Report | November 2025

How Much Does it Cost to Recycle a Solar Module in India?

Authors
Ajinkya Kale
Akanksha Tyagi

Suggested citation: Kale, Ajinkya and Akanksha Tyagi. 2025. *How Much Does it Cost to Recycle a Solar Module in India*? New Delhi: Council on Energy, Environment and Water.

Cover image: iStock. For illustrative purposes only.

Peer reviewers: Shyam Rungta, Director, Regain Energies Solutions Pvt. Ltd; Mayur Karmarkar, Managing Director, International Copper Association India; Arjun Krishna, Vice President, Swelect Energy Systems Ltd; Palash Kanwar, Partner Consultant, Columbia Petrochemicals; N.L. Selvakumar, Head–Environment and Recycling, First Solar; Sujoy Ghosh, Vice President and Country Managing Director, First Solar; Gagan Sidhu, Director, Green Finance Center, CEEW; Nitin Bassi, Senior Programme Lead, CEEW, and Sonal Kumar, Programme Lead, CEEW.

Acknowledgments: The authors would like to express their gratitude to Aditya Shah, former consultant, CEEW, Neeraj Kuldeep, former Senior Programme Lead, CEEW, Ribhav Pal, Consultant, CEEW, and Prashant Badal, former Programme Associate, CEEW, for their contributions to the study.

Publication team: Purnima P. Vijaya (CEEW); Alina Sen (CEEW); Shreyas Sharma; Twig Designs, and FRIENDS Digital Colour Solutions.

Organisation: The **Council on Energy, Environment and Water** (CEEW)—**a homegrown institution** with headquarters in New Delhi—is among the **world's leading climate think tanks**. The Council uses **data, integrated analysis, and strategic outreach** to support public policy, transform markets, shape technology, and nudge behaviour. CEEW seeks to explain—and change—the use, reuse, and misuse of resources. It addresses pressing global challenges through an **integrated and internationally focused approach**. The Council prides itself on the **independence** of its high-quality research and strives to **impact sustainable development at scale**. In over 15 years of operation, CEEW has impacted over 400 million lives and engaged with over 20 state governments. Follow us on LinkedIn and X (formerly Twitter) for the latest updates.

Council on Energy, Environment and Water
ISID Campus, 4 Vasant Kunj Institutional Area,
New Delhi-110070, India
T: +91 (0) 11 4073 3300
info@ceew.in | ceew.in | @CEEWIndia | ceewindia

How Much Does it Cost to Recycle a Solar Module in India?

Report | November 2025

Ajinkya Kale and Akanksha Tyagi


Image: iStoc

About CEEW

INTEGRATED | INTERNATIONAL | INDEPENDENT

The Council on Energy, Environment and Water (CEEW)—**a homegrown institution** with headquarters in New Delhi—is **among the world's leading climate think tanks**. We use **data, integrated analysis**, and **strategic outreach** to support public policy, transform markets, shape technology, and nudge behaviour. CEEW seeks to explain—and change—the use, reuse and misuse of resources. The Council addresses pressing global challenges through an **integrated** and **internationally focused** approach. It prides itself on the **independence** of its high-quality research and strives to **impact sustainable development at scale**.

CEEW IN NUMBERS

380+ team members
510+ peer-reviewed studies
680+ opinion articles
650+ convenings
45+ films & documentaries
12,000+ media mentions
11 Union ministries
20 state governments
115 government partnerships
400+ mn lives impacted
62,000+ livelihoods directly supported

CEEW LEADERSHIP

Board: Mr Jamshyd Godrej (Chairperson); Dr Suresh Prabhu; Mr Amitabh Kant; Dr Janmejaya Sinha; Mr Montek Singh Ahluwalia; Dr Naushad Forbes; Mr S. Ramadorai; and Ms Vinita Bali

CEO: Dr Arunabha Ghosh

CEEW's STRATEGIC PILLARS

Clean electricity penetration
Low-carbon industrialisation & circularity
Fuels of the future
Sustainable livelihoods & green economy
Quality of life of citizens
India's story to the world

SELECT POLICY ENGAGEMENTS

NATIONAL/INTERNATIONAL

2011 | National Water Resources Framework
2014 | 175 GW renewables target
2015 | International Solar Alliance
2016 | PM *Ujjwala Yojana*
2017 | *Saubhagya* Schemes
2019 | Climate Vulnerability Index
2021 | Net Zero by 2070
2022 | Mission LiFE
2022 | National Bioenergy Programme
2022 | E-waste (Management) Rules
2023 | G20 Green Development Pact
2023 | National Green Hydrogen Mission
2024 | Green Steel Taxonomy
2024 | PM *Surya Ghar Yojana*
2025 | National Critical Mineral Mission
2025 | Rajya Sabha guidelines on crop residue burning
2025 | National Adaptation Plan

STATE

2022 | Rajasthan Organic Farming Mission
2022 | Jharkhand Solar Policy
2022 | Uttar Pradesh *Vidyut Sakhi* programme
2023 | Rajasthan Green Hydrogen Policy
2023 | Uttarakhand Solar Policy
2024 | Net-zero roadmaps for Bihar & Tamil Nadu
2025 | Green Odisha Initiative
2025 | Maharashtra Climate Action Plan 2.0
2025 | 50 Heat Action Plans (GJ, OD, MH, TN)
2025 | Delhi Clean Air Action Plan
2025 | Delhi EV Policy 2.0

20 STATES SUPPORTED

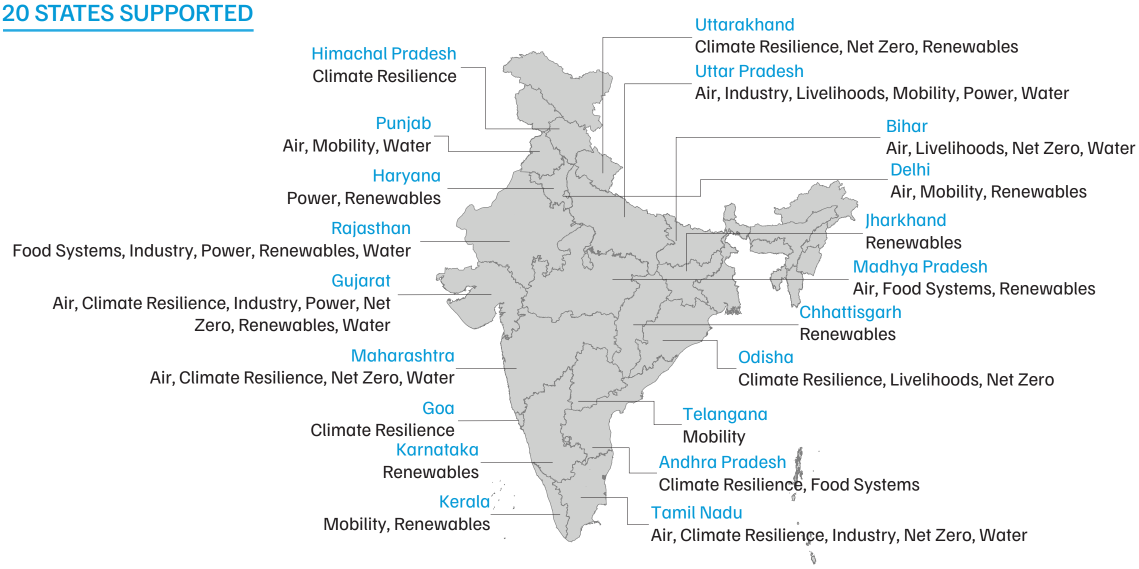



Image: iStock

Contents

Executive summary

India is projected to generate approximately 11,221 kilotonnes (kt) of cumulative solar PV module waste by 2047 (Tyagi et al. 2025). Such high volumes of waste pose a significant challenge for waste management in the country. At the same time, India is rapidly expanding its solar manufacturing ecosystem including modules, cells, wafers, and polysilicon. This in turn increases the demand for raw materials, most of which are currently imported. A circular economy approach, which involves recycling solar PV modules, can help address these twin issues of waste management and rising material demand. A study by the Council on Energy, Environment and Water (CEEW) shows that **recycling solar module waste can address approximately 60 per cent of the demand for silicon, 50 per cent for aluminium, 44 per cent for copper, 40 per cent for glass, 38 per cent for silver, 15 per cent for tellurium, and 13 per cent for cadmium by 2047** (Tyagi et al. 2025). This would reduce the dependence on material imports and support domestic production for raw materials required for solar PV manufacturing.

However, the commercial recycling of solar PV modules is still in its early stages worldwide, with only a few recyclers operating in countries such as Germany, Italy, France, Japan, South Korea, Australia, and the United States of America (USA). The main challenges include **the lack of local markets for secondary materials, problems associated with reverse logistics, and the limited potential of current recycling technologies**, leading to high costs and low revenues (IEA PVPS 2022).

In India, the Ministry of New and Renewable Energy (MNRE) has launched an innovation challenge to support the development and demonstration of various circular strategies (MNRE 2025). Furthermore, numerous research and development initiatives in recycling technologies, led by multiple research institutions and industry players, are ongoing (Prasad et al. 2023, First Solar 2025). These institutes have developed technologies capable of recovering minerals such as silicon, silver, and copper from solar modules (D. C. Sah 2022, D. C. Sah 2023).

Image: iStock

Recycling waste solar modules addresses twin issues of waste management and rising material demand.

First Solar, a leading manufacturer of thin-film solar modules, has established an in-house recycling facility at its manufacturing plant in Chennai, India, with an annual processing capacity of 9,514 tonnes.

While these developments serve to establish a solar module recycling industry in India, the industry's growth remains constrained. One of the primary obstacles **is a lack of robust assessments in India of the financial requirements and potential returns of operating a commercial-scale recycling plant**. Having a clear understanding of the costs and revenues can empower stakeholders to make informed decisions and support the growth of this emerging industry.

This study presents a first-of-its-kind financial analysis of solar module recycling in India, including a detailed assessment of the various costs and financial benefits. The assessment is designed to support the government and private sector in developing effective policy and market instruments to promote the recycling of PV modules. The findings can also aid in designing suitable incentives for the solar module recycling market to support private-sector players in developing workable business models. Ultimately, this comprehensive and comparative assessment aims to inform research and investment in scaling up efficient recycling technologies.

Methodology

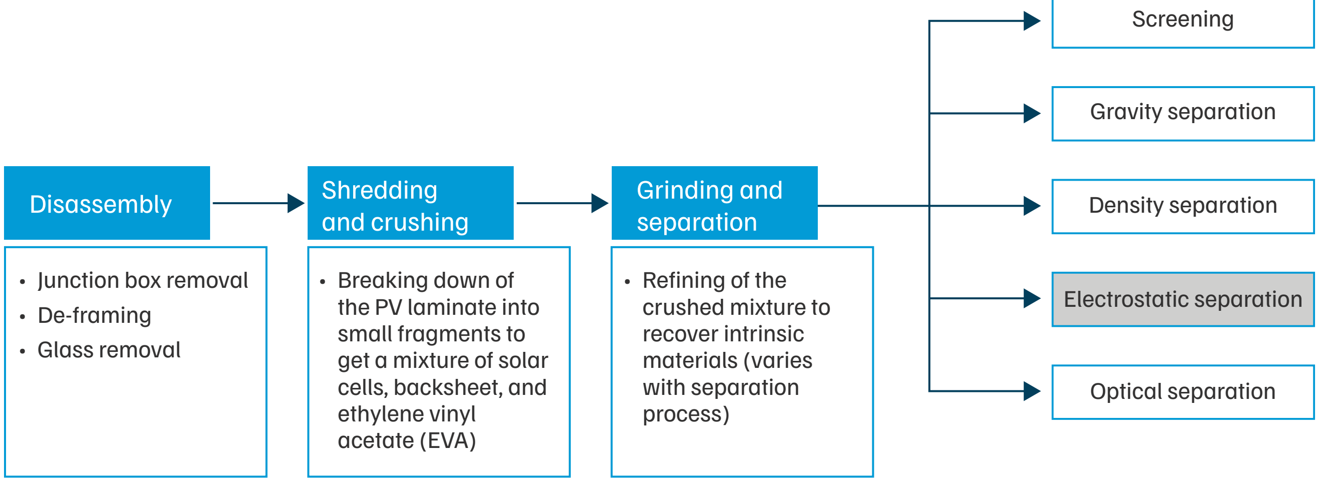
The recycling cost–benefit assessment is divided into three parts. We first estimate non-recurring costs[1], or the initial investment, followed by recurring[2] or operational costs, and finally, the benefits from the sale of recovered materials. The assessment draws on **granular solar waste generation profiles, infrastructure requirements, and the recovery rates** of various recycling technologies to estimate the costs incurred and the financial benefits that can be accrued from recycling solar modules.

We modelled two recycling pathways for the cost–benefit assessment. Each pathway employs different recycling techniques, resulting in the recovery of distinct materials.

Pathway 1 (P1)–mechanical recycling: In this pathway, mechanical operations are used to recover materials from solar modules (Figure ES1). Various methods are available to separate the refined mixture after the grinding process. For this study, we consider electrostatic separation for the separation and recovery of individual materials (highlighted in Figure ES1). P1 is able to recover aluminium, glass, copper and silicon. However, silver is not recovered by this process.

Pathway 2 (P2)–chemical recycling: This pathway involves the use of mechanical and chemical recycling processes to recover materials from solar modules (Figure ES2). P2 is able to recover all major materials from the module including silver (Table A1).

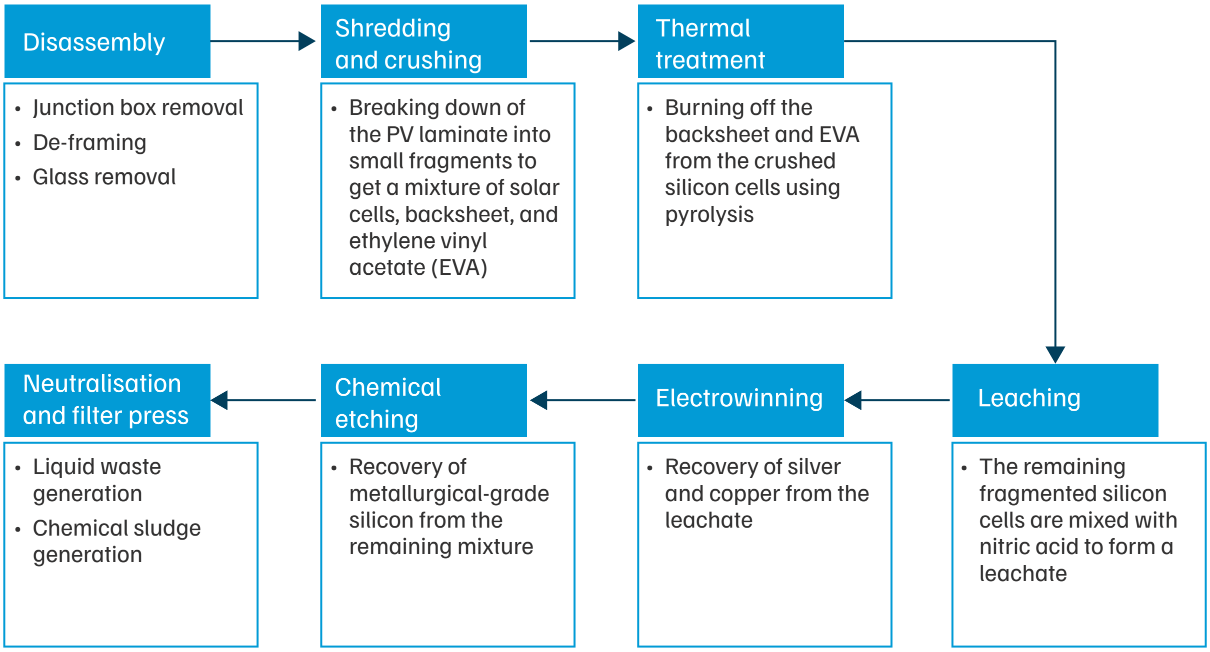
Figure ES1. Mechanical recycling is a three-step process that recovers limited materials of low grade



Source: Authors' analysis

1. Includes cost for land, construction, machinery, and compliance.
2. Includes cost for waste module procurement, collection, processing (workforce, power, material, maintenance), and disposal.

Figure ES2. A chemical recycling process is a seven-step process that can recover all metallic components of enhanced purity grades



Source: Authors' analysis

Insights from the financial analysis are used to recommend which recycling technologies to prioritise, which materials to recover, and which support mechanisms to invest in to create a viable recycling model.

Key findings

- **In India, recycling of solar modules currently costs between INR 883 and INR 1,079 per module (approximately INR 4.11 to INR 5.02 per watt)**. Among the various recurring costs, module procurement accounts for the largest share (56–68 per cent), followed by processing and collection costs.

- **Mechanical recycling in a formal setup is financially unviable, resulting in a loss of about INR 10,230 per tonne (INR 1.05 per watt)**. The recurring costs are INR 40,132 per tonne (INR 4.11 per watt), compared to the benefits of INR 29,902 per tonne (INR 3.06 per watt). The high procurement costs of waste solar modules, along with the loss of valuable materials such as silver, and the inability to recover high-purity silicon, make mechanical recycling of solar modules expensive.

