panels in China provinces based on different production and waste treatment scenarios", *Journal of Cleaner Production*, vol. 435, pp. 140453, https://doi.org/10.1016/j.jclepro.2023.140453

Atia, D. M., *et al.* (2023), "Degradation and energy performance evaluation of mono-crystalline photovoltaic modules in Egypt", *Scientific Reports*, vol. 13/1, pp. 13066, https://doi.org/10.1038/s41598-023-40168-8

Basnet, R., *et al.* (2025), "Advancing circular economy of silicon Photovoltaics: Current status and challenges of PV module reuse", *Solar Energy Materials and Solar Cells*, vol. 292, pp. 113816, https://doi.org/https://doi.org/10.1016/j.solmat.2025.113816

Baumgurtel, M., and Merwe, A. van der (2024), "Australia's solar panel recycling challenge and market outlook", Hamilton Locke, https://hamiltonlocke.com.au/australias-solar-panel-recycling-challenge-and-market-outlook (accessed 29 June 2026).

E. Bellini (2026), "Extensive testing validates reuse of 23-year-old second-life polycrystalline solar modules", pv magazine International, www.pv-magazine.com/2026/03/31/extensive-testing-validates-reuse-of-23-year-old-second-life-polycrystalline-solar-modules (accessed 30 April 2026).

Bern University of Applied Sciences (2025), "European initiative launches digital product passport prototype for PV", pv magazine International, www.pv-magazine.com/2025/06/03/european-initiative-introduces-digital-product-passport-prototype-for-pv-industry (accessed 30 April 2026).

A. Bhambhani (2025), "China dominates 2024 global polysilicon production", TaiyangNews, https://taiyangnews.info/business/china-dominates-2024-global-polysilicon-production (accessed 16 February 2026).

Bilbao, J., *et al.* (2021), *PV Module Design for Recycling Guidelines*, International Energy Agency (IEA) PVPS Task 12, Paris, https://doi.org/10.2172/1832877

Bloch, M. (2022), "Unwanted Australian solar panels powering communities in Africa", SolarQuotes Blog, www.solarquotes.com.au/blog/australia-panels-africa-mb2600 (accessed 21 May 2026).

Calero, M., *et al.* (2026), "Recycling end-of-life solar panels: A comparative study of thermal and solvent delamination techniques", *Solar Energy Materials and Solar Cells*, vol. 295, pp. 113990, https://doi.org/https://doi.org/10.1016/j.solmat.2025.113990

Chhillar, I., *et al.* (2025), "Certification for Solar Panel Reuse: A Systematic Review of Cross-Sector Practices and Gaps", *Sustainability*, vol. 17/13, https://doi.org/10.3390/su17135995

Chunduri, S. K., and Schmela, M. (2025), *Market Survey Backsheets & Encapsulation 2024-2025*, TaiyangNews, https://images.assettype.com/taiyangnews/2025-03-19/oz2uamdo/TaiyangNews_Backsheets_2025_V14.pdf

CISL, *et al.* (2025), *Circular Solar: The Opportunities for Increased Circularity in the Solar PV Industry*, University of Cambridge Institute for Sustainability Leadership, www.cisl.cam.ac.uk/files/cisl_-_circular_solar_report_2025.pdf

CPCB (2026), *Guidelines for Storage and Handling of Waste Solar Photo-Voltaic Modules or Panels or Cells under E-Waste (Management) Rules, 2022*, Central Pollution Control Board, https://eprewaste.cpcb.gov.in/assets/PDF/Guidlines%20for%20Storage%20and%20Handling%20of%20Waste%20Solar%20Photo-Voltaic%20Modules%20or%20Panels%20or%20Cell%20(Under%20E-Waste%20(Management)Rules,%202022_0001_compressed.pdf

CPIA (2017), "General Technical Requirements for Crystalline Silicon Photovoltaic Module Recovery (晶体硅光伏组件回收再利用通用技术要求)", China Photovoltaic Industry Association, www.chinapv.org.cn/Uploads/File/2019/09/13/u5d7b125db1129.pdf

CPIA (2024), "Current cost analysis of mainstream photovoltaic products, December 2024 (光伏主流产品当前成本分析, 2024年12月)", China Photovoltaic Industry Association,www.chinapv.org.cn/Association/content_1520.html (accessed 18 February 2026).

CRRA (2026), "CRRA Data", Committee for Wind and Solar Equipment Recycling, China National Resources Recycling Association, Beijing.

Curtis, T., *et al.* (2021), *A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations*, National Renewable Energy Laboratory, Golden, CO, https://doi.org/10.2172/1774574

DCCEEW (2023), "ARENA supports homegrown low-cost solar with funding for SunDrive", Government of Australia, Department of Climate Change, Energy, the Environment and Water, www.dcceew.gov.au/about/news/arena-low-cost-sundrive (accessed 21 April 2026).

DCCEEW (2026), "National solar panel recycling pilot", Government of Australia, Department of Climate Change, Energy, the Environment and Water, www.dcceew.gov.au/environment/protection/waste/solar-panels (accessed 16 March 2026).

Deboutte, G. (2022), "French consortium commissions solar module recycling facility", pv magazine International, www.pv-magazine.com/2022/10/03/french-consortium-commissions-solar-module-recycling-facility (accessed 3 January 2023).

DES (2023), *Draft Queensland E-Products Action Plan 2023-2033*, State of Queensland, Department of Environment and Science, https://assets.pc.gov.au/392558/sub267-circular-economy-attachment2.pdf?VersionId=yrCtncz0OU930nwBu59CSDfYCzt_46oH

DFFE (2021), "Extended Producer Responsibility Regulations", Government of South Africa, Department of Forestry, Fisheries and the Environment, https://solarpowerafrica.za.messefrankfurt.com/content/dam/messefrankfurt-southafrica/solar-power-africa/webinars/webinars-2021/27-may-2021/EPR%20Regulations.pdf

Dias, P. (2024), "Should I send my old solar panels abroad? An e-waste expert weighs in", SOLARCYCLE, https://www.solarcycle.us/resources/should-i-send-my-old-solar-panels-abroad (accessed 21 May 2026).

