WATTS TO WASTE

Exploring India's Solar Waste Landscape

INTERNATIONAL SOLAR ALLIANCE

UN environment programme

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About ISA

The International Solar Alliance (ISA) is a pioneering organization established during COP 21 in 2015 to create a global solar energy market. With 116 member countries, the ISA facilitates solar deployment, promotes collaboration, and fosters partnerships to accelerate the adoption of solar energy worldwide. The ISA's focus is to accelerate the worldwide adoption of solar energy by facilitating deployment, addressing energy access and security challenges, and driving energy transition. It achieves this through creating an enabling environment for solar deployment, sharing knowledge and best practices, promoting collaboration, and fostering partnerships. In pursuit of its mission, the ISA fulfills four essential roles as an accelerator, enabler, incubator, and facilitator, putting in place concrete tools, capacity-building measures, and innovative financial instruments to establish a robust global solar market.

About UNEP

The United Nations Environment Programme (UNEP) is at the forefront of solar waste management, driving policy advocacy and regulation, promoting innovative recycling technologies, and fostering a circular economy approach for responsible disposal of solar panels. As a global leader in environmental matters, UNEP collaborates with governments, businesses, and stakeholders to develop effective policies and extended producer responsibility schemes that ensure proper collection and recycling of end-of-life solar panels. Additionally, UNEP supports research and innovation to advance recycling processes, recovering valuable materials, and reducing the environmental impact of solar panel disposal, thus contributing to a more sustainable and greener energy future.

Acknowledgement

We would like to extend our heartfelt gratitude to all those who have contributed to the Solar Waste Management Strategy report for India. Their expertise, insights, and support have been invaluable in the development of this comprehensive document. First and foremost, we would like to thank the United Nations Environment Programme (UNEP) for their guidance and assistance throughout the project. We are especially grateful to Takehiro Nakamura, Michiko Ota, Shunichi Honda, and Junko Fujioka for their valuable contributions, which have significantly enriched the content of the report.

We would also like to express our appreciation to the International Solar Alliance (ISA) for their collaboration and involvement in this initiative. We are especially indebted to Mr. Joshua Wycliffe, Mr. Remesh Kumar, Mr. Saba Kalam, and especially Mr. Nar Bahadur Khatiwora, the project lead for their continued support and assistance throughout for successfully carrying out the assignment. Their unwavering dedication to promoting sustainable solar waste management practices in India has been instrumental in shaping the strategies and recommendations presented in this report.

Furthermore, we would like to acknowledge the efforts and contributions of the experts who generously shared their knowledge and insights during this project. It has been vital role in ensuring the accuracy and relevance of the information presented.

Lastly, we would like to thank all the individuals involved in the creation and production of this report. It was instrumental this document to fruition.

Foreword

Dr. Ajay Mathur
Director General
International Solar Alliance

The rapid expansion of solar energy installations around the world has undoubtedly ushered in a new era of clean and renewable power generation. India, as a founding member of ISA, has shown exemplary leadership in embracing solar energy to meet its growing power needs while contributing to global efforts in combating climate change. This transition aligns with the goals of mitigating climate change and reducing dependence on fossil fuels. However, as the solar industry continues to flourish, it brings to the forefront a critical concern that demands immediate attention: the management of solar waste.

It is thus with great pleasure and a strong sense of purpose that I introduce this significant report on solar waste management in India, prepared by the International Solar Alliance (ISA), with the United Nations Environment Programme (UNEP)'s invaluable support. As the world's premier platform for cooperation among solar-rich nations, the ISA remains steadfast in its commitment to advancing sustainable energy solutions and addressing the challenges that accompany them.

The report, which is the first in a series to assess the waste management challenges of the solar sector, delves into the various facets of solar waste management across technological innovations, regulatory frameworks, recycling processes, and sustainable practices. It underlines the importance of collaborative efforts in finding innovative solutions and best practices that can be shared across nations, promoting a circular economy for solar energy. In future reports, we will be looking at the recycling challenges in the context of a fast-changing PV manufacturing technology and infrastructure, and of the need for specific standards for this purpose.