- **Chemical recycling, which involves the recovery of high-grade materials, currently remains financially unviable in its present form**. The recurring cost is INR 49,607 per tonne (INR 5.02 per watt), a 22 per cent increase compared to mechanical recycling, due to chemical requirements and the need for proper waste disposal. The benefits, however, amount to INR 36,726 per tonne (INR 3.76 per watt), a 23 per cent rise compared to mechanical recycling, due to the recovery of silver and metallurgical-grade silicon. Combined, the difference between these costs and benefits results in a loss of INR 12,341 per tonne (INR 1.26 per watt). Higher recovery rates for silver and copper, as well as the costs associated with improving silicon purity from metallurgical grade to solar grade[3], could enhance the viability of chemical recycling.

- If **waste solar modules are available free of cost**, mechanical recycling would generate **a benefit of INR 17,000 per tonne** and chemical recycling **a benefit of INR 15,000 per tonne**. Otherwise, **procurement costs would need to decrease to INR 330–375 per module** from the current INR 600 for either recycling method to break even.

3. Metallurgical grade silicon (MG-Si) has a minimum purity level of 98 per cent whereas solar grade silicon (SoG-Si) has a purity level of 99.9999 per cent.

Recommendations

Assessing the costs and benefits of solar module recycling is essential for developing a circular solar industry. All stakeholders must collaborate to establish a recycling industry that is robust, sustainable, and economically viable. We recommend the following actions for key stakeholders.

Policymakers should undertake the following measures:

- **Incentivise the full recovery of materials** through solar module recycling by:
  - » introducing extended producer responsibility (EPR) targets for collection and recycling, including material-specific recovery targets
  - » expanding the scope of EPR certificates to silicon, copper, silver, cadmium, and tellurium
  - » introducing EPR targets for refurbishing to promote second-life modules.

The Ministry of Environment, Forest and Climate Change (MoEF&CC) should lead this effort in consultation with solar cell and module producers as well as recyclers.

- **Expand solar developers' responsibility for solar waste management**[4] under the *Electronic Waste (Management) Rules* 2022. Recommended areas include mandatory registration on the EPR portal, annual declarations of waste generated, and ensuring that discarded modules from repowering or decommissioning projects, and damaged modules from defects or natural disasters are channelised to authorised recyclers. The MoEF&CC should lead the amendment of the rules.

- **Support the scaling of affordable and efficient recycling technologies** through pilot demonstrations, industrial partnerships and market creation for recovered materials. The MNRE, Department of Science and Technology (DST), and the National Institute of Solar Energy (NISE), can lead these initiatives. They can leverage existing platforms such as Resource Efficiency Circular Economy Industry Coalition (RECEIC), conduct matchmaking events with international companies, and facilitate offtake agreements for recovered materials such as solar glass, aluminium frame and upcoming polysilicon manufacturers.

Technology providers should undertake the following measures:

- **Expedite research on efficient recycling technologies** to recover high-purity materials from waste at high recovery rates in line with evolving module technologies.

- **Recover market-ready materials** by identifying off-takers and recovering materials as per their purity specifications to improve economic viability.

Solar cell and module producers should undertake the following measures:

- **Establish reverse logistics mechanisms** to collect waste from deployed projects and leverage existing mechanism available with project developers to design mutually favourable waste management models. These include executing the ISO 14001 certification[5] with developers to channel solar waste and leveraging the salvage value of the solar project finance solar waste management.[6]

- **Collaborate with technology providers** on recycling pilots and share data on the material composition of their products.

- **Incorporate other principles of a circular economy**, such as **design for disassembly, reuse, and recycling**, to enable easy and cost-effective recovery of materials.

> Policymakers, technology developers, and manufacturers must work together to build a scalable, sustainable, and profitable solar recycling industry.

4. Refers to independent power producers (IPPs), project developers, and asset management companies.
5. Developers certified under ISO 14001 must ensure that, after decommissioning, solar waste is disposed of through authorised channels to prevent it from becoming landfill.
6. According to the Central Electricity Regulatory Commission's *Draft Renewable Energy Tariff Regulations*, a project's salvage value can be considered up to 10 per cent of its capital cost (Central Electricity Regulatory Commission 2024). A share of this financial value can be utilised by producers for decommissioning and disposing of the solar waste through authorised recyclers.

1. Why recycle solar waste?

Recycling discarded solar modules is imperative for both environmental and economic reasons. With its ambitious deployment targets, India is projected to generate about 11,221 kilotonnes (kt) of solar waste by 2047 (Tyagi et al. 2025). India regulates solar waste under the *E-Waste (Management) Rules,* 2022. The rules mandate that solar cell and module producers store their waste until 2034–2035, as per guidelines issued by the Central Pollution Control Board (CPCB) (MoEF&CC 2022). There is no obligation for producers or recyclers to collect, refurbish, recycle, or recover the stored waste. Box 1 provides an overview of the *E-Waste (Management) Rules,* 2022.

Image: iStock

Critical minerals essential for clean energy technologies will be permanently lost without solar module recycling.

Box 1. *E-Waste (Management) Rules*, 2022

The Ministry of Environment, Forest and Climate Change (MoEF&CC) brought solar waste into the ambit of the *Electronic Waste (Management) Rules* in 2022 (MoEF&CC 2022). These rules have been in effect across India since 1 April 2023. According to the rules, every manufacturer and producer of solar photovoltaic (PV) modules, panels, or cells must store the solar waste generated until 2034–2035. They must also register on the Extended Producer Responsibility (EPR) Portal for E-Waste Management and comply with the standard operating procedures and guidelines provided by the CPCB.

In September 2024, the MoEF&CC released the *Environmental Compensation (EC) Guidelines under the E-Waste (Management) Rules,* 2022 (CPCB 2024a). These guidelines impose EC in case of non-compliance by registered producers, recyclers, and refurbishers of e-waste. The rules recognise four end products of recycling e-waste (key metals) for generating and trading EPR certificates. These metals are classified into three groups: precious metals (gold), non-ferrous metals (copper and aluminium), and ferrous metals (iron). Further, for solar PV modules and cells, the average percentage composition of key metals by weight is 13 per cent aluminium and 1 per cent iron (CPCB 2024b). Although solar modules also contain copper, at present, EPR certificates can only be exchanged for aluminium and iron recovered from solar cells and modules.

The lowest and highest prices for exchanging EPR certificates are equivalent to 30 per cent and 100 per cent of the EC, respectively. The EC is determined in two ways, as per the guidelines–by the end product or by the electrical and electronic equipment (EEE) category. The exchange prices of EPR certificates, as per the end products for all four metals, are provided in Table A. Table B provides the exchange prices of EPR certificates for the EEE item category, which includes consumer electrical and electronics, and photovoltaic panels (CEEW14).

According to the guidance document for the generation and transfer of EPR certificates, these EPR certificates are generated by the CPCB through the EPR portal for registered recyclers (CPCB 2024c). The quantity eligible for generation depends on the amount of e-waste recycled. Recyclers must upload details of the e-waste collected and recycled, as well as the key metals produced and sold, to the EPR Portal for E-Waste Management to generate the required EPR certificates. Recyclers can then sell these certificates to producers to fulfil their EPR obligations. Currently, EPR targets do not apply to waste generated from solar PV modules, panels, or cells; therefore, manufacturers have no EPR obligations (MoEF&CC 2022).

In June 2025, the CPCB also issued *Draft Guidelines for Storage and Handling of Waste Solar Photovoltaic Modules or Panels or Cells under E-Waste (Management) Rules,* 2022 (CPCB 2025). They provide guidance on transporting, handling, and storing solar waste and its components, consumables, parts, and spares in an environmentally safe and sound manner.

Table A. EPR certificate cost as per the end product (key metal) recovered

	Gold (INR/gm)	Copper (INR/kg)	Aluminium (available for solar) (INR/kg)	Iron (available for solar) (INR/kg)
Lowest	772	562	30	136
Highest	2,575	1,875	101	456

Source: Authors' compilation from CPCB 2024a

Table B. EPR certificate cost as per EEE item category–CEEW

	EPR certificate cost (INR/kg)
Lowest	22
Highest	74

Source: Authors' compilation from CPCB 2024a

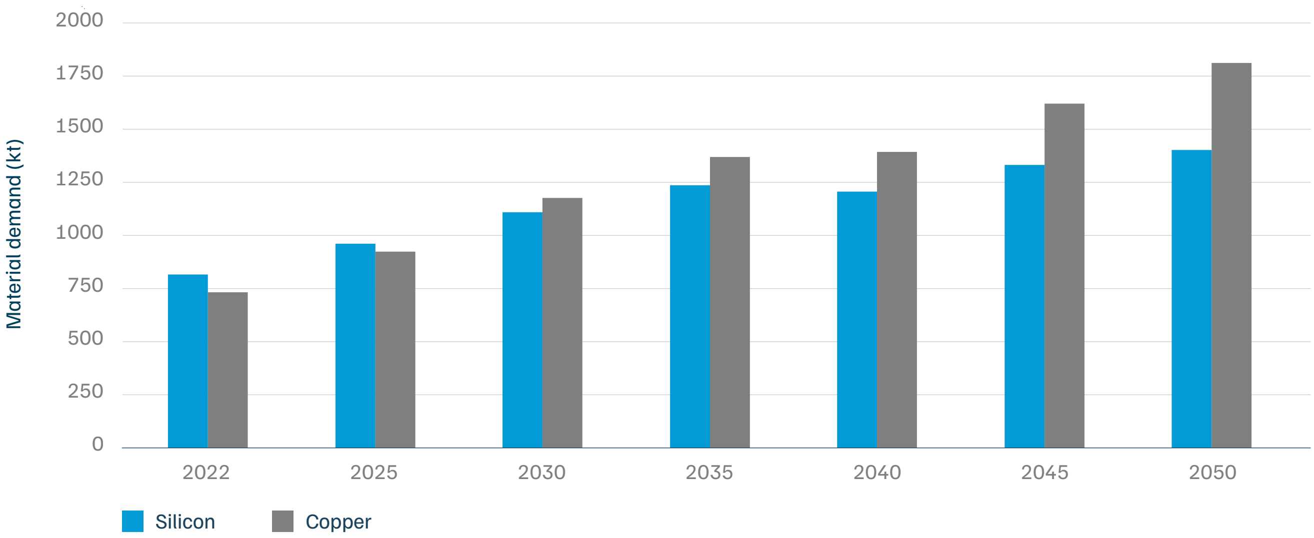
Source: Authors' compilation from MoEF&CC 2022 and CPCB 2024a, 2024b, 2024c, 2025

Recycling solar modules can strengthen domestic industries and national energy security. As of 2023, China dominated the manufacturing of all components of the solar PV value chain, including polysilicon (83 per cent), wafers (97 per cent), cells (84 per cent), and modules (77 per cent) (Wood Mackenzie 2024). Supply chain shocks arising from such concentration can impact domestic solar companies and derail the clean energy transition (ETC 2023). India has already identified silicon, copper, cadmium, and tellurium as critical minerals for domestic manufacturing (MoM 2023). Recycling and recovering these metals from solar modules improve their local availability and strengthens supply chains essential for a resilient domestic manufacturing industry. At the same time, recycling helps offset future demand for these materials and reduces reliance on virgin sources. Demand for virgin silicon and copper for use in solar PV cell and module manufacturing is set to rise rapidly in the coming years (Figure 1) (IEA 2023). A study by the Council on Energy, Environment and Water (CEEW) shows that recycling solar module waste could cover approximately 60 per cent of the demand for silicon, 50 per cent for aluminium, 44 per cent for copper, 40 per cent for glass, 38 per cent for silver, 15 per cent for tellurium, and 13 per cent for cadmium by 2047 (Tyagi et al. 2025).

Recycling, along with other circular strategies, also advances the climate agenda by supporting the attainment of various Sustainable Development Goals (SDGs) (Schröder and Barrie 2024). Actions such as using recycled materials (such as aluminium and glass) in new modules, reducing the use of critical and toxic materials, and repairing modules to extend their useful life contribute to SDG 12 (Responsible Consumption and Production), SDG 11 (Sustainable Cities and Communities), SDG 9 (Industry, Innovation and Infrastructure), and SDG 8 (Decent Work and Economic Growth). The G20 has also recognised the role of a circular economy in meeting climate goals and has committed to "enhance environmentally sound waste management, substantially reduce waste generation by 2030, and highlight the importance of zero waste initiatives" (G20 2023, p. 13). India launched the Resource Efficiency and Circular Economy Industry Coalition (RECEIC) in July 2023 to drive concrete action on resource management through technological cooperation, financial support, and impact partnerships (MoEF&CC-BCG 2023). The coalition has already taken actionable steps, such as publishing a compendium of circular economy business models in December 2024 (FICCI 2024) and announcing a call for awards on resource efficiency and the circular economy (RECEIC 2024).

As solar energy continues to expand and is poised to become the most dominant global renewable energy source by 2029, a circular economy approach will further enhance the sustainability of the solar industry and contribute to India's clean energy transition (IEA 2024). Recycling represents a low-hanging entry point for building this economy.

Figure 1. Between 2022 and 2050, the demand for silicon is projected to increase by 71%, and for copper by 147%



Source: Authors' analysis of IEA. 2023. "Critical Minerals Data Explorer." International Energy Agency.

1.1 Requirement for evaluating the costs and benefits of recycling

Despite its numerous advantages, commercial recycling of solar waste has yet to become mainstream, both domestically and globally. The barriers include highly distributed volumes of solar waste, reverse logistics challenges, the limited potential of available recycling technologies to recover individual materials (particularly high-purity materials at high recovery rates), and the absence of markets for secondary materials.

To promote the sector, governments worldwide are providing fiscal and non-fiscal incentives to recyclers to overcome barriers to module recycling. For example, the Government of New South Wales, Australia, established a fund of AUD 10 million under its *Circular Solar Grant Program* to support the effective waste management of solar modules and lithium-ion batteries (NSW EPA 2021). The Australian Renewable Energy Agency also allocated AUD 2.92 million for two projects focused on developing solar PV recycling technologies (ARENA 2020a, 2020b). In the United States of America (USA), the Office of Energy Efficiency and Renewable Energy initiated the *Solar Energy Technology Recycling Research, Development, and Demonstration Program*, funded at USD 20 million, to support the development of innovative recycling technologies (US DOE 2023). Similarly, the European Union (EU) has funded the QUASAR project, which aims to recycle and recover silicon, silver, polymers, and glass with recovery rates of 70–90 per cent (CORDIS 2023). In India, the government has launched a USD 170 million (INR 1,500 crore) incentive scheme to promote the recycling and recovery of critical minerals from multiple waste streams, including e-waste (MoM 2025).

> A thorough financial analysis of solar module recycling informs design of incentive mechanisms, business models, and investments.

In principle, the design of any support mechanism for module recycling must be informed by a detailed understanding of the costs incurred and the revenue opportunities available to recyclers. Although a few recyclers are commercially processing solar modules in India,[7] the demand would be significantly higher. A thorough financial analysis of the entire recycling value chain, encompassing procurement, transportation, and recycling within the Indian context, is therefore essential. Such an analysis would enable the government to design appropriate incentives to support the PV recycling ecosystem. A comprehensive financial assessment can also help private-sector actors develop workable business models to optimise costs, maximise financial benefits, guide infrastructure development, and identify markets for recovered materials. Lastly, comparing different technological pathways through financial assessment can inform the scaling of efficient recycling technologies, as efficiency and purity improvements often involve significant investments. A robust understanding of the financials would help identify opportunities for cost reduction and make recycling an attractive investment proposition.

1.2 Objectives

To inform decision-making and support the scaling of solar module recycling in India, this study presents a detailed financial assessment of solar module recycling. The discussion begins with an overview of the latest developments in recycling technologies, followed by a market outlook for solar module recycling, and concludes with a financial analysis. Insights from the analysis inform our recommendations for policymakers, technology providers, and solar manufacturers.

7. During our research, we found three companies commercially recycling solar waste: First Solar, Regain Energy Solutions Pvt. Ltd., and THRECO.

2. Overview of recycling processes

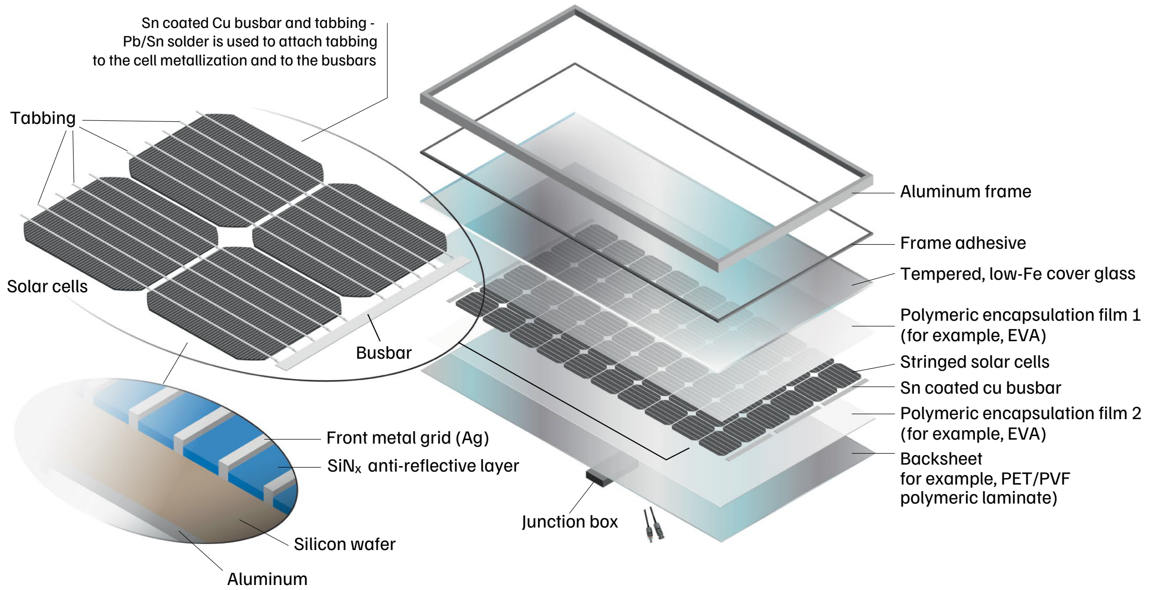
This study focuses on the recycling of crystalline silicon (c-Si) PV modules, which account for more than 95 per cent of the market share as of 2025 (Intersolar Europe 2025). The design of a typical c-Si PV module, along with the minerals used in its manufacturing, is shown in Figure 2.