Dum, S., and Chuangchote, S. (2023), "Recovery of Silicon Wafers from End-of-Life Silicon-Based Solar Cells", *IOP Conference Series: Earth and Environmental Science* (Volume 1199, p. 012031), https://doi.org/10.1088/1755-1315/1199/1/012031

ECOPV (2020), "Introduction to the China ECOPV Alliance", http://www.ecopv.org.cn/site/content/590.html (accessed 3 October 2023).

EEP Africa, *et al.* (2020), "Solar e-waste management innovations in Sub-Saharan Africa", EEP Africa, Nordic Development Fund and CLASP, https://afsiasolar.com/wp-content/uploads/2020/06/Solar-e-waste-webinar_final_26052020.pdf

Egyptian Presidency (2018), "'Benban', the largest solar power plant in Aswan", The Arab Republic of Egypt, The Presidency, www.presidency.eg/en/المشاريع-القومية/بنبان-أكبر-محطة-لإنتاج-الطاقة-الشمسية-في-أسوان (accessed 9 February 2026).

Ellen MacArthur Foundation (2021), *Universal Circular Economy Policy Goals*, Ellen MacArthur Foundation, www.ellenmacarthurfoundation.org/universal-policy-goals/overview

Ellen MacArthur Foundation (2022), "An introduction to circular design", www.ellenmacarthurfoundation.org/news/an-introduction-to-circular-design (accessed 2 October 2023).

Ellen MacArthur Foundation (n.d.), "What is the meaning of a circular economy and what are the main principles?", www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview (accessed 18 March 2026).

EPRI (2021), *Solar Photovoltaics: End-of-Life Management*, Electric Power Research Institute, https://powerquality.blog/wp-content/uploads/2021/03/epri-solar-photovoltaics_-end_of_life-management-infographic.pdf

ESMAP (2024), *Off-Grid Solar E-Waste Management Toolkit*, World Bank, Washington, D.C., http://documents.worldbank.org/curated/en/099100924165027587/P17436116fe65e0011b7bb1418188e2e137

Espinosa, N., *et al.* (2026), "Assessing Photovoltaic Recycling Capacities and Policy Gaps in the European Union", Advanced Energy and Sustainability Research, pp. e202500302, https://doi.org/10.1002/aesr.202500302

EUR-Lex (n.d.), "Waste hierarchy", Glossary of summaries, https://eur-lex.europa.eu/EN/legal-content/glossary/waste-hierarchy.html (accessed 29 April 2026).

European Commission (2026a), "Mining waste", https://environment.ec.europa.eu/topics/waste-and-recycling/mining-waste_en (accessed 2 February 2026).

European Commission (2026b), "Ecodesign for Sustainable Products Regulation (ESPR)", https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en (accessed 29 January 2026).

European Union (2012), *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast)*, Official Journal of the European Union, https://eur-lex.europa.eu/eli/dir/2012/19/oj

Eurostat (2025), "Waste electrical and electronic equipment (WEEE) by waste management operations - open scope, 6 product categories (from 2018 onwards) (dataset)", https://doi.org/10.2908/ENV_WASELEEOS (accessed 4 February 2026).

Finn, B. M., *et al.* (2025), "The informal paradox: electronic waste and the toxic circular economy in Ghana", *npj Urban Sustainability*, vol. 5/1, pp. 101, https://doi.org/10.1038/s42949-025-00299-5

Florin, N., *et al.* (2020), *Scoping Study for Solar Panels and Battery System Reuse and Recycling in NSW, Prepared for NSW Department of Planning*, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, www.epa.nsw.gov.au/sites/default/files/isf-solar-pv-and-battery-recycling-report.pdf

Fong, C. (2023), "A circular economy for rectangular solar panels", Business Renewables Centre-Canada, https://businessrenewables.ca/resource/circular-economy-rectangular-solar-panels (accessed 21 April 2026).

Fraunhofer ISE (2025), *Photovoltaics Report*, Fraunhofer ISE, Freiburg, www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Gangwar, P., *et al.* (2025), "Sustainable approaches to solar photovoltaic waste management under environmental uncertainty", *Discover Environment*, vol. 3/1, pp. 227, https://doi.org/10.1007/s44274-025-00440-2

Gebremariam, E. B., and Beall, J. (2022), "Why Integrated Solid Waste Management is so elusive – Learning from Africa and Asia", LSE Cities Working Papers Series, https://research-information.bris.ac.uk/en/publications/why-integrated-solid-waste-management-is-so-elusive-learning-from

GESP (n.d.), "Country and regional sheets", The Global E-waste Statistics Partnership, https://globalewaste.org/country-sheets (accessed 29 January 2026).

Global Energy Monitor (2026), "Global Solar Power Tracker (dataset)", https://globalenergymonitor.org/projects/global-solar-power-tracker (accessed 29 January 2026).