ISA remains dedicated to fostering international cooperation, knowledge sharing, and capacity building to ensure the sustainable growth of solar energy. This report marks the beginning of the collective determination of ISA member countries to not only harness the power of the sun but also to do so responsibly, ensuring that the benefits of solar energy are realised by current and future generations.

We extend our sincere gratitude to dss+ for their support in drafting this report. As we navigate the uncharted waters of sustainable development, the International Solar Alliance remains committed to facilitating the transition toward a cleaner, greener, and more prosperous world. This report stands as a testament to our dedication and resolve to safeguard our planet for present and future generations.

About the Report

Rapid adoption of solar PV technologies in India, while ensuring sustainable energy access, carries an impending issue of end-of-life (EoL) management of waste solar PV modules. Most solar PV modules have a warranty of about 20–25 years although premature decommissioning is not uncommon. These panels create component waste, batteries, and end-of-life PV modules. However, while other waste streams from the solar sector are regulated under specific e-waste legislations in India, solar PV modules have only recently been identified as a waste of concern and covered under the newly implemented E-Waste Management Rules, 2022. Their end-of-life fate has so far depended on the proactiveness of companies and is strongly connected with availability of collection and recycling infrastructures. In many instances, waste PV modules (predominately from premature decommissioning) end up in the vast informal sector where it is crudely dismantled and processed for valuable factions.

Effective action in the sustainable management of solar PV waste can only be facilitated by strong policies and effective interventions in the sector. Solar waste recycling technologies have still not been optimized for cost-effective recovery of high-purity materials, even in advanced markets like the European Union (EU) and Washington DC, with mandatory PV recycling policies. While the EU may be the pioneers in adopting PV recycling in their policy, India is continuously developing policy initiatives for solar PV waste management.

This report aims to provide a comprehensive view of solar PV waste management in India – nascent as it is – by contextualizing it in the current RE boom in the country and projections of waste volumes than can be anticipated in by 2040 (with mid-term projections for 2025 & 2030). We have drawn on experiences and insights shared by experts and stakeholders in the sector and rooted the recommendations in the current policy scenario. Learnings from related sectors and concepts, such as e-waste management and circular economy have been incorporated into the document alongside the deep dive into the solar PV waste sector. This report also outlines strategic recommendations towards developing a solar PV waste strategy for India and describes the key steps that ISA can take as a key enabler of the same.