The following section summarises current technological trends for these approaches and provides details on the recycling processes considered in this study.

2.1 Recycling technologies

Solar module recycling involves three broad steps: disassembly of the module, delamination, and metal recovery. Current PV recycling technologies primarily employ mechanical processes or a combination of mechanical and thermal or chemical processes (IEA PVPS 2022), as outlined in Table 1. These processes can recover ferrous and non-ferrous metals, polymers, glass, solar cell materials, and plastics. Recovery rates are generally above 80 per cent, and the processes mainly yield aluminium frames and glass. The recovered materials are then forwarded for further processing or sent directly to secondary markets, depending on their purity levels and the requirements of the off-taker. For instance, solar PV manufacturers use solar-grade silicon (SoG-Si) with a minimum purity level of 99.9999 per cent, also referred to as 6N purity (IEA PVPS 2015). In contrast, a lower grade of silicon, such as ferrosilicon with a purity level of 75 per cent, is used in the steel industry (Gasik 2013). Purity levels, therefore, vary based on the recycling processes implemented. Recycling technologies must thus be assessed with respect to recovery rates, purity levels of the recovered materials, possible limitations, and their stage of development, which is defined by technology readiness levels (TRLs). This approach facilitates the identification of recycling technologies that are technically and financially viable for implementation, as well as those that require support for further development.

Figure 2. A typical crystalline silicon (c-Si) PV module design highlighting intrinsic materials



Source: Garvin et al. 2020. "Research and Development Priorities for Silicon Photovoltaic Module Recycling to Support a Circular Economy." Nature Energy 5 (7).

Table 1. Comparison of different solar PV recycling processes at various stages of development

Recycling stage	Recycling technology	Process	Recovered materials	Limitations	Status
Disassembly	Mechanical	Physical disintegration	• Powder containing glass • Silicon wafers • Other metals	• Other processes are required to remove ethylene vinyl acetate (EVA) • Dust contains heavy metals • Breakage of solar cells • Equipment corrosion	Commercial (TRL 9) (Berger et al. 2010)
Delamination	Mechanical	Hot knife method	• Glass sheets • PV laminate	• Energy-intensive process	Commercial (TRL 9) (IEA PVPS 2023, Deng et al. 2019)
	Chemical	Nitric acid dissolution	• Glass • EVA • Wafers • Metal compounds	• Generates harmful emissions and waste in the form of spent chemicals	Pilot (TRL 6) (Bruton et al. 1994)
	Chemical	Solvent and ultrasonic irradiation	• Glass • EVA • Wafers • Metal compounds	• Expensive process • Generates harmful emissions and waste in the form of spent chemicals	Research (Kim and Lee 2012)
	Chemical	Solvent dissolution	• Glass • EVA • Wafers • Metal compounds	• Generates harmful emissions and waste in the form of spent chemicals	Research (Doi et al. 2001)
	Thermal	Thermal treatment	• Glass • Intact cells • Metal ribbons	• High energy input • Generates harmful emissions	Commercial (TRL 9) (Wang et al. 2012)
	Thermal	Pyrolysis	• Glass • EVA • Wafers • Metal compounds	• High energy input • Generates harmful emissions • Thermal stress leads to glass breakage	Pilot (TRL 6) (Frisson et al. 2000, Tao et al. 2023)
Material extraction	Chemical	Chemical etching	• Glass • Metal compounds • Silicon cells	• Generates liquid waste	Commercial (TRL 9) (Klugmann-Radziemska et al. 2010)

Source: Authors' compilation from multiple sources (listed in Table 1).

Note: The authors have assigned the TRLs to each recycling process based on their assessment of the technological readiness in each process.

2.2 Recycling pathways modelled for financial analysis

We modelled two solar module recycling pathways for the financial analysis. Each pathway employs a distinct recycling technology that results in the extraction of different materials.

Pathway 1: Mechanical recycling

This pathway uses only mechanical operations to recover materials from solar PV modules (Figure ES2). It is one of the most commonly used methods of solar module recycling (IEA PVPS 2022).

Mechanical recycling (P1) begins with the disassembly of the PV modules.[8] This yields de-framed modules, with aluminium frames and junction boxes as outputs. While modules are de-framed using machines, junction boxes can be removed either manually or mechanically. For our analysis, we assumed a mechanical process. The next step involves separating the glass from the de-framed laminated module using a machine. The remaining laminated structure is processed through a shredder, crusher, and grinder to create a fine powder containing solar cells, polymeric backsheets, and EVA encapsulants.

Various methods can then be applied to further refine this mixture (Figure ES2). Table 2 describes the mechanisms of each method and the corresponding recovered materials. For our analysis, we selected electrostatic separation as it is a low-cost, environmentally friendly method widely used to recover materials from other waste electrical and electronic equipment (WEEE) (Li et al. 2023). The equipment used to separate materials includes a screw conveyor, a cyclone, an electrostatic separator, and a dust collector. If any glass granules remain in the mixture, they can be separated through a sieving operation.

At the end of P1, the recovered materials include aluminium, crushed glass, silicon powder (ferrosilicon), low-quality copper (including polymer residues and silicon powder), and polymer powder. Silver is not recovered in this process. Both silicon and copper require further refining before they can be put to secondary use, especially in the solar industry. The dust collected during this process mainly consists of glass and polymer powder; it has buyers in the secondary market and is used as an alternative to sand in the construction industry (ENGIE 2021). Recovery rates for the various materials in P1 are presented in Table 3.

Table 2. Electrostatic separation is a widely used method to recover materials from electronic waste

Method	Mechanism	Materials obtained
Screening	• Sorts particles by size	• Polymer • Copper ribbons • Glass cullet
Gravity separation	• Sorts particles based on their specific weight	• Glass and silicon powder • Polymer
Density separation	• Uses a fluid of intermediate density so that the feeding material (ground-up mixture) either floats (less dense than the fluid) or sinks	• Backsheet • Glass and silicon
Electrostatic separation	• Sorts conducting and non-conducting materials	• Copper • Silicon powder • Glass and polymer
Optical separation	• Optical sensors and compressed air reject particles with different colours	• Glass cullet • Solar cell residues and interconnectors

Source: Authors' adaptation from Deng, Rong, Yuting Zhuo and Yansong Shen. 2022. "Recent progress in silicon photovoltaic module recycling processes." Resources, Conservation and Recycling.

8. The machinery for mechanical recycling is commercially provided by an entity from China named Suny Group (Suny Group 2023).

Pathway 2: Chemical recycling

The chemical recycling pathway (P2) combines mechanical and thermal steps with chemical recycling processes to recover individual metals from solar modules. After removing the glass from de-framed modules, which is similar to the process in P1, the remaining laminate is shredded and crushed. If any glass granules remain, they can be separated using optical or screening operations. The remaining mixture then undergoes thermal treatment, such as pyrolysis, to burn off the polymer (encapsulant and backsheet) present in it; the entire polymer is lost in this step. This is necessary to expose the silicon cell surfaces so that metals can leach out during the subsequent chemical stage (Tao et al. 2023). The resulting mixture contains fragments of silicon cells and clippings from busbars, some of which also appear as fine particles. The metals present in this mixture are silicon and silver from the cells, and copper from the ribbons in the cells and busbars.

The mixture is then leached with nitric acid (HNO_3) to extract silver from the cells and copper from the ribbons and busbars. A sequential electrowinning process is employed to recover silver and copper from this leachate, achieving recovery rates of 74 per cent and 83 per cent, respectively, with a minimum purity of 99 per cent (Wen-Hsi Huang 2017). The remaining silicon cell fragments are treated with hydrofluoric acid (HF) to remove the silicon nitride (SiN_x) anti-reflective layer from the cell's surface (see Figure 2). Aluminium is then removed from the cell's back surface using a sodium hydroxide (NaOH) solution. The final product is crushed silicon wafers or metallurgical-grade silicon (MG-Si), with a recovery rate of 90 per cent. Used chemicals are neutralised and disposed of safely.[9] Table 4 summarises the recovery rates of various materials in the chemical process.

Table 3. Mechanical recycling with electrostatic separation has an overall material recovery rate of 87% by weight

Method	Recovery rate (%)
Aluminium[a]	99
Glass[b]	89
Copper[c] (impure[d])	95
Silicon[e] (ferrosilicon[f])	95
Silver	0
Polymer	60

Source: Authors' compilation from stakeholder consultations and Suny Group. "Solutions for Solar PV Panel Recycling." 2023.

Note:
a. An aluminium recovery rate of 99 per cent is assumed. This is obtained from the extraction of the aluminium frames only. No recovery of aluminium from inside the module is assumed.
b. The glass recovery rate is taken from product specifications provided by a recycling equipment manufacturer (Suny Group 2023).
c. Electrostatic separation helps to recover a very high volume of copper, although it is impure.
d. Low-purity copper is recovered from this process.
e. A high volume of silicon powder is recovered after using the cyclone and dust collector.
f. Low-purity silicon is recovered from this process.

Table 4. Chemical recycling allows the recovery of high-purity critical and precious metals from solar modules

Method	Recovery rate (%)
Aluminium	99
Glass[a]	89
Copper (pure)	83
MG-Si	90
Silver	74
Polymer	0

Source: Authors' compliation from Wen-Hsi Huang et al. 2017. "Strategy and Technology to Recycle Wafer-Silicon Solar Modules." Solar Energy (144): 22–31 and Suny Group. 2023. "Solutions for Solar PV Panel Recycling."

Note:
a. The glass recovery rate is the same as in P1.

9. As directed in the relevant waste management regulations in the concerned legislation.

3. Market outlook for recycling

Solar PV recycling has recently gained significant attention from the industry, local communities, and governments worldwide. **The domestic solar PV recycling industry is projected to reach INR 3,709 crore in 2047** (Tyagi et al. 2025). This section summarises ongoing developments in solar module recycling across global and Indian markets.

3.1 Global market overview

Global PV recycling markets are diverse because companies employ different recycling processes to recover materials. First Solar, a leading US-based manufacturer of thin-film solar cells, is considered the first commercial recycler of solar waste. The company claims to have recovered more than 400,000 tonnes of solar waste since 2005 (First Solar 2025). In Europe, Return of Silicon (ROSI) Solar, a French PV recycling company, recently formed a strategic partnership with Yingli Solar, a leading solar module manufacturer, to recycle solar waste (ROSI 2023). In Germany, Reiling, a waste management company, has opened the country's first solar PV recycling facility, having successfully recycled 6,000 tonnes of solar waste in 2022 (PV Europe 2023). In the USA, SOLARCYCLE, a PV recycling company, has established partnerships with Ørsted (SOLARCYCLE 2023a) and EDF Renewables North America (SOLARCYCLE 2023b), key developers in the country, to recycle decommissioned and damaged PV modules, respectively. We Recycle Solar is another US-based recycling firm (We Recycle Solar 2023). An EU-funded project, PHOTORAMA (Photovoltaic waste management–advanced technologies for recovery and recycling of secondary raw materials from end-of-life modules), aims to develop and demonstrate innovative PV recycling solutions. Its pilot has reached TRL 7 (PHOTORAMA 2023a). Table 5 summarises the recycling technologies used by these companies to recover materials from solar waste.

Image: iStock

Public-private partnerships and evolving regulations are driving innovation, robust infrastructure, and growth in solar module recycling worldwide.

Table 5. Comparison of various recycling processes adopted by companies aiming for high-purity materials

Entity	Recycling process used	Key features
First Solar, USA (Krueger 2010)	• Mechanical for disassembly and delamination • Chemical to recover metals in the form of a filter cake made of semiconductor material	Recovery of more than 90 per cent of module materials
ROSI, France (Beyer 2022)	• Pyrolysis to isolate metals from solar cells • Chemical operations to recover metals	• Separation of metals from solar cells • Recovery of silicon, silver, and copper
Reiling, Germany (Reiling Group 2023)	• Mechanical processes such as shredding and sorting	• Recovery of glass, aluminium, silicon, and busbars
SOLARCYCLE, USA (Cain 2024)	• Automated process to extract the glass cleanly from the PV laminate • Shredding of the remaining laminate • Multi-step process to separate the plastics and recover valuable metals from the shredded material (limited information available on the process)	• Recovery of silicon, silver, copper, and aluminium • Recovery rate of 95 per cent
We Recycle Solar, USA (We Recycle Solar 2023)	• Multi-step process to recover individual materials from the PV laminate (limited information available on the process)	• Recovery of glass, aluminium, and copper
PHOTORAMA, EU (PHOTORAMA 2023b)	• Mechanical delamination using diamond wire cutting • Fluid delamination applying CO_2 at the supercritical state • Ionic liquid extraction • Electrowinning	• Recovery of high-purity (98–99.99 per cent) silver and silicon

Source: Authors' compilation from multiple sources (listed in Table 5).

3.2 Indian market overview

Solar PV recycling is gaining momentum in India as well. Numerous developments are underway, driven by technological advancements, industry participation, and government support. Table 6 presents some of the progress made in the country.

Next, we present the first detailed financial assessment of solar module recycling in India. The proposed model is based on a comprehensive list of cost components (machinery and equipment, materials, and utilities) required for waste processing, as well as the impact of changes in material recovery rates and purity levels on financial benefits. We also highlight opportunities for cost reduction for recyclers that could make recycling financially competitive.

Table 6. Developments in the Indian solar PV recycling ecosystem made by the government, industry, and research

Entity	Associated developments
Ministry of New and Renewable Energy (MNRE)	Solar PV recycling is identified as a key area of focus under the *Renewable Energy Research and Technology Development Programme* (RE-RTD) (PIB 2023). Call for proposals under the 'Innovation Challenge for Circularity in Renewable Energy Technologies–Batteries and Solar Photovoltaic' in June 2025 to promote and scale up research and development of circular economy strategies in batteries and solar (MNRE 2025).
Ministry of Mines (MoM)	Incentive scheme for critical mineral recycling approved by the Union Cabinet under the *National Critical Mineral Mission* (NCMM) to develop India's recycling capacity for the separation and production of critical minerals from e-waste, lithium-ion battery waste, and components of end-of-life vehicles (PIB 2025).
National Solar Federation of India (NSEFI)	The *SolarREcycle India* initiative was launched to create a platform for addressing all solar waste management–related issues, policies, regulations, and technological advancements (NSEFI 2024).
Department of Science and Technology (DST)	Call for proposals on 'Recovery and Recycling of End-of-life Solar PV modules' in mid-2024 to identify advanced recycling technologies that are economically viable (DST 2024).
First Solar	3.3 GW fully vertically integrated solar manufacturing facility established in Tamil Nadu, with an in-house recycling unit capable of processing 24,000 tonnes of solar waste per year (First Solar 2024).
Centre for Materials for Electronic Technology	Recycling technology under development to recover silicon, silver, and copper from solar waste (Prasad et al. 2023).

Source: Authors' compilation from multiple sources (listed in Table 6); list not exhaustive.

4. Methodology

This section describes the approach used for the financial assessment of c-Si module recycling, focusing on the various costs incurred and the benefits accrued. Broadly, the analysis is divided into three parts (Figure 3), estimating:

- non-recurring costs, or the initial investment made by the recycler
- recurring costs, or the operational costs
- financial benefits accrued from the sale of recovered materials

The weight of one c-Si module is assumed to be 22 kg, with the composition shown in Table 7 (Paiano 2015).

Table 7. Material composition of crystalline silicon PV module assumed in the study

Method	Share by weight (%)
Aluminium	10.30
Glass	74.16
Copper	0.57
Silicon	3.35
Silver	0.006
Polymer	11.31

Source: Authors' compilation from Paiano, Annarita. 2015. "Photovoltaic Waste Assessment in Italy." Renewable and Sustainable Energy Reviews 41 (1): 99–112.

The processing capacity of the recycling facility is assumed to be 5,400 tonnes per annum. Based on consultations with recyclers, the capacity utilisation factor for the recycling facility is set at 67 per cent. Operating at full capacity is generally considered detrimental due to the smaller margins for error and the increased frequency of maintenance requirements. For our analysis, a 67 per cent capacity utilisation factor reduces the effective annual processing capacity to 3,600 tonnes, translating to a processing capacity of 12 tonnes per day.