Goel, S. and ILO (2019), *From Waste to Jobs: Decent Work Challenges and Opportunities in the Management of E-Waste in Nigeria*, International Labour Organization, Geneva, https://labordoc.ilo.org/discovery/fulldisplay/alma995218883502676/41ILO_INST:41ILO_V1

GOGLA (2024), *Senegal*, Global Off-Grid Lighting Association, www.gogla.org/wp-content/uploads/2024/11/Senegal-Country-Brief.pdf

Greenpeace and ACEF (2022), *Zero-Waste Future of Renewable Energy: A Study on the Development of Recycling Industry for Wind and Solar Energy* (可再生能源零废未来：风电、光伏回收产业发展研究), Greenpeace and All-China Environment Federation, www.greenpeace.org.cn/wp-content/uploads/2022/07/renewable_zerowaste_2022.pdf

Han, Q., *et al.* (2023), "Hydrometallurgy recovery of copper, aluminum and silver from spent solar panels", *Journal of Environmental Chemical Engineering*, vol. 11/1, pp. 109236, https://doi.org/https://doi.org/10.1016/j.jece.2022.109236

Hansen, U. E., *et al.* (2022), "Managing e-waste from off-grid solar systems in Kenya: Do investors have a role to play?", *Energy for Sustainable Development*, vol. 69, pp. 31–40, https://doi.org/https://doi.org/10.1016/j.esd.2022.05.010

Heath, G. A., *et al.* (2022), "A critical review of the circular economy for lithium-ion batteries and photovoltaic modules – status, challenges, and opportunities", *Journal of the Air & Waste Management Association*, vol. 72/6, pp. 478–539, https://doi.org/10.1080/10962247.2022.2068878

IAI (2026), "Primary aluminium production (dataset)", International Aluminiunm Institute, https://international-aluminium.org/statistics-overview (accessed 12 March 2026).

ICA (2022), "Future sustainability trends in copper demand", International Copper Association, https://internationalcopper.org/resource/future-sustainability-trends-in-copper-demand (accessed 29 June 2026).

IEA (2022), *Special Report on Solar PV Global Supply Chains*, International Energy Agency, Paris, www.iea.org/reports/solar-pv-global-supply-chains

IEA, *et al.* (2023), *Tracking SDG7: The energy progress report 2023*, International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, the World Bank and World Health Organization, Geneva, www.irena.org/Publications/2023/Jun/Tracking-SDG7-2023

IEA (2025), *Global Critical Minerals Outlook 2025*, International Energy Agency, Paris, www.iea.org/reports/global-critical-minerals-outlook-2025

IEA-PVPS (2018), *End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies*, International Energy Agency Photovoltaic Power Systems Programme, https://iea-pvps.org/key-topics/end-of-life-management-of-photovoltaic-panels-trends-in-pv-module-recycling-technologies-by-task-12

IEA-PVPS (2022), *Status of PV Module Recycling in Selected IEA PVPS Task12 Countries*, International Energy Agency Photovoltaic Power Systems Programme, https://iea-pvps.org/key-topics/status-of-pv-module-recycling-in-selected-iea-pvps-task12-countries

IISD (2023), *ASEAN-IGF Minerals Cooperation: Scoping Study on Critical Minerals Supply Chains in ASEAN*, International Institute for Sustainable Development, Winnipeg, https://asean.org/wp-content/uploads/2024/01/ASEAN-IGF-Scoping-Study-on-Critical-Minerals-Supply-Chains-in-ASEAN-final.pdf

ILO, *et al.* (2023), *Decent Work in the Circular Economy: An Overview of the Existing Evidence Base*, International Labour Organization, Circle Economy, and Solutions for Youth Employment, www.ilo.org/publications/decent-work-circular-economy-overview-existing-evidence-base (accessed 21 April 2026).

IRENA (2017), *Boosting solar PV markets: The role of quality infrastructure*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2017/Sep/Boosting-solar-PV-markets-The-role-of-quality-infrastructure

IRENA (2023), *Geopolitics of the energy transition: Critical materials*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jul/Geopolitics-of-the-Energy-Transition-Critical-Materials

IRENA (2024a), *World Energy Transitions Outlook 2024: 1.5°C Pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024

IRENA (2024b), *Solar PV supply chains: Technical and ESG standards for market integration*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Sep/Solar-PV-supply-chains-Technical-and-ESG-standards-for-market-integration (accessed 29 October 2025).

IRENA (2025a), *Renewable power generation costs in 2024*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024

IRENA (2025b), *Renewable energy statistics 2025*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2025/Jul/Renewable-energy-statistics-2025

IRENA (2025c), *Off-grid renewable energy statistics 2025*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2025/Dec/Off-grid-Renewable-Energy-Statistics-2025

IRENA (2025d), *From energy crisis to energy security: Actions for policy makers*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2025/Nov/Sodium-ion-batteries-A-technology-brief

IRENA (2025e), "G20+ Countries Hold the Key to the Global Renewable Target by 2030", www.irena.org/News/pressreleases/2025/Mar/G20-plus-Countries-Hold-the-Key-to-the-Global-Renewable-Target-by-2030 (accessed 3 February 2026).

IRENA (2026a), *Renewable capacity statistics 2026*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2026/Mar/Renewable-capacity-statistics-2026

IRENA (2026b), *Local environmental impacts and benefits of large-scale solar PV plants*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2026/Jan/Local-environmental-effects-and-benefits-of-large-scale-solar-PV-plant

IRENA (2026c), *Solar PV Supply Chain Cost Tool: Methodology, results and analysis*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2026/Feb/Solar-PV-Supply-Chain-Cost-Tool-Methodology-results-and-analysis

IRENA and NUPI (2024), *Constructing a ranking of critical materials for the global energy transition*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Oct/Constructing-a-ranking-of-critical-materials-for-the-global-energy-transition

IRENA and CPI (2025), *Global landscape of energy transition finance 2025*, International Renewable Energy Agency and Climate Policy Initiative, Abu Dhabi, www.irena.org/Publications/2025/Nov/Global-landscape-of-energy-transition-finance-2025

IRENA and IEA-PVPS (2016), *End of Life Management: Solar Photovoltaic Panels*, International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems, www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

IRENA and ILO (2026), *Renewable energy and jobs: Annual review 2025*, International Renewable Energy Agency and International Labour Organization, Abu Dhabi, www.irena.org/Publications/2026/Jan/Renewable-energy-and-jobs-Annual-review-2025

ITU and UNITAR (2024), Global E-waste Monitor 2024, International Telecommunication Union and United Nations Institute for Training and Research, https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2025/d-gen-e_waste.01-2024-pdf-e.pdf

Jakson (2025), "Jakson leads India's shift to circular solar economy with nation's first Hi-Tech PV recycling facility", www.jakson.com/wp-content/uploads/2025/12/15_12_2025_Press-release-Jakson-Engineers-Limited-to-set-up-Indias-First-Full-Scale-Solar-PV-Recycling-Plant.pdf (accessed 16 March 2026).