Table of Contents

List of Figures

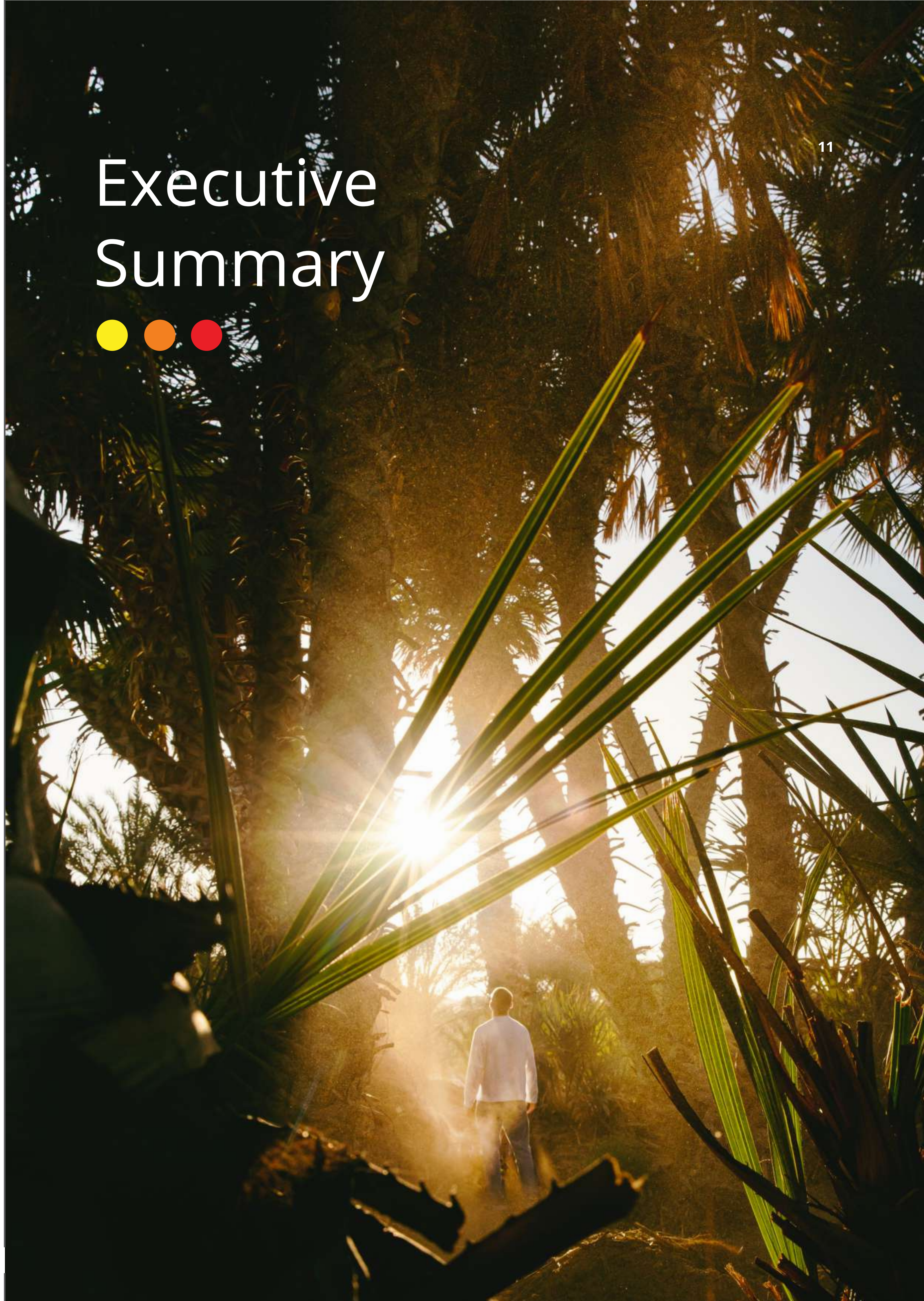
List of Tables

List of Abbreviations

APSPPCL: Andhra Pradesh Solar Power Corporation Pvt. Ltd.
CdTe: Cadmium Telluride
CEEW: Council on Energy, Environment and Water
CENELEC: European Committee for Electrotechnical Standardization
CERC: Central Electricity Regulatory Commission
CFI: Central Financial Incentive
CIGS: Copper indium gallium selenide
CPCB: Central Pollution Control Board
CRM: Critical Raw Materials
CSR: Corporate Social Responsibility
DCR: Domestic Content Requirement
DISCOM: Distribution Company
DPR: Detailed Project Report
DSSC: Dye-sensitized solar cell
EEE: Electric and Electronic Equipment
EoL: End-of-Life
EPC: Engineering, Procurement and Contruction
EPR: Extended Producer Responsibility
ESCOM: Electric Supply Companies
EU: European Union
EVA: Ethylene Vinyl Acetate
EWMR: E-Waste Management Rules
GoT: Government of Telangana
GW: Gigawatt
IESS: India Energy Security Scenarios
IFC: International Finance Corporation
IREDA: Indian Renewable Energy Development Agency
IRENA: International Renewable Energy Agency
ISA: International Solar Alliance
JNNSM: Jawaharlal Nehru National Solar Mission
MDS: Medium Density Scenario
MeitY: Ministry of Electronics and Information Technology
MFA: Material Flow Analysis
MNRE: Ministry of New and Renewable Energy
MoEF&CC: Minitry of Environment, Forests and Climate Change
MT: Metric tonne per annum
MW: Megawatt
NRSE: New and Renewable Sources of Energy
NSM: National Solar Mission

OGS: Offgrid Solar
PCB: Pollution Control Board
PET: Polyethylene Terephthalate
PLI: Production-linked Incentive
PV: Photovoltaic
PVC: Polyvinyl Chloride
RE: Renewable Energy
RoHS: Restriction on Hazardous Substances
RTPV: Rooftop Solar Photovoltaic
SECI: Solar Energy Corporation of India Limited
SPECS: Promotion of Manufacturing of Electronic Components and Semiconductors
SPPD:Solar Power Park Developer
SVT: Silicon Valley Toxins Coalition
SWAP: Solar Waste Action Plan
SWOT: Strengths-Weaknesses-Opportunities-Threats
UNEP: United Nations Environment Programme
US: United States
VAT: Value Added Tax
VGF: Viability Gap Funding
WEEE: Waste from Electric and Electronic Equipment