We also define the distance between the recycling facility and the project site(s) for obtaining solar PV waste as 360 km. Our previous study found that 67 per cent of India's solar waste will come from five states: Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Maharashtra, reflecting capacity installation trends (MNRE-CEEW 2024). In this study, we take the average distance between the top three districts with the highest installed solar capacity and the district with the highest number of e-waste recyclers in these five states (CPCB 2023). An important assumption in this analysis is that the entire solar waste generated in the country is available for collection and recycling. This means exports of solar waste, leakages to the informal sector, or withholding of solar waste by consumers are not considered in the analysis.

Further details on the general assumptions are provided in Annexure A.

4.1 Assessment of recycling costs

There are two types of recycling costs — non-recurring and recurring. Non-recurring costs are further divided into four components: land, facility construction, machinery, and compliance.

i. **Land**: Land costs vary depending on factors such as the state and district in which the facility is located, as well as the type of land (for example, converted land, land in industrial parks, or land in special economic zones). For mechanical recycling (P1), the estimated land requirement is 30,000 square feet (sq ft),[10] costing approximately USD 0.42 million (INR 3.56 crore). Chemical recycling (P2) requires more space due to additional chemical equipment and storage for new and spent chemicals, increasing the requirement to 40,000 sq ft,[11] with an estimated cost of approximately USD 0.57 million[12] (INR 4.75 crore). However, the *E-Waste (Management) Rules, 2016*, require a minimum facility area of 500 square metre (sq m) for processing 1 tonne of e-waste per day, irrespective of the recycling pathway (CPCB 2016). Based on this, the

10. Information acquired from stakeholder consultations.
11. Information acquired from stakeholder consultations.
12. The average conversion rate in 2024, 1 USD = INR 83 (X-rates n.d.).

land requirement can be up to 64,400 sq ft,[13] costing approximately USD 0.92 million (INR 7.64 crore) for both modelled pathways.

ii. **Facility construction**: An industrial shed is the minimum requirement for a module recycling facility. However, its design would vary based on the modelled recycling pathway. For P1, the construction of an industrial shed could cost about USD 0.22–0.27 million (INR 1.8–2.2 crore). For P2, the increased space requirement for additional equipment and storage tanks could result in a 15 per cent increase in construction costs, amounting to USD 0.25–0.30 million (INR 2.1–2.5 crore).

iii. **Machinery**: Machinery costs include procurement and installation. Procurement costs can vary depending on whether machines are domestically manufactured or imported. Under these considerations, for P1, machinery costs are estimated at around USD 0.43–0.56 million (INR 3.60–4.63 crore), with procurement accounting for 70 per cent, i.e., USD 0.30–0.43 million (INR 2.50–3.53 crore) and installation accounting for the remaining USD 0.13 million (INR 1.10 crore). For P2, additional equipment is required beyond the machinery used for mechanical operations. This includes a pyrolysis unit with a wet scrubber system for thermal operations, reactor vessels, and storage tanks for both new and spent chemicals, as well as instrumentation and control systems to facilitate the chemical processes. Depending on the extent of automation, the cost of this equipment ranges from USD 0.27 to 0.84 million (INR 2.21–7.0 crore). The total machinery cost for P2, including installation, is estimated at approximately USD 0.75–1.38 million (INR 6.21–11.52 crore).

iv. **Compliance**: As per the *E-Waste (Management) Rules*, 2022, authorised recyclers must adhere to several compliance requirements, such as those related to facility discharge. Due to the difference in the nature of the processes, compliance costs are estimated at USD 18,000 (INR 0.15 crore) for P1 and approximately USD 24,000 (INR 0.20 crore) for P2, which is about 33 per cent higher than for P1.

> Currently, recyclers incur a cost of INR 600/module to procure waste modules from module manufacturers.

Recurring costs are also divided into four parts: waste procurement, collection, processing, and disposal.

i. **Waste procurement costs**: Recyclers often incur additional costs to procure waste solar modules, typically ranging from INR 25,000 to INR 30,000 per tonne, depending on market fluctuations.[14] For this analysis, we consider a value of INR 27,300 per tonne or INR 600 per module, based on stakeholder consultations.

ii. **Collection costs**: These costs comprise the charges incurred for transporting solar waste to the recycling facility. Stakeholder consultations suggest that the collection cost varies from INR 2,909 to INR 5,455 per tonne, equivalent to INR 8–15 per tonne per km. For this analysis, we consider collection costs to be INR 4,454 per tonne[15] or INR 12 per tonne per km.

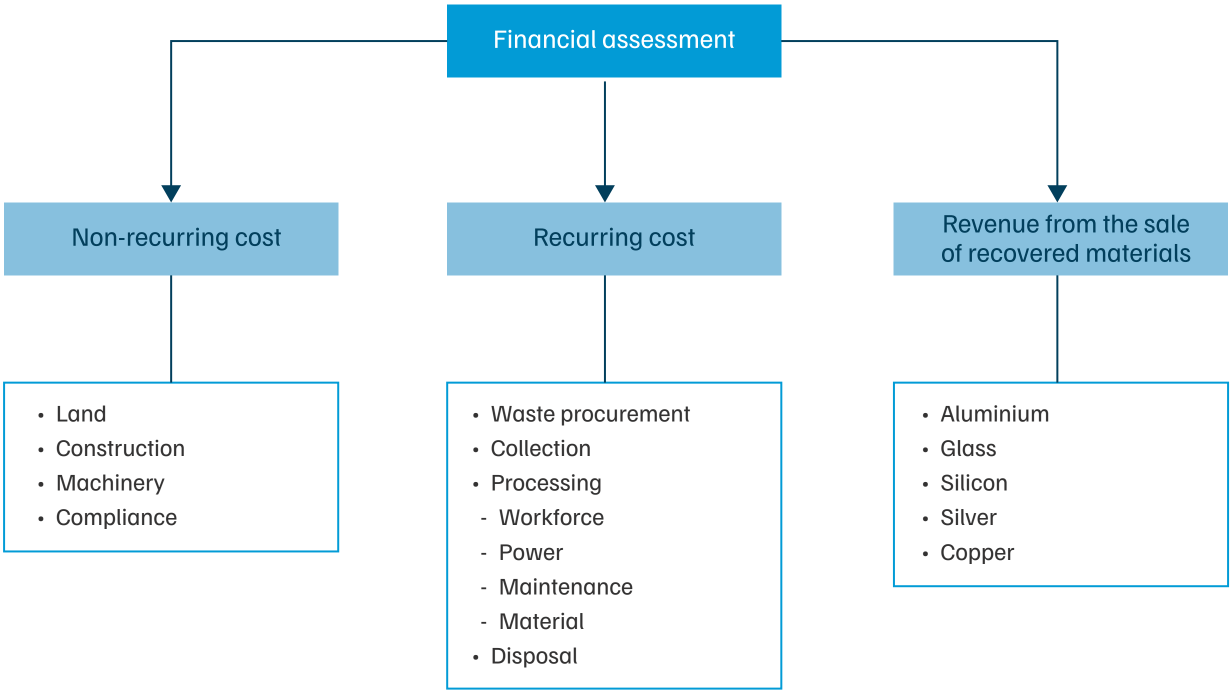
iii. **Processing costs**: These costs are associated with the modelled recycling pathway and include workforce, power, maintenance, and material expenses. Workforce requirements for efficient recycling facility operations include process operators, floor labour, maintenance personnel, supervisors, and a plant manager. Power and maintenance costs for P2 are 20 per cent and 33 per cent higher than P1, respectively, due to the additional chemical equipment, workforce, and processes involved. Material costs–chemicals and electrodes–are INR 5,913 per tonne for P2, while for P1, they are zero, since no chemicals are used.

iv. **Disposal costs**: These refer to the expenses incurred for disposing of residual waste or spent materials. They vary depending on the modelled recycling pathway, as the nature and volume of waste generated differ. The chemical process produces liquid and chemical waste, resulting in disposal costs. In contrast, the mechanical process creates dust, which has secondary market value in industries such as construction, eliminating disposal costs (ENGIE 2021).

Annexure A contains further details about the assumptions made specific to the modelled recycling pathways.

13. According to the *E-Waste (Management) Rules, 2016*, a 1 tonne/day processing capacity requires a minimum area of 500 sq m, i.e., 5,382 sq ft. Hence, a 12 tonne/day capacity would require approximately 64,400 sq ft of land.
14. Information acquired from stakeholder consultations.
15. The average value is determined by adding all the inputs provided by the stakeholders divided by the total number of inputs.

Figure 3. The financial assessment of solar module recycling includes recurring costs, non-recurring costs, and revenue from the sale of recovered materials



Source: Authors' analysis

4.2 Assessment of benefits

We assess the financial benefits of solar module recycling based on the sale of recovered materials, such as aluminium, glass, copper, silicon, and silver. The resale values of these materials vary based on their purity levels (Table 8).

Both recycling pathways recover glass and aluminium. In addition, P1 recovers low-quality copper and ferrosilicon, while P2 recovers pure copper and MG-Si. The recovered materials can be utilised in various industries, including cement (recovered glass), steel (recovered silicon), and metal manufacturing (recovered aluminium). However, further processing is required before these recovered materials can be reused in solar module manufacturing. For instance, Trina Solar, a Chinese module manufacturer, has demonstrated the ability to manufacture modules using recycled silicon, silver, aluminium frames, and discarded glass from old modules (Trinasolar 2024). The company reported an efficiency of 20.7 per cent and a maximum power output of 645 W.

This assessment includes a sensitivity analysis to examine variations in costs, including the waste module procurement cost, collection cost, recovery rates of materials, purity levels of recovered materials, and module composition.

Table 8. Resale value of recovered materials increases with purity levels

Material	Resale value in secondary markets (INR/kg)
Aluminium	177[a]
Glass	7[b]
Copper	750 (low-quality[c]), 800 (pure[d])
Silicon	100 (ferrosilicon[e]), 200 (metallurgical grade[f])
Silver	95,775[g]
Polymer	-

Source: Authors' compilation from stakeholder consultations and online marketplaces.

Note: The resale of the balance of systems (which consists of all components of a solar PV system except the PV modules, such as junction boxes, inverters, and copper cables) is not considered in the recycling benefit assessment.
a. An average value of aluminium is considered from different sources on Indiamart (an online marketplace).
b. An average value of glass is considered from different online marketplaces.
c. An average value of copper is considered from different sources on Indiamart.
d. Average commodity price in the period (March 2024–January 2025) is INR 825 per kg. A marginally lower value of INR 800 per kg is considered due to the recovered copper's 99 per cent purity, compared to the 99.7+ per cent purity of exchange-grade copper.
e. An average value of ferrosilicon is considered from different sources on Indiamart.
f. An average value of metallurgical grade silicon is considered from different sources on Indiamart.
g. Average commodity price in the period May 2024–April 2025.

4.3 Limitations

Our study is based on several assumptions and discussions with diverse stakeholders. Accordingly, the final results are influenced by these assumptions. The key limitations are as follows:

1. A direct USD–INR conversion was applied to determine the costs of machines used for the mechanical processes in P1.
2. The financial analysis does not account for the recoverable aluminium, tin, and zinc found in solar cells.
3. Compliance costs do not include additional fees that may apply to facilities located outside industrial areas or to zero liquid discharge plants.
4. The cost of demineralised water requirements has not been added to the compliance costs.
5. The power and maintenance costs may vary depending on the ancillary machinery, motors, pumps, and other equipment used at a recycling facility, as well as the associated maintenance and repair work.
6. The secondary value of recovered silicon is assumed to be equal to the average value of industrial-grade silicon available in the Indian market. A lower secondary value than assumed could impact the overall revenue. The same applied to recovered silver.
7. The cost–benefit assessment does not include any benefits from the resale of polymer powder (recovered in P1) in the secondary market (ENGIE 2021).

5. Findings and discussion

This section presents the results of the financial analysis and discusses trends observed across various scenarios.

5.1 Recycling costs

Figure 4 illustrates the distribution of recurring costs. Waste procurement accounts for the most significant share—68 per cent in P1 and 56 per cent in P2. Collection costs represent about 10 per cent in both pathways. Stakeholders typically consider transportation costs as the sum of module procurement and collection costs; however, analysing them separately provides a clearer understanding of the individual impact and relative weight of each cost parameter. Processing costs account for only 21 per cent in P1, compared to nearly 33 per cent in P2, reflecting the additional power consumed by the thermal and chemical equipment, as well as the use of chemicals (Table 9). P2 also requires additional personnel to manage chemical processes, further increasing processing costs. Disposal costs are higher for P2 due to the additional management of chemical and liquid waste generated at the end of recycling operations.

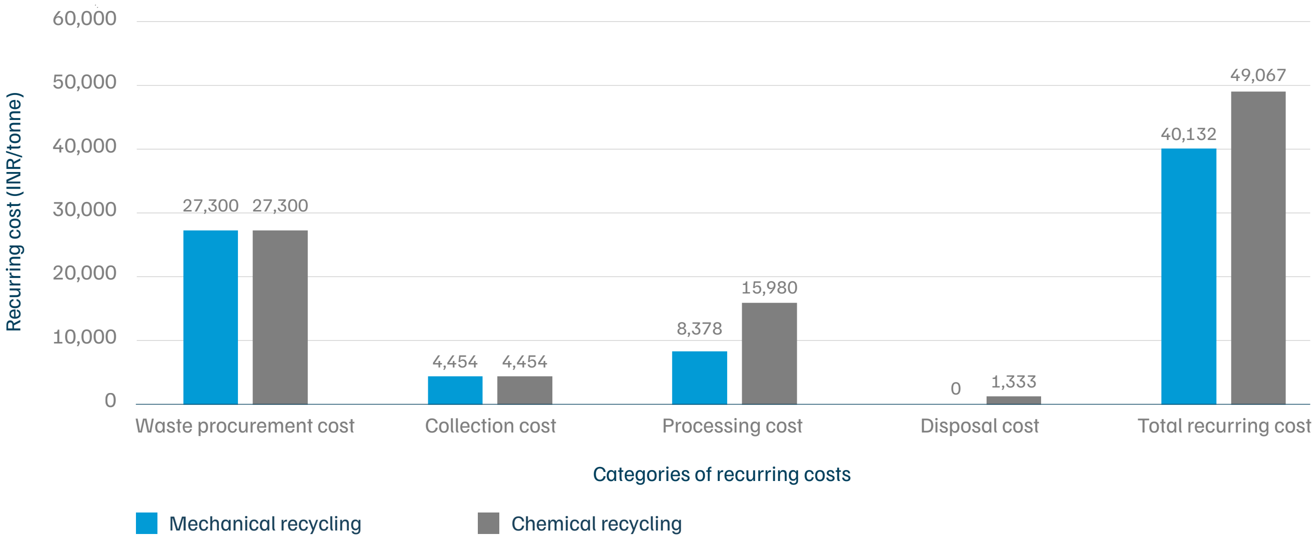
> Waste procurement forms the largest cost share: 68% in mechanical recycling and 56% in chemical recycling.

Among non-recurring costs, machinery accounts for the largest share—nearly 50 per cent in P2 and 45 per cent in P1. This is because recycling machinery for mechanical operations is currently imported from abroad, which increases costs. Stakeholder consultations suggest that producing similar machinery domestically could cut costs by 43 per cent (approximately USD 0.3 million, or INR 2.5 crore). This would result in savings of more than INR 1 crore in non-recurring costs. Land is the second-highest contributor to non-recurring costs, accounting for about 33–34 per cent in both pathways. Construction costs are 15 per cent higher in P2 due to the requirement for thermal and chemical equipment for processing, as well as storage vessels for new and spent chemicals inside the facility. Table 9 summarises these expenses.

5.2 Recycling benefits

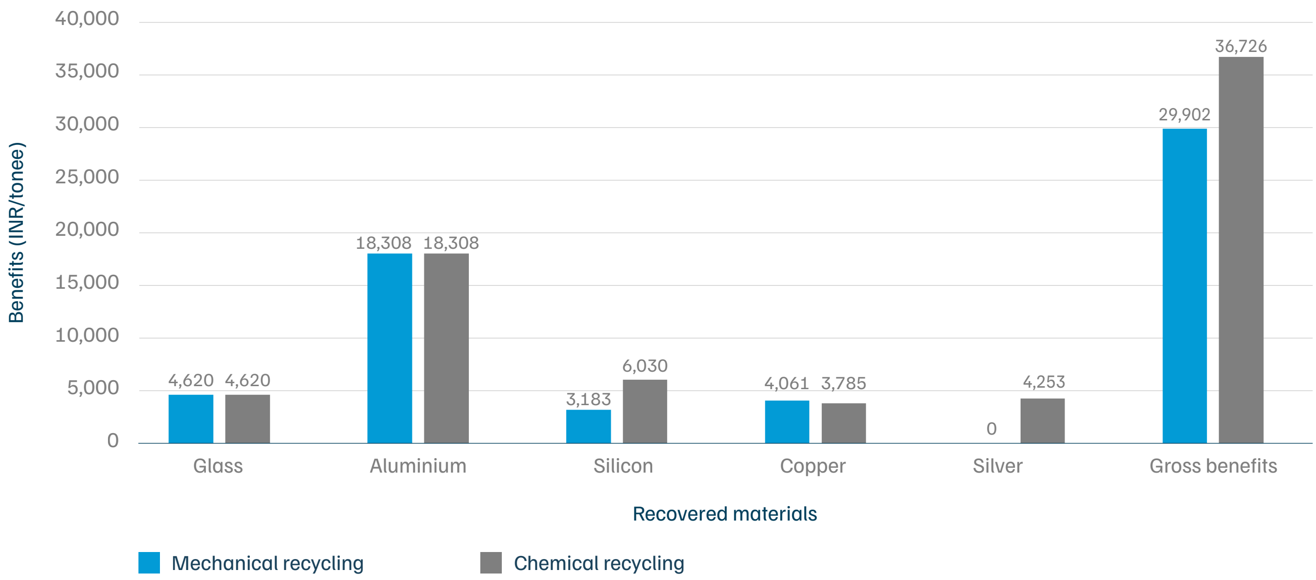
The mechanical pathway with electrostatic separation yields aluminium frames, glass cullet, low-quality copper, and ferrosilicon. Among these recovered materials, the sale of aluminium generates the highest revenue, followed by glass, copper, and silicon. Figure 5 and Table 10 summarise the financial benefits from the sale of these recovered materials.