Jiang, B. (2023), "Where do decommissioned photovoltaic modules go (废旧光伏组件流向何处)", Economic Daily, http://paper.ce.cn/pc/content/202307/02/content_276736.html (accessed 23 February 2024).

Jiji Press (2025), "Used solar panel disposal likely to be big problem in Japan", The Japan News, https://japannews.yomiuri.co.jp/science-nature/environment/20250105-231426 (accessed 5 July 2026).

JPEA (2022), "To those considering the disposal of residential solar power systems [in Japanese]", Japan Photovoltaic Energy Association, www.jpea.gr.jp/house/waste (accessed 23 February 2024).

Kalogirou, S.A. (2017), "McEvoy's Handbook of Photovoltaics", Elsevier, https://doi.org/10.1016/C2015-0-01840-8

Keane, J., *et al.* (2024), *State of Repair in the Off-Grid Solar Sector*, SolarAid, London, https://solar-aid.org/wp-content/uploads/2024/10/State-of-Repair-Off-Grid-Solar-Sector-Oct-2024.-UNSW-SolarAid.pdf

K-eco (2024), "Allbaro System [in Korean]", *Allbaro*, www.allbaro.or.kr/index.jsp (accessed 20 February 2024).

Kinally, C., *et al.* (2022), "Off-grid solar waste in Sub-Saharan Africa: Market dynamics, barriers to sustainability, and circular economy solutions", *Energy for Sustainable Development*, vol. 70, pp. 415–29, https://doi.org/10.1016/j.esd.2022.08.014

Kirchherr, J., *et al.* (2023), "Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions", *Resources, Conservation and Recycling*, vol. 194, pp. 107001, https://doi.org/https://doi.org/10.1016/j.resconrec.2023.107001

Kirchherr, J., *et al.* (2017), "Conceptualizing the circular economy: An analysis of 114 definitions", *Resources, Conservation and Recycling*, vol. 127, pp. 221–32, https://doi.org/10.1016/j.resconrec.2017.09.005

Kwon, S., *et al.* (2025), "Sustainability Impact Evaluation of the Recycling of End-of-Life Crystalline Silicon Solar Photovoltaic Panel Waste in South Korea", *Sustainability*, vol. 17/2, https://doi.org/10.3390/su17020431

Lakshman, S. (2024), "More Critical Minerals Mining Could Strain Water Supplies in Stressed Regions", www.wri.org/insights/critical-minerals-mining-water-impacts (accessed 18 May 2026).

Laporte-Bisquit, A., and Morgan, A. (2019), "Digging Deeper: How WWF's Water Risk Filter is unearthing new insights in the mining sector", WWF, https://wwf.medium.com/digging-deeper-how-wwfs-water-riskfilter-is-unearthing-new-insights-in-the-mining-sector-9494760746a (accessed 23 July 2026).

Lebbie, T. S., *et al.* (2021), "E-Waste in Africa: A Serious Threat to the Health of Children", *International Journal of Environmental Research and Public Health*, vol. 18/16, pp. 8488, https://doi.org/10.3390/ijerph18168488

Lee, S.-H., and Jang, Y.-C. (2023), "Analysis for End-of-Life Solar Panel Generations by Renewable Energy Supply towards Carbon Neutrality in South Korea", *Energies*, vol. 16/24, pp. 8039, https://doi.org/10.3390/en16248039

Lighting Global/ESMAP, *et al.* (2022), *Off-Grid Solar Market Trends Report 2022: State of the Sector*, World Bank, Washington, D.C., www.esmap.org/Off-Grid_Solar_Market_Trends_Report_2022

Lila, D. (2024), "Canada's solar panel waste problem is quickly becoming a challenge, but also an opportunity", PVBuzzMedia, https://pvbuzz.com/canada-solar-panel-waste-problem (accessed 18 February 2026).

Ma, K. (2023), "Solar panel recycling pilot goes into overtime", St. Albert Gazette, www.stalbertgazette.com/local-news/solar-panel-recycling-pilot-goes-into-overtime-gugenheimer-tao-6511734 (accessed 17 March 2024).

MCEE (2026a), "Mandatory recycling of specially managed products in 2026 [in Korean]", Government of the Republic of Korea, Ministry of Climate, Energy and Environment, www.law.go.kr/LSW/admRulInfoP.do?admRulSeq=2100000273458&chrClsCd=010202&urlMode=admRulLsInfoP (accessed 27 April 2026).

MCEE (2026b), "Enforcement Decree of the Act on Resource Circulation of Electrical and Electronic Products and Automobiles [in Korean]", Government of the Republic of Korea, Ministry of Climate, Energy and Environment, https://www.law.go.kr/법령/전기·전자제품및자동차의자원순환에관한법률시행령 (accessed 27 April 2026).

METI (2026), 事業計画策定ガイドライン（太陽光発電）[*Business Plan Formulation Guidelines (Solar Power)*], Government of Japan, Ministry of Economy, Trade and Industry, www.enecho.meti.go.jp/category/saving_and_new/saiene/kaitori/dl/fit_2017/legal/guideline_solar.pdf

METI and MOE (2026), "The 10th joint meeting material: Recycling systems for solar panels [in Japanese]", Government of Japan, Ministry of Economy, Trade and Industry and Ministry of the Environment, www.meti.go.jp/shingikai/sankoshin/sangyo_gijutsu/resource_circulation/solar_power_generation/010.html (accessed 16 March 2026).