Executive Summary



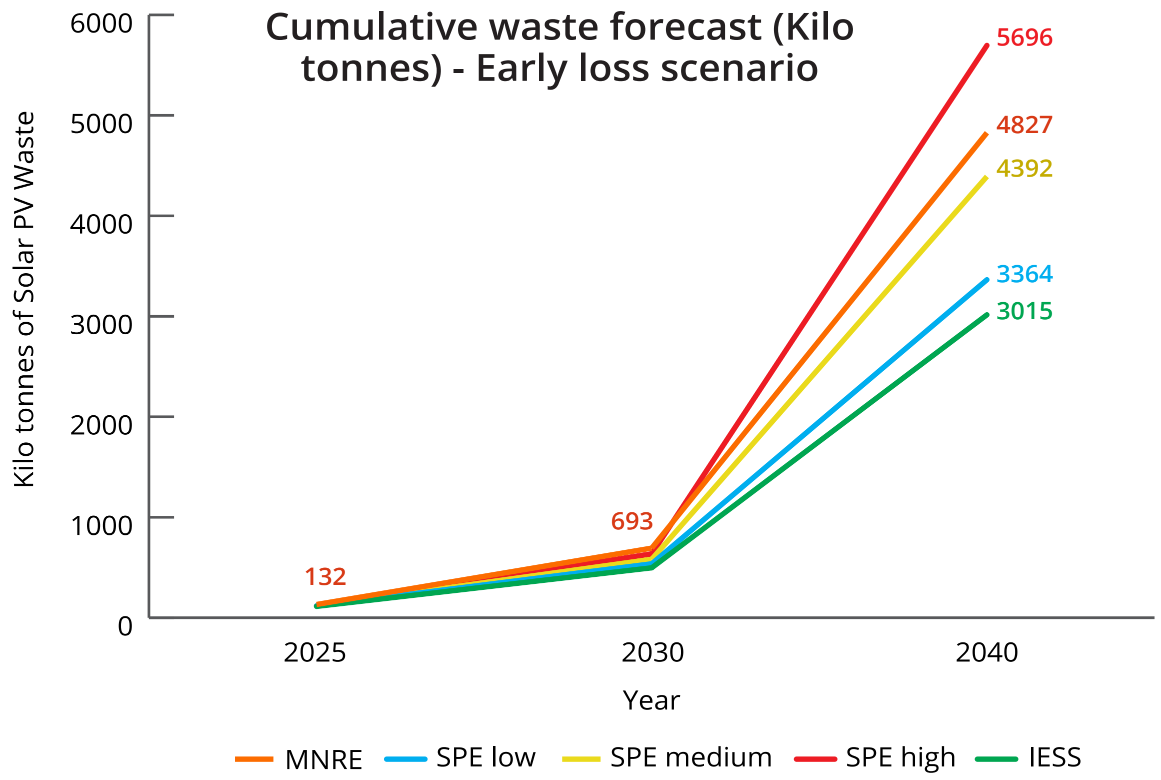
India's solar industry has been growing in leaps and bounds in the past years, particularly since 2015. With a target of 500 GW non-fossil fuel-based energy generation by 2030, the country is required to add close to or over 40 GWs of solar energy every year till the target year, most of which is crystalline-silicon PV panels (~95%) and the remaining thin-film panels. This ambitious vision has placed India amongst the top countries globally in terms of solar capacity. Policies, regulatory initiatives, and schemes such as the Jawaharlal Nehru National Solar Mission, the Solar Park Scheme and more recently the Production-Lined Incentive scheme, have provided the enabling environment to further augment this growth. In 2022, India installed an annual solar capacity addition of 17.4 GW, retaining its position as the world's third-largest country for new solar installations after China and the USA. However, the past few years have also seen a growing volume of prematurely decommissioned PV panels (i.e. an "early loss" of panels before completion of their "regular" life) in the country, leading to greater focus on the End of Life (EoL) management of Solar PV panels.