Figure 4. Use of chemicals leads to higher processing costs in chemical recycling



Source: Authors' analysis

Figure 5. The higher costs for chemical recycling are balanced by its superior revenue potential due to the recovery of silver and silicon of a higher grade



Source: Authors' analysis

The chemical pathway yields MG-Si, copper and silver (both at a purity level of 99 per cent), aluminium frames, and glass cullet. Due to its higher content, aluminium contributes the largest revenue share in P2, although its share is relatively lower (11 per cent lower) than in P1 (Figure 4 and Table 10). The recovery of higher-grade silicon (metallurgical rather than ferrous) and silver is the primary driver of P2's higher benefits compared to P1. Conversely, the revenue generated from recovered copper is lower in P2 than in P1, due to a lower recovery rate (83 per cent in P1 compared to 95 per cent in P2).

Table 9. Chemical recycling has higher costs than mechanical recycling, mainly due to the need for additional equipment and the chemicals used

	Associated cost (INR/tonne)	
Component	**Mechanical recycling (P1)**	**Chemical recycling (P2)**
Non-recurring	**28,745** (18,542–40,648)	**39,959** (27,812–60,752)
Land	9,896 (3,125–21,243)	13,194 (4,167–21,243)
Construction	5,556 (5,000–6,111)	6,389 (5,833–6,944)
Compliance	417	556
Machinery	12,877 (10,000–12,877)	19,820 (17,256–32,008)
Recurring	**40,132** (36,287–43,833)	**49,067** (45,222–52,768)
Waste procurement	27,300 (25,000–30,000)	27,300 (25,000–30,000)
Collection	4,454 (2,909–5,455)	4,454 (2,909–5,455)
Processing	8,378	15,980
Workforce	2,961	3,511
Power	5,000	6,000
Maintenance	417	556
Material	0	5,913
Disposal	0	1,333

Source: Authors' analysis

Note: The numbers within brackets indicate the range of the parameters as described in the preceding sections.

Table 10. Chemical recycling offers greater benefits than mechanical recycling due to the recovery of higher-purity silicon and silver

Material recovered	P1 (INR/tonne)	P2 (INR/tonne)
Glass	4,620	4,620
Aluminium	18,038	18,038
Copper	4,061	3,785
Silicon	3,183	6,030
Silver	0	4,253
Polymer	0	0
Total	**29,902**	**36,726**

Source: Authors' analysis

5.3 Discussion

Based on the costs incurred and benefits accrued, we conclude that solar module recycling in its current form is financially unviable. Mechanical recycling generates a loss of INR 10,230 per tonne of waste processed (Table 11). Although chemical recycling recovers higher-grade materials, including precious metals such as silver, the result is still a loss of INR 12,341 per tonne, 21 per cent more than mechanical recycling (Table 11). Notably, P1 has a higher recovery rate for copper than P2. So, despite the lower-grade copper recovered in P1, it yields greater benefits than P2 which gives high-purity copper but in smaller amounts. As of Q2 2025, the cost of a 500 Wp domestic mono-PERC solar module is INR 17.72 per watt (JMK Research and Analytics 2025). In comparison, our analysis finds that recycling costs account for a substantial 23–28 per cent of this cost, at INR 4.11–5.02 per watt. However, as the recycling technologies mature and the volumes to treat increase, this cost is likely to come down.

In recent years, the production cost of polysilicon has declined sharply to approximately USD 15–20 per kg (INR 1,245–1,660 per kg) (PV Magazine 2024) outside China. Meanwhile, the average production cost in China for the first two quarters of 2025 was just USD 7.42 per kg[16] (INR 616 per kg) (Casey 2025). Recovering MG-Si from solar waste using P2 costs INR 1,627 per kg–approximately 2.5 times more expensive compared to China, although within the same range as production outside China.

Several reasons contribute to the poor financial outlook of solar module recycling, the most significant being the high procurement costs of waste modules. If waste solar modules were available to recyclers at no cost, the process could become revenue-positive. Specifically, mechanical recycling would generate a benefit of around INR 17,000 per tonne, while chemical recycling would generate a benefit of around INR 15,000 per tonne. Additional factors contributing to the poor financial outlook include:

i. **Low recovery rates of materials**: P2 recovers only 74 per cent of silver and 83 per cent of copper, which reduces the benefits for recyclers.

ii. **Low-purity grades of recovered materials**: P1 produces impure or low-purity materials, such as ferrosilicon and copper, reducing their benefits. Similarly, the recovery of only MG-Si instead of solar-grade silicon reduces the benefits of P2.

iii. **Low or no recovery of precious materials**: P1 does not recover silver, which has the highest salvage value of all materials present in the modules.

> High procurement costs for waste solar modules make formal recycling financially unviable.

16. The production cost considered here is as per one of China's largest polysilicon manufacturers, Daqo New Energy Corporation.

Table 11. Summary of the recycling costs and benefits

a) Costs and benefits in INR/tonne

Component	Mechanical recycling (P1)	Chemical recycling (P2)
Recurring costs	40,132 (36,287–43,833)	49,067 (45,222–52,768)
Gross benefits	29,902	36,726
Net impact	**−10,230 (−6,385–−13,931)**	**−12,341(−8,496–−16,042)**

b) Costs and benefits in INR/W

Component	P1	P2
Recurring costs	4.11 (3.71–4.49)	5.02 (4.63–5.40)
Gross benefits	3.06	3.76
Net impact	**−1.05 (−0.65–−1.43)**	**−1.26 (−0.87–−1.64)**

c) Costs and benefits in INR per module

Component	P1	P2
Recurring costs	883 (798–964)	1,079 (995–1,161)
Gross benefits	658	808
Net impact	**−225 (−140–−306)**	**−271 (−187–−353)**

Source: Authors' analysis

Note: The numbers mentioned within brackets represent the range for costs and benefits.

In addition to the free procurement of waste solar modules and improvements in recycling processes, EPR certificate trading is another potential revenue source that can help improve recyclers' financials (Box 1). Currently, the *E-Waste (Management) Rules,* 2022, do not prescribe EPR targets for producers of solar cells, panels, or modules. However, to assess the likely impact of the recent CPCB guidelines, we modelled a scenario in which EPR certificate trading is available to solar waste recyclers. The inclusion of EPR certificate sales increases gross benefit for recyclers by 74–124 per cent for mechanical recycling and 60–101 per cent for chemical recycling, compared to the scenario without EPR certificate trading.[17] This results in a positive net impact of INR 11,770–26,770 per tonne (INR 259–589 per module) for P1 and INR 9,659–24,659 per tonne (INR 213–543 per module) for P2. These results suggest that setting EPR targets for solar could significantly enhance the profitability of solar module recycling. Furthermore, our analysis indicates that incorporating EPR can significantly enhance returns on investment. The Internal Rate of Return (IRR) for P1 is calculated to be in the range of 21 to 64 per cent, while for P2, it is 9 to 40 per cent. Annexure C provides details on the capital structure and cash flow analysis.

17. The price range for the exchange of EPR certificates as per the EEE item category considered here is 30–50 per cent of the EC.

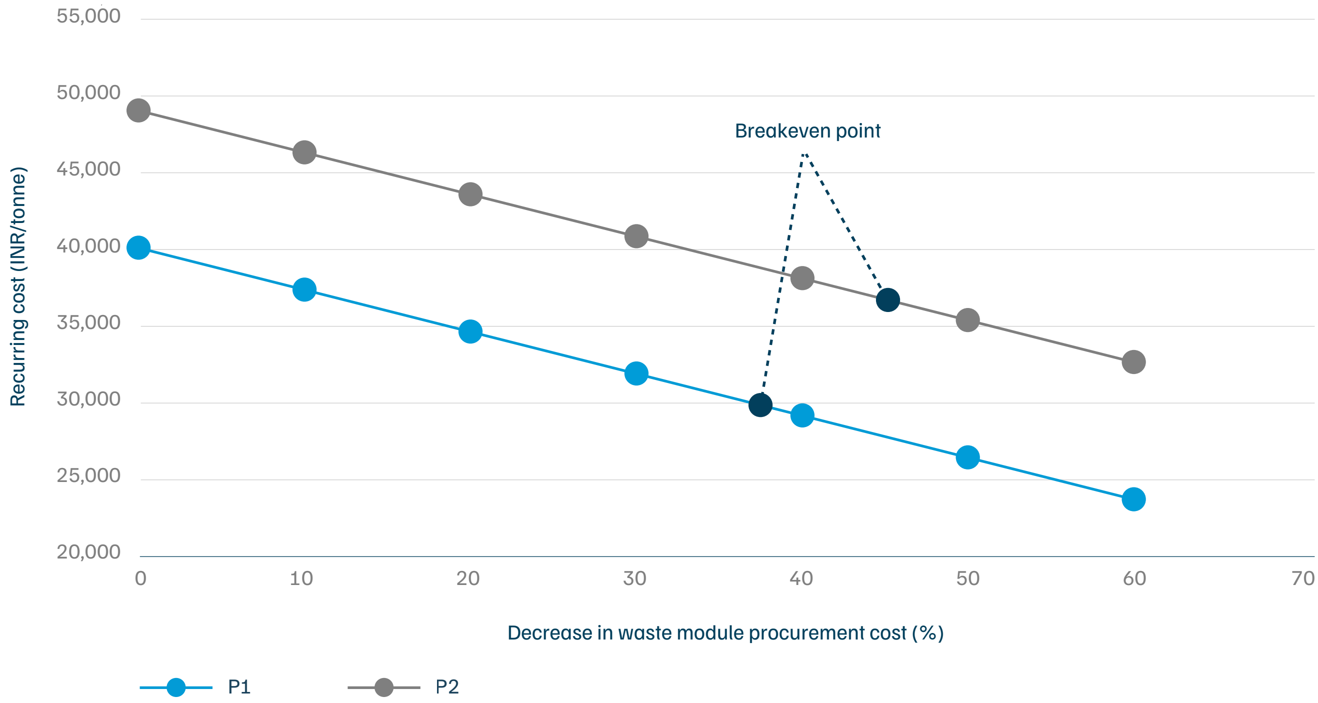
5.4 Sensitivity analysis

Several factors influence the financial viability of solar module recycling. This section presents the results of a sensitivity analysis conducted on three factors with the most significant influence on costs and benefits: waste procurement cost, collection cost and material composition. Annexures D and E provide results for additional parameters, including recovery rates of materials and their corresponding purity levels.

Waste procurement cost: Among the recurring expenses, the cost of purchasing the modules constitutes the highest share – 68 per cent for P1 and 56 per cent for P2. While the free procurement of waste solar modules would make recycling profitable, this is a challenging proposition for Indian markets, where consumers typically expect a certain salvage value in return for their waste. To model more realistic scenarios, we varied this cost. Our analysis suggests that for recycling to generate a positive net impact, waste procurement costs must be lower than INR 17,070 per tonne (INR 375 per module) for P1 and lower than INR 14,959 per tonne (INR 330 per module) for P2, assuming all other cost components remain unchanged. This translates to a drastic reduction of 37–45 per cent from the current level of INR 600 per module. The result is a recurring cost of INR 29,902 for P1 and INR 36,726 for P2, which would enable both recycling pathways to break even[18] (Figure 5).

Waste collection cost: Collection costs are directly proportional to the distance between waste centres and recycling units. Our analysis suggests that reducing the transportation distance from 360 km to 100 km would lower recurring costs by INR 3,217 per tonne (INR 71 per module) for both recycling pathways. This reduction translates to an 8 per cent decrease in recurring costs for P1 and 7 per cent for P2. Figure 6 shows the differences in collection costs for the five states with the highest installed solar capacities. Among these, Gujarat and Karnataka stand out with favourable conditions for strategically deploying recycling infrastructure.

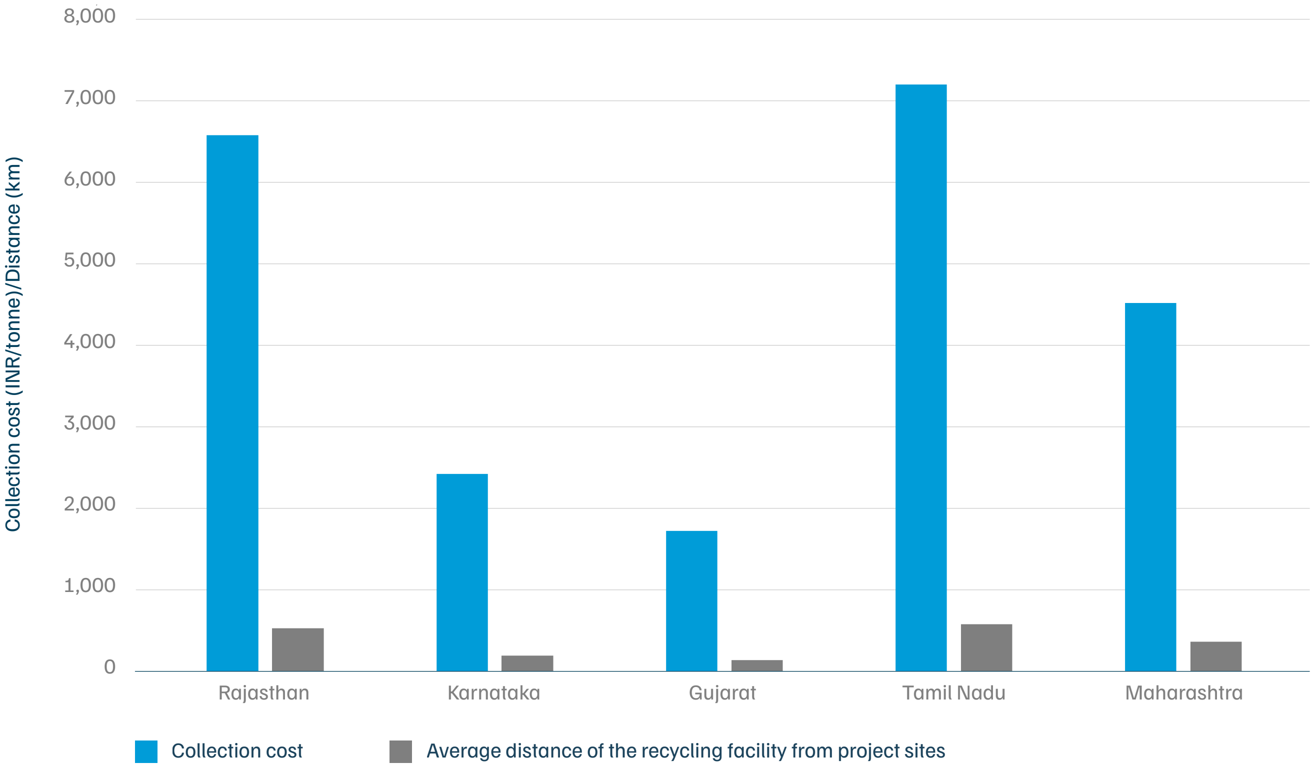
Figure 6. Module procurement cost should be below INR 375/module and INR 330/module for mechanical and chemical recycling to break even



Source: Authors' analysis

18. The point at which both the recurring costs and benefits become equal is termed as break even.

Figure 7. Short distances between project sites and recycling units lead to lower collection costs, such as in Gujarat



Source: Authors' analysis

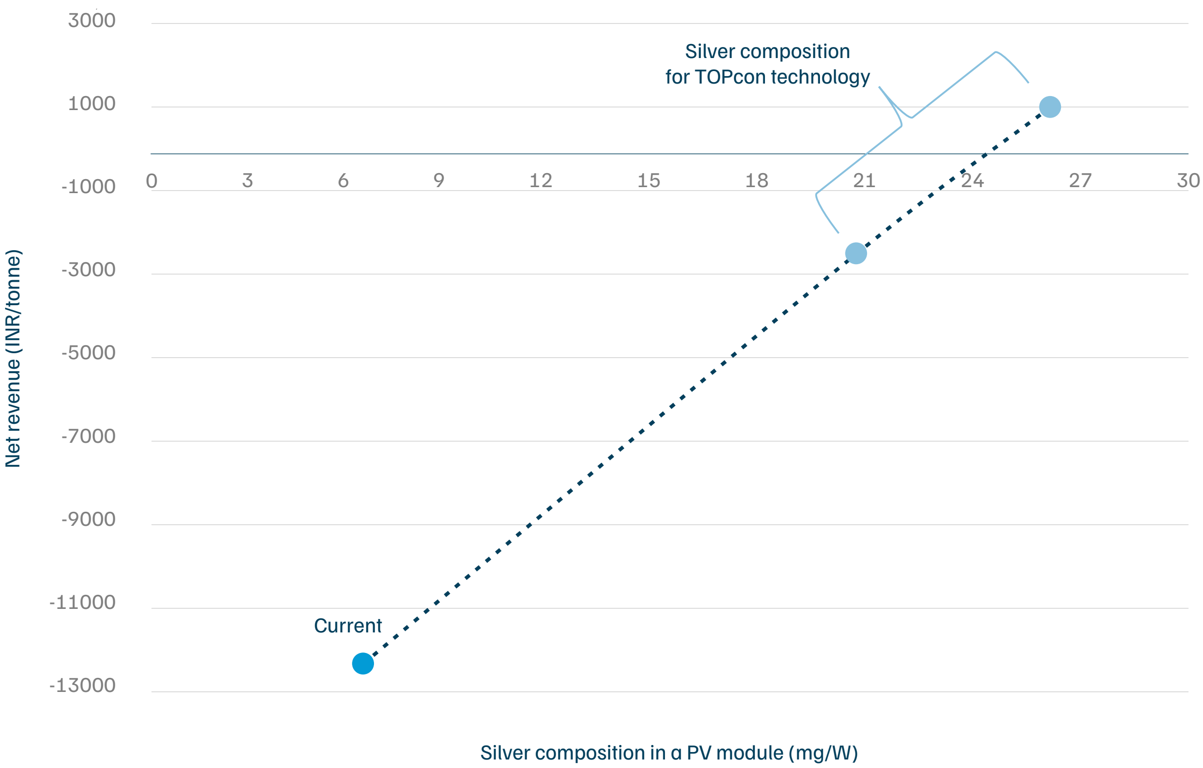
As solar projects are dispersed across districts in every state, distributed centres need to be identified to collect and process waste modules from nearby regions. A recent study developed an algorithm to determine optimal locations of solar module recycling centres in Karnataka (Taneja et al. 2023). Using agglomerative hierarchical clustering, it identified six collection centres[19] and two recycling centres across six clusters comprising 222 solar projects in the state.[20] Such an approach could be applied to strategically deploy recycling infrastructure.