MIIT, *et al.* (2026), *Guiding Opinions on Promoting the Comprehensive Utilisation of Solar Photovoltaic Modules* (关于促进光伏组件综合利用的指导意见), Government of China, Ministry of Industry and Information Technology, Ministry of Ecology and Environment, Ministry of Commerce, State Administration for Market Regulation, and National Financial Regulatory Administration, https://wap.miit.gov.cn/jgsj/jns/zhlyh/art/2026/art_5ba797db4ca8483f822208572368ab46.html

Ministry of Mines (2025), *National Critical Mineral Mission*, Government of India, Ministry of Mines, https://mines.gov.in/admin/storage/ckeditor/24_pages__desktop_1752835254.pdf

MoEFCC (2022), *E-Waste (Management) Rules, 2022*, Government of India, Ministry of Environment, Forest and Climate Change, New Delhi, https://eprewaste.cpcb.gov.in/assets/PDF/e-waste_rules_2022.pdf

MOF, *et al.* (2021), "Announcement on Publishing the 'Catalogue of Enterprise Income Tax Preferences for Environmental Protection, Energy and Water Conservation Projects (2021 Edition)' and the "Catalogue of Enterprise Income Tax Preferences for Comprehensive Utilization of Resources (2021 Edition) (关于公布《环境保护、节能节水项目企业所得税优惠目录(2021年版)》以及 《资源综合利用企业所得税优惠目录(2021年版)》的公告)", Government of China, Ministry of Finance, State Taxation Administration, National Development and Reform Commission, and Ministry of Ecology and Environment, www.gov.cn/zhengce/zhengceku/2021-12/29/content%5F5665116.htm (accessed 30 June 2026).

MSE (2022), "Written reply to parliamentary question on efforts and plans to tackle solar panel waste and solar panel recycling by Ms Grace Fu, Minister for Sustainability and the Environment", Government of Singapore, Ministry of Sustainability and the Environment, www.mse.gov.sg/latest-news/written-reply-to-pq-on-solar-panel-recycling (accessed 25 March 2024).

Munro, P., *et al.* (2023), *Off-Grid Solar Repair in Africa: From burden to opportunity*, SolarAid, London, https://solar-aid.org/wp-content/uploads/2023/10/SolarAid-Whitepaper-off-grid-solar-repair-in-Zambia-12.10.2023_compressed.pdf

Munro, P. G., *et al.* (2022), "Towards a repair research agenda for off-grid solar e-waste in the Global South", *Nature Energy*, vol. 8/2, pp. 123–8, https://doi.org/10.1038/s41560-022-01103-9

Nain, P., and Kumar, A. (2023), "Understanding manufacturers' and consumers' perspectives towards end-of-life solar photovoltaic waste management and recycling", *Environment, Development and Sustainability*, vol. 25/3, pp. 2264–84, https://doi.org/10.1007/s10668-022-02136-6

National Minerals Information Center (2025), *U.S. Geological Survey Mineral Commodity Summaries 2025 Data Release (ver. 2.0, April 2025)*, U.S. Geological Survey, https://doi.org/10.5066/P13XCP3R

National Minerals Information Center (2026a), "Antimony statistics and information", U.S. Geological Survey, www.usgs.gov/centers/national-minerals-information-center/antimony-statistics-and-information (accessed 12 March 2026).

National Minerals Information Center (2026b), "Silicon statistics and information", U.S. Geological Survey, www.usgs.gov/centers/national-minerals-information-center/silicon-statistics-and-information (accessed 12 March 2026).

NDRC, *et al.* (2023), *Guiding Opinions on Promoting the Recycling of Decommissioned Wind Power and Photovoltaic Equipment* (关于促进退役风电、光伏设备循环利用的指导意见), Government of China, National Development and Reform Commission, National Energy Administration, Ministry of Industry and Information Technology, Ministry of Ecology and Environment, Ministry of Commerce, and State-owned Assets Supervision and Administration Commission of the State Council, www.ndrc.gov.cn/xxgk/zcfb/tz/202308/t20230817_1359879.html

NDRC (2024), Notice on Issuing the 'Administrative Measures for the Special Central Budgetary Investment in Energy Conservation and Carbon Reduction' (关于印发《节能降碳中央预算内投资专项管理办法》的通知), Government of China, National Development and Reform Commission, www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202404/t20240408_1365534.html

NEA (2021), "New nationwide e-waste management system kicks in on 1 July 2021", Government of Singapore, National Environment Agency, www.nea.gov.sg/media/news/news/index/new-nationwide-e-waste-management-system-kicks-in-on-1-july-2021 (accessed 25 March 2024).

NEA (2026), "2025 Renewable Energy Grid Integration and Operation Status (2025年可再生能源并网运行情况)", Government of China, National Energy Administration, www.nea.gov.cn/20260212/742b8c6a078347b0b39de676c05c5d58/c.html (accessed 16 March 2026).

A. Neris (2025), "Latin America's largest PV plant expands to 1.6 GW", *pv magazine Brazil*, www.pv-magazine.com/2025/01/14/latin-americas-largest-pv-plant-expands-to-1-6-gw (accessed 9 February 2026).

Neves, L. (2021), "Increasing volumes for PV module recycling in Brazil", pv magazine International, www.pv-magazine.com/2021/08/26/increasing-volumes-for-pv-module-recycling-in-brazil (accessed 19 May 2026).

NSW EPA (2023), "Circular solar grants program", NSW Environment Protection Authority, www.epa.nsw.gov.au/Working-together/Grants/infrastructure-fund/Circular-solar-trials (accessed 3 October 2023).

OECD (2017), *OECD Environmental Performance Reviews: Korea 2017*, OECD Publishing, Paris, https://doi.org/10.1787/9789264268265-en

Okinaga, S. (2023), "Japan's Mitsubishi Chemical to slash solar panel recycling costs 20%", Nikkei Asia, https://asia.nikkei.com/spotlight/environment/japan-s-mitsubishi-chemical-to-slash-solar-panel-recycling-costs-20 (accessed 23 February 2024).