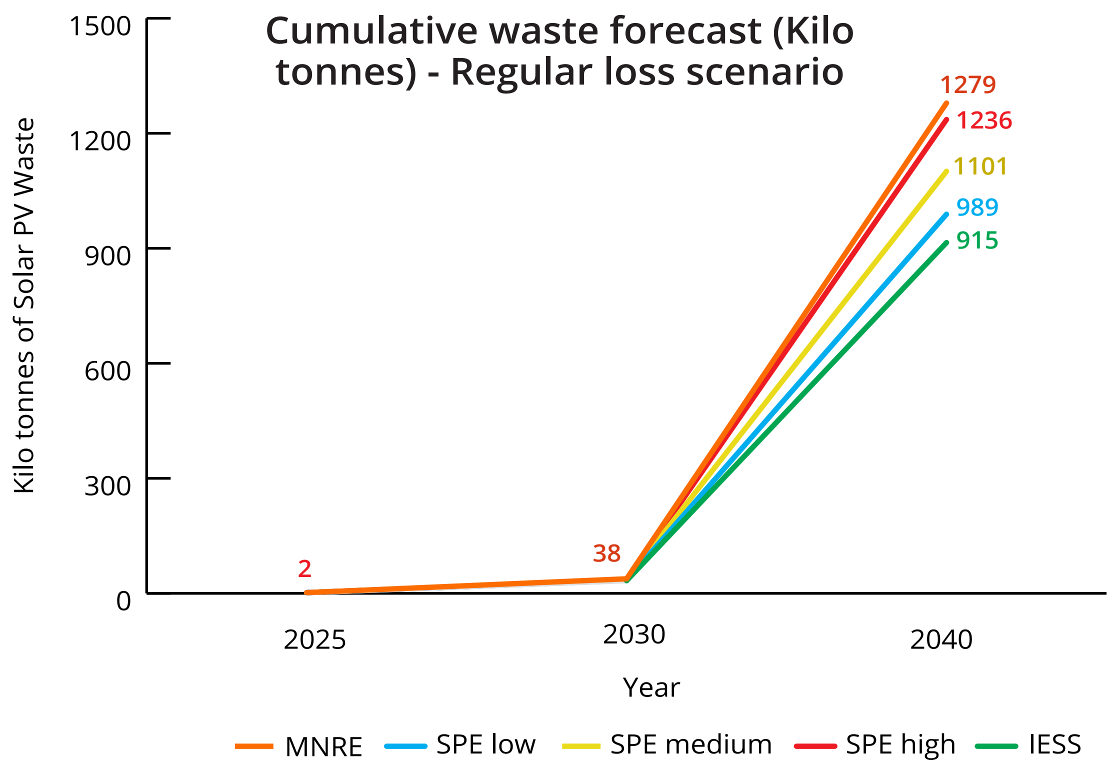
Solar panels have a useful life span of 25 to 30 years, based on a "Regular loss" scenario[01]. However, not all panels are useful throughout their lifespan, and many are decommissioned earlier due to a variety of reasons, leading to the mounting waste volumes the country is already seeing. The Council on Energy, Environment, and Water (CEEW) estimated that the cumulative solar waste in FY21 was about 285 kilo-tonnes due to early losses from the existing 40 GW grid-connected installed capacity[02]. A waste forecasting exercise for the horizon year 2040 based on five cumulative PV installation targets until 2030[03] shows that under the "Regular loss" scenario, waste volumes between 915 to 1279 kilo tonnes could be expected by 2040. Under the "Early loss" scenario, the waste forecast for 2040 was significantly higher, with volumes ranging from 3015 kilo tonnes (based on IESS target) to 5696 kilo tonnes (based on SPE – High target). Projections for the different scenarios are presented below:

[01] 'Regular loss': Assume a 30-year useful lifespan of a solar panel with no early attrition. 'Early loss': A panel with an earlier attrition, taking into account 'infant', 'mid-life' or 'wear-out' failures. More information on the two scenarios is presented in Chapter 3.