Material composition: According to stakeholders, the next generation of PV installations in India will primarily use n-type Tunnel Oxide Passivated Contact (TOPCon) solar cell technology, which offers a record-breaking efficiency of more than 22 per cent (Waaree 2024). This technology has a high silver content in its material composition, ranging from 20.4 to 26 mg/W (Hallam et al. 2022), which is approximately 3.3–4.2 times the silver composition used in the current analysis.[21] A higher concentration of silver would substantially increase the benefits by 27–37 per cent. Assuming no additional processing costs for recovering this higher volume of silver from the solar waste through chemical recycling, the facility could achieve benefits of INR 1,125 per tonne (INR 25 per module) at a silver composition of 26 mg/W (Figure 7). Annexure D provides further details.

Other parameters, such as recovery rates of materials and their purity levels, also have a positive impact on the financials of recycling (Annexure E).

19. Collection centres are designated PV plants within each cluster that function as collection points for waste PV modules from other PV plants within the cluster.
20. Clusters are groups of PV plants located near one another.
21. The share of other materials in the module composition is assumed to be the same as before.

Figure 8. An increase in silver composition due to a change in module technology turns chemical recycling profitable



Source: Authors' analysis

Note: No other parametric values were changed during this calculation.

6. Conclusions and recommendations

Solar module recycling is an emerging industry, but the financial returns associated with the sector remain unattractive. Nevertheless, given the strategic and potential future economic opportunities, the industry must be scaled immediately. Recycling technologies must be developed to meet both current requirements and new trends in solar module manufacturing.

Mechanical recycling has been the preferred method for recycling various types of e-waste for over a decade. It is a familiar technology, with machinery that is well established and easy to scale. Being chemical-free, it avoids the use of harmful substances and the risk of generating hazardous by-products. Among the various recycling methods, it has the lowest recurring costs at INR 40,132 per tonne (INR 4.11

per watt or INR 883 per module). However, the materials recovered through mechanical recycling contain high concentrations of impurities. These low-purity end products have limited resale value in secondary markets, resulting in reduced benefits for recyclers–INR 29,902 per tonne (INR 3.06 per watt or INR 658 per module). Meanwhile, **chemical recycling enables the recovery of high-purity metals from solar waste**, including silver, which commands higher prices in secondary markets. This has the potential to increase revenues from recycling to INR 36,726 per tonne (INR 3.76 per watt or INR 808 per module). However, the process requires the additional use of chemicals, resulting in higher recurring costs of INR 49,067 per tonne (approximately INR 5.02 per watt or INR 1,079 per module). Chemical recycling technologies will, therefore, need further advancement and optimisation to enable the recovery of higher-grade silver and SoG-Si at scale.

In general, the **high procurement costs of waste modules and the low purity of recovered materials hinder module recycling**. Furthermore, given the volatility of commodity prices, it is prudent to focus on reducing both recurring and non-recurring costs to improve the financial viability of solar module recycling.

India must prioritise the development and scaling of solar module recycling pathways that can supply high-quality raw materials to existing and upcoming manufacturing industries. With polysilicon production expected to commence soon in the country, the demand for high-purity MG-Si, a raw material required for this process, is expected to rise significantly. Similarly, pure silver is essential for a range of applications beyond solar energy, including electronics, electric vehicles, aerospace, medical devices, and water purification (The Silver Institute 2025). Chemical-based recycling technologies have already demonstrated their capability to recover such high-purity materials. Ongoing industrial and academic research in such technologies is advancing process efficiencies, recovery rates, and the quality of recovered materials. To establish a reliable and efficient recycling ecosystem, policymakers must support existing and emerging technologies capable of recovering high-quality outputs.

Beyond technological challenges, the absence of regulatory mandates and market linkages for recovered materials limits the financial sustainability of solar module recycling. For example, Reclaim PV, a major player in Australia's solar PV recycling market, went bankrupt at the end of 2022 after attempting to develop an in-house low-cost recycling technology (Peacock 2023). Difficulties in establishing manufacturer networks, collection channels, and investor interest also contributed to the company's downfall. This case illustrates that numerous factors must align consistently to sustain such initiatives. These factors include a continuous supply of waste PV modules at low or no cost, an efficient recovery process to obtain high-purity materials from solar waste, low-cost reverse logistics mechanisms, and affordable electricity and material costs for processing solar waste. The recently launched mineral recycling incentive scheme under the *National Critical Mineral Mission* will support reducing recycling costs (MoM 2025). However, additional support can be provided at the state level.

We make the following recommendations for policymakers, technology providers, and the solar industry to establish a financially viable solar module recycling ecosystem in India.

For policymakers

1. Strengthen solar waste management regulations and incentivise the full recovery of materials.

a. **The MoEFCC should amend the E-Waste (Management) Rules, 2022, to introduce EPR targets for solar waste from 2027**. The current rules only mandate storage of solar PV waste until 2034–2035. Removing these obligations and introducing EPR targets would ensure two critical outcomes: solar waste will be channelled more efficiently to registered recyclers, and recyclers will be assured consistent volumes of solar waste. These **EPR targets should include separate collection and recycling targets as well as material-specific recovery targets**. This approach would ensure the recovery of all materials specified under the rules. In contrast, notifying an overall recovery rate could lead to the recovery of only certain materials, such as glass and aluminium, which together account for about 85 per cent of module weight. For instance, existing EU recyclers using mechanical processes can easily achieve a WEEE-compliant overall recovery rate of 85 per cent (EUR-Lex n.d.). **The EPR targets should also be extended to the refurbishing of solar modules, allowing producers**

India must prioritise the development and scaling of solar module recycling pathways that can supply high-quality raw materials to manufacturing industries.

to offset recycling EPR targets. The Bureau of Indian Standards and the National Institute of Solar Energy (NISE) should jointly develop standards for second-life modules. This measure would facilitate the creation of a repair and reuse industry for solar modules.

b. **The MoEF&CC and CPCB should expand the scope of EPR certificates beyond aluminium and iron to include other metals commonly found in solar modules, such as copper, silver, silicon, cadmium, and tellurium**. For instance, trading EPR certificates for recovered copper and aluminium could generate net positive impacts of INR 6,682 per tonne (INR 147 per module) for mechanical recycling and INR 4,186 per tonne (INR 92 per module) for chemical recycling.[22]

c. **The MoEF&CC should increase the solar developers' responsibility for solar waste management under the *E-Waste (Management) Rules*** 2022. Project developers should be made responsible for declaring their waste from repowering and decommissioning projects and channelling it to authorised recyclers. Developer must ensure that the asset management companies managing their projects also comply with these responsibilities. Furthermore, any damage to the project are managed by insurance companies, who, as per our stakeholder consultations, currently auction the rejected modules to different entities. **It is important that developers mandate their insurers to adhere to the current E-Waste (Management) Regulations and supporting collection and storage obligations**. Later, as the responsibilities evolve, the contracts between developers and insurers must also change to reflect these additional responsibilities.

2. Design mechanisms to reduce investments and costs.

a. **State industrial departments and state industrial development corporations (SIDCs) should provide capital incentives, tax breaks and create recycling clusters**. State industrial departments should extend capital incentives and tax breaks to invest in land, buildings, machinery, equipment, and associated utilities and technologies. Where such provisions already exist under state industrial policies, their scope should be expanded to include solar module recycling. States can also develop integrated recycling clusters that leverage shared infrastructure and feedstock. For example, Rajasthan has initiated such an effort by formulating an *Integrated Resource Recovery Park Scheme*, which allocates land for waste recycling units (including electronics, plastic, hazardous waste, batteries, and end-of-life vehicles) through e-auctions (RIICO 2023). More SIDCs should notify similar provisions to support the development of recycling clusters.

b. **The state pollution control boards and pollution control committees should facilitate demand aggregation for solar waste**. Aggregating the demand of waste PV modules within the state boundaries will help local recyclers reach critical volumes to process. For this purpose, the pollution control boards and committees may also involve urban local bodies or panchayats, particularly to manage the waste coming from distributed solar installations.

3. Nurture technology innovation.

a. **The DST and MNRE should support technology development and demonstration of efficient recycling technologies**. Most high-efficiency module recycling technologies are still in early stages of development, with limited proven commercial feasibility. To address this gap, policymakers must support both the development and demonstration of new technologies through research grants for both academic institutions and private companies. The Division of Climate, Energy, and Sustainable Technology under the DST and the MNRE have already initiated several efforts; however, sustained efforts are needed with greater focus on technology demonstration and scale up. Institutions such as NISE can also lead these technology demonstrations efforts to have a better visibility on the technology landscape. For instance, NISE and Attero (a battery recycler) have signed an MoU to test and pilot new PV recycling technologies (Gupta 2025).

b. **The MNRE, in collaboration with NISE, should foster partnerships among the solar producers and recyclers**. Besides technology development, equivalent emphasis is required on creating market linkages and partnerships between recyclers and the solar industry. Such linkages could include offtake agreements with companies manufacturing solar glass, aluminium

> States with solar manufacturing facilities could also develop recycling clusters that will help recyclers leverage shared infrastructure and feedstock to reduce their costs.

22. The lowest price for the exchange of EPR certificates as per the end product recovered is considered here, i.e., 30 per cent of EC.

frames, and upcoming ones to manufacture polysilicon, which would not only improve recyclers' revenues but also help establish a closed-loop circular economy. The MNRE may also leverage the Resource Efficiency Circular Economy Industry Coalition (RECEIC), launched during India's G20 presidency, to promote technology use cases and drive the on-ground implementation of circular solutions. Matchmaking events should also be organised to identify high-impact solutions for solar module recycling, similar to the successful India–EU collaboration in electric vehicle battery recycling (PIB 2024b).

For technology providers

1. **Develop efficient technologies via strategic partnerships**. Academics and recyclers should expedite the research, development, and demonstration of efficient and scalable recycling technologies, with a focus on achieving high recovery rates and high purity. For instance, **recovering SoG-Si for reuse in the manufacturing of new modules could lead to a 66 per cent increase in gross benefits accrued through using chemical recycling**, though it would necessitate additional investment.[23]

Technology providers should also track the evolution of PV module design and material composition. Shifts in design can render current recycling technologies obsolete, pose a risk to current investments. The industry should therefore invest in recycling technologies that can handle current modules and adapt to future technologies. In addition, recyclers should incorporate current recycling standards at new or existing facilities. This will lead to the implementation of rigorous safety standards and protocols, ensuring a safe and environmentally friendly work environment at recycling facilities. For example, recyclers can adopt the *Sustainable Electronics Reuse and Recycling (R2) Standard*, developed by Sustainable Electronics Recycling International, which provides guidelines for the safe handling of solar waste at recycling facilities.

2. **Recover market-ready materials**. Technology providers should identify end-users for recovered materials, extending beyond the solar industry to include other secondary markets. This includes the cement industry, where recovered glass (Máčalová et al. 2021) and crushed PV laminate can serve as substitutes for sand (Zele et al. 2024), and the battery industry, where recovered MG-Si can replace the silicon anode in lithium-ion batteries (Sim et al. 2023). **Determining the purity levels of recovered materials can help with identifying their applications in the secondary market**. For example, recovered MG-Si with a purity level above 98.5 per cent can be used in the production of anodes for lithium-ion batteries (Feyzia et al. 2024). Identifying such secondary markets will help ensure the financial viability of current recycling technologies that can recover materials of only limited grade. Thus, recycling costs are kept in check.

For solar cell and module producers

1. **Invest in waste management infrastructure**. Solar cell and module producers should go beyond the limited obligations outlined in the *E-Waste (Management) Rules* to establish reliable, cost-effective collection and reverse logistics mechanisms, thereby enhancing the financial viability of solar module recycling. **Manufacturers should also collaborate with technology providers to improve lab-scale recycling technologies** to make them commercially viable, supported by adequate fiscal incentives and knowledge-sharing. Developing effective business models that guarantee a continuous stream of waste modules to recyclers would strengthen both the recycling sector and overall solar waste management. Academia–industry collaborations should also be encouraged to help translate research into commercially scalable recycling technologies. In this way, all stakeholders can work towards the common goal of developing financially viable recycling technologies.

2. **Leverage existing financial mechanisms available with project developers for financing solar waste management**. Several renewable energy implementation agencies already incorporate provisions for the safe disposal of solar waste within their 'Request for Selection' documents, making developers liable for these requirements.[24] Such an arrangement would encompass all the stages from the decommissioning of installed solar modules to their safe disposal. Additionally, developers certified under ISO 14001 must ensure

> Technology providers must scale module recycling with efficient, and cost-effective technologies while securing end-users for recovered materials within and beyond the solar sector.

23. The price of solar grade silicon is considered to be five times the MG-Si price (Heath et al. 2020).
24. The provision of safe disposal of solar waste is included in the section termed as "Safe disposal of solar PV modules" under the annexure titled–"Technical parameter of PV module and various other components for use in grid connected solar power plants" in the Request for Selection document released by entities such as SECI (SECI 2024), SJVN (SJVN Limited 2024), UPNEDA (UPNEDA 2025), etc.

that, after decommissioning, solar waste is disposed of through authorised channels to prevent it from becoming landfill; they must ensure that it is sent for recycling to recover valuable materials. Furthermore, according to the Central Electricity Regulatory Commission's *Draft Renewable Energy Tariff Regulations*, a project's salvage value can be considered up to 10 per cent of its capital cost (Central Electricity Regulatory Commission 2024). A share of this financial value can be utilised by developers for decommissioning and disposing of the solar waste through authorised recyclers.[25] Producers can tap into these provisions and create a mutually agreed-upon financing model for solar waste management with project developers.

3. **Improve module design**. The PV industry should incorporate circular design principles, such as design for disassembly, reuse, and recycling, to enable easier and more cost-effective recovery of components and materials from PV modules. Since module composition determines recovery processes, producers should disclose detailed material composition data so that technology providers can design and develop efficient processes that ensure high-purity recovery. This could be achieved by including material composition data as a field on the Radio Frequency Identification tags already mandated by the MNRE for all solar modules manufactured or installed in the country. Another method to achieve this is introducing digital product passports for solar modules, also known as PV passports, which carry relevant information on various data categories and fields, including material composition data. Such measures can effectively guide investments.

> Solar cell and module producers should incorporate circular design principles to support easy and efficient recycling.

25. However, this may lead to a marginal increase in solar tariffs, as developers would incorporate these costs in project planning to preserve their profit margins.

Annexures

Annexure A

General assumptions

The recycling facility operates in 2 shifts per day, each lasting 8 hours, for 315 working days a year. A downtime of 15 days is considered.

The pathway-specific assumptions are outlined as follows:

Assumptions for recycling P1 (mechanical pathway)

1. The workforce required to operate the facility during a single shift is 14. This includes 10 process operators and other labour on the facility floor, 2 maintenance technicians, 1 plant supervisor, and 1 plant manager.