Ozawa, K. (2023), "Businesses in Okayama give 2nd life to old solar panels", The Asahi Shimbun, www.asahi.com/ajw/articles/15055646 (accessed 24 March 2024).

Paç, A. B., and Gok, A. (2024), "Assessing the Environmental Benefits of Extending the Service Lifetime of Solar Photovoltaic Modules", *Global Challenges*, vol. 8/8, pp. 2300245, https://doi.org/10.1002/gch2.202300245

PILATUS (2024), "Rebuilding made-in-Europe Photovoltaic production", https://pilatus-project.eu (accessed 23 March 2024).

PV CYCLE (2026), "PV CYCLE homepage", http://pvcycle.org (accessed 23 April 2026).

T. Rayner (2024), "European study shows continent exports solar waste", *pv magazine International*, www.pv-magazine.com/2024/04/16/european-study-shows-continent-exports-solar-waste (accessed 21 May 2026).

Riedl, D., *et al.* (2026), "A new era of US mineral mining must put communities first", World Resources Institute, www.wri.org/insights/us-critical-mineral-mining-community-impacts (accessed 14 March 2026).

RREUSE (2021), *Job creation in the re-use sector: Data insights from social enterprises, Reuse and Recycling European Union Social Enterprises*, Brussels, www.rreuse.org/publications/job-creation-in-the-re-use-sector-data-insights-from-social-enterprises

Salim, H., *et al.* (2023), *Enabling a responsible second-hand market for photovoltaic systems in Australia*, Institute for Sustainable Futures, University of Technology Sydney, www.uts.edu.au/globalassets/sites/default/files/2023-07/enabling-a-responsible-reuse-market.pdf

Satpathy, R. and Pamuru, V. (2021), "Solar PV Power: Design, Manufacturing and Applications from Sand to Systems", Elsevier, https://doi.org/10.1016/C2018-0-02530-X

SAWIC (2026), "EPR System", South African Waste Information Centre, Department of Forestry, Fisheries & the Environment, https://sawic.dffe.gov.za/SAWIC/EPR (accessed 27 April 2026).

SEC (2025), *Joint Statement - Mandatory product stewardship for solar photovoltaic (PV) panels*, Smart Energy Council, https://smartenergy.org.au/wp-content/uploads/2025/09/Joint-Statement-2025_PRINT-WITH-NO-BLEED-1-1.pdf

SEIA (2025), *Solar Panels Are Designed for Decades of Safe Use & Decommissioning*, Solar Energy Industries Association, Washington, D.C., https://seia.org/wp-content/uploads/2025/06/PV-Toxicity-Factsheet_5-2025.pdf

SESA (2024), "E-Waste from off-grid solar solutions", Smart Energy Solutions for Africa, https://toolbox.sesa-euafrica.eu/projects/e-waste-from-off-grid-solar-solutions (accessed 18 February 2026).

Shafie, S., *et al.* (2025), "Photovoltaic Waste Management for Sustainability in Malaysia: A Review", *Journal of Renewable Energy and Environment*, vol. 12/2, Materials and Energy Research Center (MERC) Iranian Association of Chemical Engineers (IAChE), https://doi.org/10.30501/jree.2025.486221.2150

Shin, J., *et al.* (2017), "A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers", *Solar Energy Materials and Solar Cells*, vol. 162, pp. 1–6, https://doi.org/10.1016/j.solmat.2016.12.038

Shinryo (2022), "Recycling (reuse) of photovoltaic panels", www.iges.or.jp/sites/default/files/inline-files/4-1_Mr.%20Tetsuya%20TAMAI_Shinryo_202203.pdf (accessed 22 April 2024).

Shrestha, N., and Zaman, A. (2024), "Decommissioning and Recycling of End-of-Life Photovoltaic Solar Panels in Western Australia", *Sustainability*, vol. 16/2, pp. 526, https://doi.org/10.3390/su16020526

Silver Institute and Oxford Economics (2025), *Silver, the Next Generation Metal*, https://silverinstitute.org/wp-content/uploads/2025/12/Silver_The-Next-Generation-Metal_DECEMBER-Release.pdf

Sinha, P., *et al.* (2020), *Human Health Risk Assessment Methods for PV, Part 3: Module Disposal Risks*, International Energy Agency PVPS Task 12, Paris, https://doi.org/10.2172/2308820

SOLARCYCLE (2024), "Qcells partners with SOLARCYCLE on recycling solar panels to accelerate domestic supply chain", www.solarcycle.us/press-releases/qcells-partners-with-solarcycle-on-recycling-solar-panels (accessed 25 March 2024).

SolarPower Europe (2024), *End-of-Life Management: Best Practice Guidelines*, SolarPower Europe, www.solarpowereurope.org/insights/thematic-reports/end-of-life-management-best-practice-guidelines-version-1-0

South Africa (2020), *Extended Producer Responsibility Regulations, 2020*, Government Notice No. 1184, Government Gazette, Department of Environment, Forestry and Fisheries, https://commons.laws.africa/akn/za/act/gn/2020/1184/media/publication/za-act-gn-2020-1184-publication-document.pdf

SPI (2021a), *Solar and Wind Energy in Canada: Value Recovery and End-of-Life Considerations*, Smart Prosperity Institute, Ottawa, https://institute.smartprosperity.ca/sites/default/files/Policy%20Brief%20-%202021%20-%20Solar%20Wind%20-%20October20.pdf

SPI (2021b), *Primary Materials in the Emerging Circular Economy: Implications for Upstream Resource Producers and Primary Material Exporters*, Smart Prosperity Institute, Ottawa, https://institute.smartprosperity.ca/sites/default/files/emerging_circular_economy_report.pdf

SPW (2021), "Think before trashing: The second-hand solar market is booming", Solar Power World, www.solarpowerworldonline.com/2021/01/think-before-trashing-the-second-hand-solar-market-is-booming (accessed 18 February 2026).