2. No disposal costs are incurred, as the waste generated at the end of this pathway, i.e., the dust produced during shredding and grinding operations, is sold in the secondary market.

Assumptions for recycling P2 (chemical pathway)

1. The workforce required at the facility during a single shift of operation is 19, as P2 involves more individual operations than P1. This includes 15 process operators and other labour required on the facility floor, 2 maintenance technicians, 1 plant supervisor, and 1 plant manager. Apart from the processes involved in P1, an additional workforce is required to feed the mixture obtained at the end of the mechanical processing into chemical treatment and to neutralise the chemical waste.

2. The chemicals required to process 1 tonne of solar waste into silicon cells, along with the necessary electrodes, cumulatively cost INR 5,913.[26]

3. The disposal cost of chemical waste generated at the end of P2 is taken as INR 4,00,000 per month.

26. Number determined by summation of average prices of individual chemicals and electrodes used obtained from online marketplaces.

Table A1. Input values for various parameters in the mechanical and chemical recycling processes

Parameter	Value	Unit
Annual PV waste volume processed	3,600	tonnes
Number of shifts in a day	2	-
Number of hours in a shift	8	hours
Total number of working days in a year	315	days
Downtime	15	days
Weight of a PV module	22	kg
Average transportation distance from the project site to the recycling facility	360	km
Land required for P1	30,000	sq ft
Land required for P2	40,000	sq ft
Land cost	1,188	INR/sq ft
Mechanical machinery cost for P1	3,53,58,000	INR
Mechanical machinery cost for P2	3,42,30,500	INR
Installation costs for P1	1,10,00,000	INR
Thermal and chemical equipment cost for P2	2,21,21,429	INR
Installation costs for P2	1,50,00,000	INR
Compliance cost for P1	15,00,000	INR
Compliance cost for P2	20,00,000	INR
Waste module procurement cost	27,300	INR/tonne
Power cost		
P1	15,00,000	INR/month
P2	18,00,000	
Maintenance cost		
P1	15,00,000	INR/year
P2	20,00,000	
Chemicals and electrodes cost to process silicon cells in 1 tonne of solar waste	5,913	INR
Workforce required		
P1	14	INR/month
P2	19	
Chemical waste disposal cost for P2	4,00,000	INR/month

Source: Authors' compilation of their analysis and stakeholder consultations

Annexure B

The following sections describe the various recurring and non-recurring costs associated with solar module recycling.

I. **Non-recurring costs**

These are one-time costs incurred during the setup of the infrastructure for a solar module recycling facility. They include:

1. Land: Cost of procuring land for the facility (via direct acquisition).
2. Construction: Cost of constructing the recycling facility and associated infrastructure.
3. Machinery: Cost of the machinery required to process the desired volume of waste.
4. Compliance: Cost of obtaining certifications, authorisations, and clearances required to construct and operate the facility.

II. **Recurring costs**

These are annual costs incurred by recyclers to process the desired volume of solar waste. They include:

1. Waste module procurement: Cost of procuring waste solar PV modules from manufacturers.
2. Collection: Cost of transporting waste solar PV modules from solar project sites to the recycling facility.
3. Processing: Cost of conducting all recycling operations at the facility. This can be further subdivided into

a) Workforce: Cost of labour required to run the recycling facility.

b) Power: Cost of electricity to run the recycling facility.

c) Maintenance: Cost of the workforce needed to maintain the recycling facility.

d) Material: Cost of materials, such as chemicals, required during the recycling operations.

4. Disposal: Cost associated with the disposal of waste generated at the recycling facility. This includes the cost of transporting waste to treatment, storage, and disposal facilities, as well as costs associated with incineration and landfilling.

Annexure C

Table A2. Capital structure for the modelled recycling pathways

Parameter	Value
Debt-to-equity ratio	70:30
Cost of debt	9%
Repayment period	15 years
Cost of equity	14%
Tax rate	25%
Discount rate	9%

Source: Authors' analysis

Based on this capital structure, we assess the cash flow statement as per the following assumptions:

i. A 5 per cent year-on-year growth in the benefits accrued.

ii. A compound annual growth rate of 53 per cent in P1 and 64 per cent in P2 for the processing costs.

iii. A 5 per cent increase in the waste module procurement cost for the initial period of 5 years.

Annexure D

Table A3. Chemical recycling becomes profitable due to the increase in silver content in PV modules

Scenario	Silver content (mg/W)	Silver share in overall composition (%)	Silver benefits (INR/tonne)	Gross benefits (INR/tonne)	Net impact (INR/tonne)	Net impact (INR/module)
Base	6.14	0.006	4,252	36,726	−12,341	−271
TOPCon (Low)	20.4	0.020	14,175	46,648	−2,419	−53
TOPCon (High)	26	0.025	17,718	50,192	1,125	25

Source: Authors' analysis

Annexure E

Recovery rates of materials: Recovery rates are a critical parameter influencing the revenue of recycling operations. In P2, the recovery rates for silver and copper are influenced by various factors. For instance, different chemistries and processes can achieve increased recovery rates, such as 97 per cent for silver (Tao et al. 2019) and 95 per cent for copper (Latunussa et al. 2016). In contrast, recovery rates can decrease due to the simultaneous reduction of other metals present in the solution (Kanellos et al. 2024), high solid-to-liquid ratios of the chemical solution (Jiajia Tian et al. 2024), as well as variations in temperature, time, and other factors.

Purity levels of materials: The purity grade of recovered materials has a significant impact on their resale value. Market prices can increase by orders of magnitude as the grade of the material improves. For instance, ferrosilicon recovered through P1 has a low market price, whereas MG-Si recovered in P2 is more valuable. MG-Si requires further processing to produce SoG-Si for module manufacturing. Further technological improvements that enable SoG-Si recovery could yield higher profits, though they may also involve additional costs associated with process innovation.

Similarly, the recovered crushed glass is sold as scrap in the secondary market at a relatively low price. However, intact glass has the potential to be reused in new PV modules, offering higher profit opportunities (Bellini 2021). Careful handling during transportation is essential to prevent the intact glass from getting damaged. Hence, recycling technologies need to focus on recovering high-purity materials to generate high revenues while considering the recycling costs.

Acronyms

CPCB	Central Pollution Control Board
DST	Department of Science and Technology
EC	environmental compensation
EEE	electrical and electronic equipment
EPR	extended producer responsibility
EVA	ethyl vinyl acetate
EU	European Union
FICCI	Federation of Indian Chambers of Commerce and Industry
GW	gigawatt
IEA	International Energy Agency
MG-Si	metallurgical grade silicon
MNRE	Ministry of New and Renewable Energy
MoEF&CC	Minister for Environment, Forest and Climate Change
MoM	Ministry of Mines
NISE	National Institute of Solar Energy
NSEFI	National Solar Energy Federation of India
PV	photovoltaic
RECEIC	Resource Efficiency Circular Economy Industry Coalition
RE-RTD	*Renewable Energy Research and Technology Development Programme*
ROSI	Return of Silicon
SDG	Sustainable Development Goals
SECI	Solar Energy Corporation of India
SIDC	State Industrial Development Corporation
SJVN	Satluj Jal Vidyut Nigam Limited
SoG-Si	solar-grade silicon
TOPCon	Tunnel Oxide Passivated Contact
TRL	technology readiness level
UPNEDA	Uttar Pradesh New and Renewable Energy Development Agency
USA	United States of America
USD	United States dollar
WEEE	waste electrical and electronic equipment

References

ARENA. 2020a. “Efficient, Low-Cost, Eco-Friendly Solar PV Recycling Technology.” Australian Renewable Energy Agency. https://arena.gov.au/projects/efficient-low-cost-eco-friendly-solar-pv-recycling-technology/.

ARENA. 2020b. “Closed-Loop Recycling and Remanufacturing EoL Solar PV.” Australian Renewable Energy Agency. https://arena.gov.au/projects/closed-loop-recycling-and-remanufacturing-eol-solar-pv/.

Bellini, Emiliano. 2021. “European Consortium Develops Pilot Line for Complete PV Module Recycling.” *PV Magazine*, November 17. https://www.pv-magazine.com/2021/11/17/european-consortium-develops-pilot-line-for-complete-pv-module-recycling/.

Berger, Wolfgang, Simon Franz-Georg, Karin Weimann, and Erik A. Alsema. 2010. “A Novel Approach for the Recycling of Thin Film Photovoltaic Modules.” *Resources, Conservation and Recycling* 54 (10): 711–718. https://doi.org/10.1016/j.resconrec.2009.12.001.

Beyer, Marie. 2022. “New PV Recycling Tech from France.” *PV Magazine*, February 15. https://www.pv-magazine.com/2022/02/15/new-pv-module-recycling-tech-from-france/.

Bruton, T. M., R. D. W. Scott, and J. P. Nagle. 1994. “Recycling of High Value, High Efficiency Content Components of Silicon PV Modules.” In Proceedings of the 12th EC PVSEC, Amsterdam, 1994: 303–304.

Cain, Nicholas. 2024. “Solar Panel Recycling: Why and How to Recycle Solar Panels.” SOLARCYCLE, April 12. https://www.solarcycle.us/resources/why-and-how-to-recycle-solar-panels.

Casey, J. K. 2025. “Daqo Losses Stabilise as Polysilicon Production Exceeds Sales for the First Time this Year.” PVTECH, August 26. https://www.pv-tech.org/daqo-losses-stabilise-polysilicon-production-exceeds-sales-first-time-this-year/.

Central Electricity Regulatory Commission. 2024. “Draft Renewable Energy Tariff Regulations, 2024.” New Delhi, India: Central Electricity Regulatory Commission, Government of India. https://cercind.gov.in/2024/draft_reg/DN170224.pdf.

CORDIS. 2023. “Sustainable Solutions for Solar Panel Waste.” European Commission. https://cordis.europa.eu/project/id/101122298.

CPCB. 2016. “Guidelines on Implementation of E-Waste (Management) Rules, 2016.” New Delhi, India: Central Pollution Control Board, Government of India. https://cpcb.nic.in/displaypdf.php?id=aHdtZC9HVUlERUxJTkVTX0VXQVNURV9SVUxFU18yMDE2LnBkZg==.

CPCB. 2023. “List of Dismantlers/Recyclers as per the Authorisation Issued by SPCBs/PCCs under E-waste (Management) Rules, 2026.” New Delhi, India: Central Pollution Control Board, Government of India. https://www.ndmc.gov.in/pdf/cpcb_approved_list_of_e-waste_recyclers_dismantler.pdf.

CPCB. 2024a. “Environmental Compensation Guidelines under E-Waste Management Rules, 2022.” New Delhi, India: Central Pollution Control Board, Government of India. https://cpcb.nic.in/openpdffile.php?id=TGF0ZXN0RmlsZS80MjBfMTcyNTg4MzY3N19tZWRpYXBob3RvMzM0OC5wZGY=.

CPCB. 2024b. “Framework for Generation of EPR Certificate under E-Waste (Management) Rules, 2022.” New Delhi, India: Central Pollution Control Board, Government of India. https://cpcb.nic.in/openpdffile.php?id=TGF0ZXN0RmlsZS8zOTBfMTY5NTM1ODM1OF9tZWRpYXBob3RvMjA2MzgucGRm.

CPCB. 2024c. “Guidance Document for Generation and Transfer of EPR Certificate Under E-Waste Management Rules, 2022.” New Delhi, India: Central Pollution Control Board, Government of India. https://eprewastecpcb.in/assets/Guidance%20document%20for%20E-Waste%20-%20generation%20and%20transfer%20of%20EPR%20Certificate_Final%20(1).pdf.

CPCB. 2025. “Draft Guidelines for Storage and Handling of Waste Solar Photo-Voltaic Modules or Panels or Cells Under E-Waste Management Rules, 2022.” New Delhi, India: Central Pollution Control Board, Government of India. https://cpcb.nic.in/openpdffile.php?id=UmVwb3J0RmlsZXMvMTc0NV8xNzQ5MDM0NjU5X21lZGlhcGhvdG8xMTY0Ni5wZGY=.

Deng, Rong, Nathan L. Chang, Zi Ouyang, and Chee Mun Chong. 2019. “A Techno-Economic Review of Silicon Photovoltaic Module Recycling.” *Renewable and Sustainable Energy Reviews* 109 (1): 532–550. https://doi.org/10.1016/j.rser.2019.04.020.

Deng, Rong, Yuting Zhuo and Yansong Shen. 2022. “Recent progress in silicon photovoltaic module recycling processes.” Resources, Conservation and Recycling. 187 (1): 106612. https://doi.org/10.1016/j.resconrec.2022.106612.

Doi, T., I. Tsuda, H. Unagida, A. Murata, K. Sakuta, K. Kurokawa. 2001. "Experimental Study on PV Module Recycling with Organic Solvent Method." *Solar Energy Materials and Solar Cells* 67 (1): 397–403. https://doi.org/10.1016/S0927-0248(00)00308-1.

DST. 2024. "Recovery and Recycling of End-of-Life Solar PV Panels/Modules." Department of Science and Technology, Government of India. https://dst.gov.in/callforproposals/recovery-and-recycling-end-life-solar-pv-panelsmodules.

ENGIE. 2021. "How are Solar Panels Recycled?" *ENGIE*, September 8. https://www.engie.com/en/activities/renewable-energies/solar-energy/recycling-solar-panels?.

ETC. 2023. "Better, Faster, Cleaner: Securing Clean Energy Technology Supply Chains." Energy Transitions Commission. https://www.energy-transitions.org/wp-content/uploads/2023/06/ETC_Barriers_SupplyChains_InsightsBriefing.pdf.

Feyzia, Ebrahim, Anil Kumar M R, Xia Lia, Sixu Deng, Jagjit Nanda, and Karim Zaghib. 2024. "A Comprehensive Review of Silicon Anodes for High-Energy Lithium-Ion Batteries: Challenges, Latest Developments, and Perspectives." Next Energy 5: 100176. https://doi.org/10.1016/j.nxener.2024.100176.

FICCI. 2024. "Future-Proofing Growth: Accelerating Adoption of the Circular Economy A Compendium of Circular Business Models." Federation of Indian Chambers of Commerce and Industry. https://www.ficci.in/study_details/24045.

First Solar. 2025. *Corporate Responsibility Report*. https://www.firstsolar.com/en-IN/-/media/First-Solar/Sustainability-Documents/FirstSolar_Corporate-Responsibility-Report_2025.pdf.

First Solar. 2024. "First Solar Inaugurates 3.3 GW Manufacturing Facility in India." First Solar, January 11. https://investor.firstsolar.com/news/news-details/2024/First-Solar-Inaugurates-3.3-GW-Manufacturing-Facility-in-India/default.aspx.
Frisson, L., K. Lieten, K. Declercq, J. Szlufcik, H. de Moor, M. Goris, A. Benali, and O. Aceves. 2000. "Recent Improvements in Industrial PV Module Recycling." May 1-5 2000. Glasgow UK. 16th European Photovoltaic Solar Energy Conference.

G20. 2023. "G20 New Delhi Leaders' Declaration." https://www.mea.gov.in/Images/CPV/G20-New-Delhi-Leaders-Declaration.pdf.

Gasik, M., ed. 2013. *Handbook of Ferroalloys: Theory and Technology*. Butterworth-Heinemann. https://www.sci¬encedirect.com/book/9780080977539/handbook-of-fer¬roalloys.

Gupta, Uma. 2025. Attero Enters Solar Panel Recycling MoU with NISE. *PV Magazine*, April 16. https://www.pv-magazine-india.com/2025/04/16/attero-enters-solar-panel-recycling-mou-with-nise/.

Heath, Garvin A., Timothy J. Silverman, Michael Kempe, et al. 2020. "Research and Development Priorities for Silicon Photovoltaic Module Recycling to Support a Circular Economy." *Nature Energy* 5 (7). https://doi.org/10.1038/s41560-020-0645-2.

Hallam, Brett, Moonyong Kim, Yuchao Zhang, et al. 2022. "The Silver Learning Curve for Photovoltaics and Projected Silver Demand for Net-Zero Emissions by 2050." *Progress in Photovoltaics Research and Applications* 31 (6): 598–606. https://doi.org/10.1002/pip.3661.

IEA. 2024. *Renewables 2024*. International Energy Agency. https://iea.blob.core.windows.net/assets/17033b62-07a5-4144-8dd0-651cdb6caa24/Renewables2024.pdf.

IEA. 2023. "Critical Minerals Data Explorer." International Energy Agency. Last modified May 21, 2025. https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.

IEA PVPS. 2022. *Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries*. International Energy Agency Photovoltaic Power Systems Programme. https://iea-pvps.org/wp-content/uploads/2022/09/Report-IEA-PVPS-T12-24_2022_Status-of-PV-Module-Recycling.pdf.

IEA PVPS. 2023. "Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology." International Energy Agency Photovoltaic Power Systems Programme. https://iea-pvps.org/wp-content/uploads/2023/07/Report_IEA-PVPS_T12-25-2023_LCA-PV-Recycling-Hot-Knife.pdf.

IEA PVPS. 2015. "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems." International Energy Agency Photovoltaic Power Systems Programme. https://iea-pvps.org/key-topics/life-cycle-inventories-and-life-cycle-assessments-of-photovoltaic-systems/.