Ssebugere, P., *et al.* (2025), "Electronic wastes in Sub-Saharan Africa: A critical review of environmental and health impacts, regulatory responses, and future perspectives", *Journal of Hazardous Materials Advances*, vol. 20, pp. 100873, https://doi.org/https://doi.org/10.1016/j.hazadv.2025.100873

Tan, V., *et al.* (2024), "Solar photovoltaic waste and resource potential projections in Australia, 2022–2050", *Resources, Conservation and Recycling,* vol. 202, pp. 107316, https://doi.org/10.1016/j.resconrec.2023.107316

Tao, M., *et al.* (2020), "Major Challenges and Opportunities in Silicon Solar Panel Recycling", 2020 47th IEEE Photovoltaic Specialists Conference (PVSC) (pp. 0292–4), In 2020 IEEE 47th Photovoltaic Specialists Conference (PVSC), IEEE, Calgary, AB, Canada, https://doi.org/10.1109/PVSC45281.2020.9300650

Taylor., *et al.* (2025), *Deep dive on critical raw materials for solar photovoltaics in the EU*, Publications Office of the European Union, Luxembourg, https://data.europa.eu/doi/10.2760/0883326

The Silver Institute (n.d.), "Silver supply & demand", https://silverinstitute.org/silver-supply-demand (accessed 11 March 2026).

Theristis, M., *et al.* (2023), "Onymous early-life performance degradation analysis of recent photovoltaic module technologies", *Progress in Photovoltaics: Research and Applications*, vol. 31/2, pp. 149–60, https://doi.org/10.1002/pip.3615

Thou, S. (2024), "Solar panel waste to reach crisis levels in next two to three years, Australian experts warn", The Guardian, www.theguardian.com/australia-news/2024/mar/30/solar-panel-waste-levels-crisis-point-disposal (accessed 21 May 2024).

Tongwei (2023), "How much polysilicon is used in solar panels", https://en.tongwei.cn/blog/36.html (accessed 17 February 2026).

Triolo N., J. (2024), "The circle of solar panel life", *Arizona State University Engineering News,* https://news.engineering.asu.edu/2024/03/the-circle-of-solar-panel-life (accessed 25 March 2024).

Tyagi, A., and Kuldeep, N. (2021), *How India can Manage Solar Photovoltaic Module Waste Better: Learnings from Global Best Practices*, Council on Energy, Environment and Water, New Delhi, www.ceew.in/sites/default/files/ceew-study-on-photovoltaic-solar-panel-waste-management-disposal-india.pdf

UNDP (2023), "What is circular economy and why does it matter?", United Nations Development Programme, https://climatepromise.undp.org/news-and-stories/what-is-circular-economy-and-how-it-helps-fight-climate-change (accessed 18 March 2026).

UNEN (2023), "New economics for sustainable development: Circular economy", United Nations Economist Network, www.un.org/en/unen/new-economics-sustainable-development-circular-economy

UNEP (2021), *Towards a Circular Economy for the Electronics Sector in Africa: Overview, Actions and Recommendations*, United Nations Environment Programme, Nairobi, https://wedocs.unep.org/handle/20.500.11822/40108

UNEP (2023), "Sustainable future of E-waste", United Nations Environment Programme, https://www.unep.org/ietc/news/story/sustainable-future-e-waste (accessed 24 February 2024).

UNEP (2024a), *Climate Risks in the Metals and Mining Sector*, United Nations Environment Programme, Geneva, https://www.unepfi.org/themes/climate-change/climate-risks-in-the-metals-and-mining-sector

UNEP (2024b), *Global Waste Management Outlook 2024 - Beyond an Age of Waste: Turning Rubbish into a Resource*, United Nations Environment Programme, Nairobi, www.unep.org/resources/global-waste-management-outlook-2024

UNEP (2024c), "Extended Producer Responsibility", United Nations Environment Programme, www.unep.org/ietc/what-we-do/extended-producer-responsibility (accessed 5 February 2026).

UNEP (2026), "Measuring Circular Economy Statistical guidelines for 'Material life-cycle and value chain' and 'Interactions with the environment' indicators", United Nations Environment Programme, https://sdgs.unep.org/article/measuring-circular-economy-indicators (accessed 11 March 2026).

US DOE (2022), *Solar Energy Technologies Office Photovoltaics End-of -Life Action Plan,* US DOE Office of Energy Efficiency & Renewable Energy, Washington, D.C., https://doi.org/10.2172/1863490

US DOE (2023a), "Biden-Harris administration announces $82 Million to increase domestic solar manufacturing and recycling, strengthen the American clean energy grid", DOE Office of Critical Minerals and Energy Innovation, https://content.govdelivery.com/accounts/USEERE/bulletins/355e4ba (accessed 17 March 2024).

US DOE (2023b), "Funding notice: Materials, operation, and recycling of photovoltaics (MORE PV)", United States Department of Energy, www.energy.gov/cmei/systems/articles/funding-notice-materials-operation-and-recycling-photovoltaics-more-pv (accessed 17 March 2024).

US EPA (2025), "Recycling basics and benefits", United States Environmental Protection Agency, www.epa.gov/recycle/recycling-basics-and-benefits (accessed 30 April 2026).

VDMA (2022), *International Technology Roadmap for Photovoltaic (ITRPV): Results 2021 including maturity report 2022*, www.vdma.eu/en/international-technology-roadmap-photovoltaic

VDMA (2025), *International Technology Roadmap for Photovoltaic (ITRPV): 2024 Results*, www.vdma.eu/en/international-technology-roadmap-photovoltaic

Verasol (n.d.), "Quality Standards", Verasol, https://verasol.org/solutions/quality-standards (accessed 22 May 2026).