Intersolar Europe. 2025. "Solar Technology is Undergoing Great Changes." *Intersolar Europe*, January 28. https://www.intersolar.de/market-trends/solar-cell-development.

ISO. 2015. "ISO 14001:2015. Environmental Management Systems – Requirements with Guidance for Use." International Organization for Standardization. https://www.iso.org/standard/60857.html#:~:text=ISO%2014001%20is%20the%20internationally,continually%20improve%20their%20environmental%20performance.

Schröder, P. and Barrie, J. 2024. “How the circular economy can revive the Sustainable Development Goals: Priorities for immediate global action, and a policy blueprint for the transition to 2050.” London: Royal Institute of International Affairs. https://doi.org/10.55317/9781784136222.

JMK Research and Analytics. 2025. “RE Update – Q2 2025 (Apr–Jun).” https://jmkresearch.com/renewable-sector-published-reports/q2-2025-apr-jun-india-re-update/#:~:text=In%20Q2%202025%2C%20the%20price,year%2Dover%2Dyear%20increase.&text=In%20Q2%202025%2C%209.4%20GW,contributed%20around%20~54%25%20share.

Kanellos, G., A. Tremouli, P. Tsakiridis, et al. 2024. “Silver Recovery from End-of-Life Photovoltaic Panels Based on Microbial Fuel Cell Technology.” *Waste Biomass Valor* 15: 75–86. https://doi.org/10.1007/s12649-023-02128-1.

Kim, Youngjin, and Jaeryeong Lee. 2012. “Dissolution of Ethylene Vinyl Acetate in Crystalline Silicon PV Modules using Ultrasonic Irradiation and Organic Solvent.” *Solar Energy Materials and Solar Cells* 98: 317–322. https://doi.org/10.1016/j.solmat.2011.11.022.

Klugmann-Radziemska, E., P. Ostrowski, K. Drabczyk, P. Panek, and M. Szkodo. 2010. “Experimental Validation of Crystalline Silicon Solar Cells Recycling by Thermal and Chemical Methods.” *Solar Energy Materials and Solar Cells* 94 (12): 2275–2282. https://doi.org/10.1016/j.solmat.2010.07.025.

Krueger, Lisa. 2010. “Overview of First Solar’s Module Collection and Recycling Program.” First Solar. https://www.yumpu.com/en/document/view/2944270/overview-of-first-solars-module-collection-and-recycling-program.

Latunussa, Cynthia E. L., Fulvio Ardente, Gian Andrea Blengini, and Lucia Mancini. 2016. “Life Cycle Assessment of an Innovative Recycling Process for Crystalline Silicon Photovoltaic Panels.” *Solar Energy Materials and Solar Cells* 156 (1): 101–111. https://doi.org/10.1016/j.solmat.2016.03.020.

Li, Jiayan, Shuang Yan, Yaoyao Li, Zhiqiang Wang, Yi Tan, Jin Li, Mingxu Xia, and Pengting Li. 2023. “Recycling Si in Waste Crystalline Silicon Photovoltaic Panels after Mechanical Crushing by Electrostatic Separation.” *Journal of Cleaner Production* 415 (1): 137908. https://doi.org/10.1016/j.jclepro.2023.137908.

Máčalová, Kateřina, Vojtěch Václavík, Tomáš Dvorský, Róbert Figmig, Jakub Charvát, and, Miloslav Lupták. 2021. “The Use of Glass from Photovoltaic Panels at the End of Their Life Cycle in Cement Composites.” *Materials* 14 (21): 6655. https://doi.org/10.3390/ma14216655.

MarketsandMarkets. 2025. *Solar Panel Recycling Market*. https://www.marketsandmarkets.com/Market-Reports/solar-panel-recycling-market-2927896.html.

Mercom India. 2025. “Daqo’s Q4 2024 Revenue Drops as Polysilicon ASPs Fall.” Mercom India, March 5. https://www.mercomindia.com/daqos-q4-2024-revenue-drops-as-polysilicon-asps-fall.

MoM. 2023. *Critical Minerals for India*. Ministry of Mines, Government of India. https://mines.gov.in/admin/download/649d4212cceb01688027666.pdf.

MoM. 2025. “National Critical Mineral Mission.” Ministry of Mines, Government of India. https://mines.gov.in/admin/storage/ckeditor/NCMM_1739251643.pdf.

MNRE. 2025. “Call for Proposals on Innovation Challenge for Circularity in Renewable Energy Technologies – Batteries and Solar Photovoltaic.” New Delhi, India: Ministry of New and Renewable Energy, Government of India. https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2025/06/20250616466820912.pdf.

MNRE-CEEW. 2024. “Enabling a Circular Economy in India’s Solar Industry – Assessing the Solar Waste Quantum.” New Delhi, India: Ministry of New and Renewable Energy, Government of India; Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/how-can-india-enable-circular-economy-with-solar-waste-management.pdf.

MoEF&CC. 2022. “E-Waste (Management) Rules, 2022.” Ministry of Environment, Forest and Climate Change. https://cpcb.nic.in/uploads/Projects/E-Waste/e-waste_rules_2022.pdf.

MoEFCC-BCG. 2023. “Resource Efficiency and Circular Economy Industry Coalition.” New Delhi: G20 India 2023. Ministry of Environment, Forest and Climate Change, Government of India; Boston Consulting Group. https://www.g20.utoronto.ca/2023/G20_ECSWG-Resource_Efficiency_and%20_Circular_Economy_Industry_Coalition.pdf.

NSEFI. 2024. “SolarREcycle India with Modern Ideas and Strategies.” National Solar Energy Federation of India. https://www.nsefi.in/solarecycle_india.

NSW EPA. 2021. “Circular Solar Grants Program.” New South Wales Environment Protection Authority. https://www.epa.nsw.gov.au/working-together/grants/infrastructure-fund/circular-solar-trials.

Paiano, Annarita. 2015. “Photovoltaic Waste Assessment in Italy.” *Renewable and Sustainable Energy Reviews* 41 (1): 99–112. https://doi.org/10.1016/j.rser.2014.07.208.

Peacock, Bella. 2023. “Australia’s Most Recognisable Solar Recycler Handed Windup Notice by Victorian Court.” *PV Magazine*, September 15. https://www.pv-magazine-australia.com/2023/09/15/australias-most-recognisable-solar-recycler-handed-windup-notice-by-victorian-court/.

PHOTORAMA. 2023a. “The Project.” https://www.photorama-project.eu/theproject/.

PHOTORAMA. 2023b. “About Us.” https://www.photorama-project.eu/about-us/.

PIB. 2023. “MNRE has identified Solar PV Recycling as one of the Priority Thrust Areas under ‘Renewable Energy Research and Technology Development Programme (RE-RTD)’: Union Power & NRE Minister Shri R. K. Singh.” New Delhi, India: Press Information Bureau (PIB), Ministry of New and Renewable Energy, Government of India. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1941108.

PIB. 2024a. “Ministry of Mines to Organize Budget Seminar on National Critical Minerals Mission Tomorrow.” New Delhi, India: Press Information Bureau, Ministry of Mines, Government of India. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2044914#:~:text=This%20initiative%20comes%20as%20part,incentives%20for%20Critical%20Minerals%20recycling.

PIB. 2024b. “Interaction with Startups from India and EU – An Outcome of the Matchmaking Event on EV Battery Recycling under the India–EU Trade and Technology Council WG2.” New Delhi, India: Press Information Bureau, Government of India. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2062183#:~:text=The%20interaction%20highlighted%20the%20significant,transition%20to%20a%20circular%20economy.

PIB. 2025. “Cabinet Approves Rs. 1,500 Crore Incentive Scheme to Promote Critical Mineral Recycling in the Country.” New Delhi, India: Press Information Bureau, Government of India. https://www.pib.gov.in/PressReleasePage.aspx?PRID=2163454.

Prasad, D. S., B. Sanjana, D. Sai Kiran, P. P. Srinivasa Kumar, and R. Ratheesh. 2023. “A Unique Sustainable Chemical Method for the Recovery of Pure Silicon from Waste Crystalline Silicon Solar Panels.” *Sustainable Materials and Technologies* 37 (1): e00671. https://doi.org/10.1016/j.susmat.2023.e00671.

PV Europe. 2023. “New Centre for Solar Module Recycling in Münster, Germany.” *PV Europe*, August 6. https://www.pveurope.eu/maintenance/reiling-new-centre-solar-module-recycling-muenster-germany.

PV Magazine. 2024. “Polysilicon Prices Further Decouple, Adverse Factors Thwart Contract Negotiations.” *PV Magazine*, March 8. https://www.pv-magazine.com/2024/03/08/polysilicon-prices-further-decouple-adverse-factors-thwart-contract-negotiations/.

RECEIC. 2024. “RECEIC Awards on Resource Efficiency and Circular Economy.” Resource Efficiency and Circular Economy Industry Coalition. https://receic.com/receic-awards/#:~:text=15%20January%202025&text=The%20RECEIC%20Awards%20on%20Resource,visit%20www.ficcices.in.

Reiling Group. 2023. “Photovoltaics – Testing for Reuse & Recycling.” https://www.reiling.de/en/recycling-products#progress--anchor--157.

RIICO. 2023. “Integrated Resource Recovery Park.” Rajasthan State Industrial Development and Investment Corporation Limited. https://environment.rajasthan.gov.in/content/dam/environment/RPCB/Publication/RIICO%20RSPCB%20Booklet.pdf.

ROSI. 2023. “ROSI and Yingli Solar Establish a Strategic Partnership for a Circular Solar Energy Economy in Europe.” Last modified November 20, 2023. https://www.rosi-solar.com/rosi-and-yingli-solar-establish-a-strategic-partnership-for-a-circular-solar-energy-economy-in-europe/.

Sah, Dheeraj, Chitra Sulkan, and Sushil Kumar. 2023. “Investigation and Recovery of Copper from Waste Silicon Solar Module.” *Materials Chemistry and Physics* 296 (1): 127205. https://doi.org/10.1016/j.matchemphys.2022.127205.

Sah, Dheeraj, Chitra Sulkan, Kalpana Lodhi, Chander Kant, Sanjay Srivastava, and Sushil Kumar. 2022. “Extraction and Analysis of Recovered Silver and Silicon from Laboratory Grade Waste Solar Cells.” *Silicon* 14 (1): 9635–9642. https://doi.org/10.1007/s12633-022-01715-6.

SECI. 2024. *Request for Selection (RfS) Document for Selection of Solar Power Developers for Setting up of 1000 MW ISTS-Connected Solar PV Power Projects in India under Tariff-Based Competitive Bidding*. Solar Energy Corporation of India Limited. https://www.seci.co.in/Upload/Tender/SECI000186-3997659-RfSfor1000MWSolar-ISTS-XVIII-finalupload.pdf.

Sim, Ying, Yeow Boon Tay, Ankit, Xue Lin, and Nripan Mathews. 2023. “Simplified Silicon Recovery from Photovoltaic Waste Enables High Performance, Sustainable Lithium-ion Batteries.” *Solar Energy Materials and Solar Cells* 257 (1): 112394. https://doi.org/10.1016/j.solmat.2023.112394.

SJVN Limited. 2024. *Request for Selection (RfS) Document for Selection of Hybrid Power Developers for setting up of 1200 MW ISTS-connected Wind-Solar Hybrid Power Projects in India under Tariff-Based Competitive Bidding*. Satluj Jal Vidyut Nigam Limited. https://sjvnindia.com/UploadFiles/TenderUploadedFile/19971/RfS%20HYBRID%203%20280624%20Final.pdf.

SOLARCYCLE. 2023a. "Ørsted Partners with SOLARCYCLE® to Recycle Solar Modules." Last modified June 6. https://www.solarcycle.us/press-releases/orsted-partners-with-solarcycle-to-recycle-solar-modules.

SOLARCYCLE. 2023b. "EDF Renewables North America Selects SOLARCYCLE® to be its Preferred Solar Recycling Partner." Last modified November 1. https://www.solarcycle.us/press-releases/edf-renewables-north-america-selects-solarcycle-to-be-its-preferred-solar-recycling-partner.

Suny Group. 2023. "Solutions for Solar PV Panel Recycling." Last modified September 15, 2023. https://www.sunygroup.cn/news/Solution-for-solar-PV-Panel-Recycling.html?srsltid=AfmBOopPZ-KQVNWPt1pttj_nRx8EzfLqN5PaZ2CGTv0-hNWW5HZKMTZ7o.

Taneja, Anjali, Khushboo Garg, Revathy S. M., and Thirumalai N. C. 2023. "Addressing the Impending Crisis of Solar Photovoltaic Waste in India." Center for the Study of Science, Technology and Policy. https://cstep.in/drupal/node/2504.

Tao, C., W. H. Huang, Z. Zhou, et al. 2019. "Technologies for Profitable Recycling of Si Modules." *Proceedings of the 29th International Photovoltaic Science and Engineering Conference*. https://par.nsf.gov/servlets/purl/10144076.

Tao, Meng, Theresa Chen, Natalie Click, and Randall Adcock. 2023. "Recent Progress and Future Prospects of Silicon Solar Module Recycling." *Current Opinion in Green and Sustainable Chemistry* (44): 100863. https://doi.org/10.1016/j.cogsc.2023.100863.

The Silver Institute. 2025. *World Silver Survey 2025*. https://silverinstitute.org/wp-content/uploads/2025/04/World_Silver_Survey-2025.pdf.

Trinasolar. 2024. "Trinasolar Produces World's First Fully Recycled c-Si module, a Milestone in Sustainability." Trinasolar, September 24. https://static.trinasolar.com/eu-en/resources/newsroom/eu-trinasolar-produces-world%E2%80%99s-first-fully-recycled-c-si-module-milestone.

Tyagi, Akanksha, Prashant Badal and Ajinkya Kale. 2025. "*How Big is the Solar Module Recycling Industry in India? - Sizing the Market, Investment, and Emission Reduction Opportunity*." New Delhi: Council on Energy, Environment and Water.

UPNEDA. 2025. *Request For Selection (RfS) Document for Selection of Solar Power Developers (SPDs) for Setting up 110 MW Grid Connected Solar PV Power Project in Kanpur Dehat & Kanpur Nagar Solar Park (U.P) under Tariff-Based Competitive Bidding*. Uttar Pradesh New and Renewable Energy Development Agency, Government of Uttar Pradesh. https://upneda.org.in/MediaGallery/Tender/KsP_RfS_UPNEDA_110MW_28April2025.pdf.

US DoE. 2023. "Solar Recycling Research & Development." United States Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/solar-recycling-research-development.

Waaree. 2024. "Topcon Technology Solar Cell: What Is It?" *Waaree*, March 19. https://waaree.com/blog/topcon-technology-solar-cell-what-is-it/#:~:text=Advantages%20of%20Topcon%20Solar%20Cells,%E2%80%A2.

Wang, T. Y., J. C. Hsiao, and C. H. Du. 2012. "Recycling of Materials from Silicon-Based Solar Cell Module." Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE. https://doi.org/10.1109/PVSC.2012.6318071.

EUR-Lex. n.d. "WEEE Directive (2012/19/EU)." European Commission. Accessed October 1, 2024. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:02012L0019-20180704.

Wen-Hsi Huang, Woo Jung Shin, Laidong Wang, Wen-Cheng Sun, and Meng Tao. 2017. "Strategy and Technology to Recycle Wafer-Silicon Solar Modules." *Solar Energy* (144): 22–31. https://doi.org/10.1016/j.solener.2017.01.001.

We Recycle Solar. 2023. "About Us." https://werecyclesolar.com/about-us/.

Wolfgang Berger, Franz-Georg Simon, Karin Weimann, and Erik A. Alsema. 2010. "A Novel Approach for the Recycling of Thin Film Photovoltaic Modules." *Resources, Conservation and Recycling* 54 (10): 711–718. https://doi.org/10.1016/j.resconrec.2009.12.001.

Wood Mackenzie. 2024. "Not Made in China: The US$6 Trillion Cost of Shifting the World's Cleantech Manufacturing Hub." https://go.woodmac.com/l/131501/2024-03-27/321m82/131501/1711546884PSg8mhE5/Not_made_in_China.pdf.
X-rates. n.d. "Monthly Average 2024." https://www.x-rates.com/average/?from=USD&to=INR&amount=1&year=2024.

Zele, Sarita, Amrut Joshi, Nivedita Gogate, Deepti Marathe, and Amar Shitole. 2024. "Experimental Investigation on Utilization of Crushed Solar Panel Waste as Sand Replacement in Concrete." *Solar Energy* 269 (1): 112338. https://doi.org/10.1016/j.solener.2024.112338.

The authors

Ajinkya Kale

ajinkya.kale@ceew.in

Ajinkya Kale

Ajinkya is a Programme Associate with The Council's Energy Transition team. His role involves conducting in-depth investigations into the industry's requirements, advancements in renewable technologies, and exploring pathways towards achieving a circular economy.

Dr Akanksha Tyagi

akanksha.tyagi@ceew.in

Dr Akanksha Tyagi

Akanksha is a Programme Lead with The Council's Energy Transition team. Her research aims to make India's clean energy transition responsible and inclusive. She works on enabling a circular economy in RE sectors, estimating the employment co-benefits of RE technologies, and developing solutions to ensure responsible large-scale RE deployment.

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi - 110070, India
T: +91 (0) 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewindia

Scan to download the study