Vijayakumar Nair, H., *et al.* (2024), "Solar photovoltaic recycling strategies", *Solar Energy*, vol. 270, pp. 112379, https://doi.org/10.1016/j.solener.2024.112379

WA Government (2025), "E-waste to landfill ban in WA", Government of Western Australia, www.wa.gov.au/service/building-utilities-and-essential-services/waste-management/e-waste-landfill-ban-wa (accessed 10 April 2026).

Wei, G., *et al.* (2025), "Review of c-Si PV module recycling and industrial feasibility", *EES Solar*, vol. 1/1, pp. 9–29, https://doi.org/10.1039/D4EL00017J

WHO (2024a), "Lead poisoning", www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health (accessed 20 May 2026).

WHO (2024b), "Electronic waste (e-waste)", World Health Organization, www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste) (accessed 18 February 2026).

Yazdi, M., *et al.* (2024), "E-waste circular economy decision-making: a comprehensive approach for sustainable operation management in the UK", *Neural Computing and Applications*, vol. 36/22, pp. 13551–77, https://doi.org/10.1007/s00521-024-09754-3

APPENDIX A

END-OF-LIFE MANAGEMENT POLICIES FOR SOLAR PV MODULES IN SELECTED MARKETS

COUNTRY/ REGION	MAIN POLICY	FINANCIAL AND LEGAL RESPONSIBILITY	TARGETS ON COLLECTION AND MATERIAL RECOVERY	COLLECTION	TREATMENT AND RECYCLING	REUSE
European Union	Directive 2012/19/EU (WEEE 2 Directive)	Producers should finance collection, treatment, recovery and environmentally sound disposal.	From 2019, the minimum annual collection rate is 85% of weight. From 2018, 85% of the weight of collected panels collected shall be recovered, and 80% shall be prepared for reuse and recycled.	Distributors or producer responsibility organisations are responsible for waste takeback. Producers can set up and operate takeback systems.	Permits are necessary for treatment operations. Standards on the collection, logistics and treatment requirements are provided. The WEEE label of excellence (WEEELABEX) is a European auditing and certification scheme.	Standards: IEC TR 63525:2025, PV modules and circular economy – Reuse of PV modules.
China	Promoting the Comprehensive Utilization of Solar Photovoltaic Modules (MIIT *et al.*, 2026)	Utility-scale solar PV plant operators and owners bear the legal responsibility for decommissioned solar PV equipment and components. Unauthorised disposal and landfilling are prohibited.	Aiming to achieve the cumulative utilisation (recycling and reusing) of 250 000 tonnes of end-of-life PV modules by 2027.	Solar PV manufacturers must establish collection and recycling systems and provide takeback services.	The Ministry of Ecology and Environment released the Technical Specification for Pollution Control of Waste Photovoltaic Equipment Recycling and Treatment (HJ 1463–2026).	A national standard General Specification for Echelon Use[8] of Decommissioned Photovoltaic Modules (GB/T 45075-2024) is released.
United States	US Resource Conservation and Recovery Act	Responsibility distribution varies across states. Many states have policies in place to require decommissioning plans and funds.	No mandatory requirement at the national level. Some states require manufacturers to takeback and to reuse or recycle at least 85% by weight of collected waste.	On the national level, strict collection rules apply as solar PV is categorised as hazardous waste. State-level requirements vary.	Efforts are largely driven by industry initiatives.	

8 "Echelon Use" is defined in this standard as the process of reapplying decommissioned PV modules – either directly or after processing, repairing or similar technical procedures – to maintain all or part of their original functionality.

COUNTRY/ REGION	MAIN POLICY	FINANCIAL AND LEGAL RESPONSIBILITY	TARGETS ON COLLECTION AND MATERIAL RECOVERY	COLLECTION	TREATMENT AND RECYCLING	REUSE
India	E-Waste (Management) Rules, 2022	Producers are responsible for implementing recycling targets.	Solar PV producers are required to store PV module waste generated up to the years 2034 2035 per CPCB guidelines.	Producers are required to establish takeback programmes and provide details to their consumers.	E-waste recyclers must register on the CPCB portal and ensure their facilities and processes comply with CPCB standards and guidelines.	
Japan	The Waste Management and Public Cleaning Act, 1970	Dismantling and removal contractors are responsible for waste processing. Solar PV facilities with a capacity of 10 kW and above are to set aside money as a decommissioning reserve fund.		Collection and transportation to be carried out by project owners or by licensed collection and transportation operators.	Guidelines for Promoting the Recycling of Solar Power Generation Equipment (2024) serves as the official technical and procedural manual.	The Guidelines for Promoting Proper Reuse of Solar Modules (2021) specify requirements and verification methods for proper reuse.
Australia	A national regulatory product stewardship scheme is under development for solar PV systems.	The proposed scheme requires producers to join the scheme and pay administration fees to cover the costs of collection, transport, processing, recycling, disposal and other fees.		The proposed scheme requires network operators to manage collection, transportation and recycling services within a certain geographic area.		Reuse is not required. It may be reconsidered when practicality and safety issues are appropriately addressed.
Republic of Korea	The Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles (Latest version: Law No. 21065, October 2025)	Electrical and electronic equipment producers are subject to mandatory recycling and shall bear all expenses incurred in collecting, transferring and recycling WEEE.	Annual recycling targets for solar panels are calculated and published by the national government. The 2026 total mandatory recycling quantity for solar panels is 2 382 tonnes.	Producers should collect the waste and transfer it for recycling to permitted recyclers or join a scheme to jointly collect, transfer and recycle the waste.		The government-backed "Future Waste Resource Hub Collection Centers" may perform the task of performance evaluation.

Note: This summary is non-exhaustive and represents a selection of key policies and practices as of March 2026.

IRENA
International Renewable Energy Agency

www.irena.org