[02] Council on Energy, Environment and Water (CEEW), Policy brief on "How India can manage Solar Photovoltaic Module Waste Better, 2021. Accessed on: https://www.ceew.in/sites/default/files/ceew-study-on-photo-voltaic-solar-panel-waste-management-disposal-india.pdf

[03] The sources include: MNRE, India Energy Security Scenarios (IESS), SPE Market Outlook – Low, SPE Market Outlook – Medium, and SPE Market Outlook – High.





Scenario	Cumulative waste forecast (Kilo tonnes) by 2025		Cumulative waste forecast (Kilo tonnes) by 2030		Cumulative waste forecast (Kilo tonnes) by 2040	
	Regular scenario	Early scenario	Regular scenario	**Early scenario**	Regular scenario	Early scenario
MNRE	2	**132**	**38**	**693**	**1279**	4827
SPE (Low)	2	113	33	497	915	3015
SPE (Medium)	2	118	34	537	989	3364
SPE (High)	2	117	34	582	1101	4392
IESS	2	118	34	636	1236	**5696**

As it can be seen, even in the most optimistic scenario, India is likely to face around 0.9 million tonnes of solar PV waste by 2040, 95% of which is expected be from crystalline silicon panels, which will impact the kind of recycling infrastructure required, the kind of valuable material which can be recovered from the available recycling technologies and the potential for circularity in the sector.

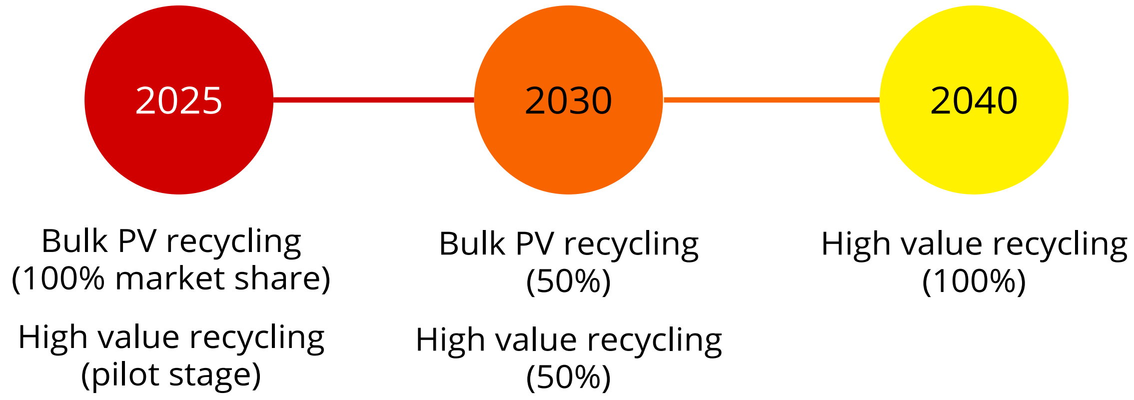
To address the growing concern around the EoL management of Solar PV panels, the Government of India introduced the new E-Waste Management Rules in November 2022. Under these rules, waste solar PV modules are now classified as e-waste, and upstream stakeholders, including producers and manufacturers, are held accountable for e-waste management through the Extended Producer Responsibility (EPR) framework[04]. As part of the EPR, solar waste manufacturers are required to collect and store PV modules until 2034, allowing ample time to establish a robust recycling infrastructure. Subsequently, manufacturers will assume responsibility for waste management and recovery throughout the entire lifecycle of solar PV modules.

The report dwells deeper into the composition break-down of each of the type of panels in the market and the potential recovery of materials in two scenarios, namely, bulk recycling & high value recycling. Bulk recycling refers to the recovery

[04] Extended Producer Responsibility (EPR) is a policy approach that holds producers and manufacturers accountable for managing the environmental impact of their products throughout their entire lifecycle, including recycling and disposal.

of major elements of PV panel alone by weight like Glass, Aluminium frame, copper from cables. Upto 85% of the materials can be recovered through bulk recycling. In contrast, high-value recycling refers to the recovery of even trace elements like copper, aluminium, silver present in a c-Si PV panel with close to 100% material recovery. However, the technical capabilities required for each would be significantly different – while mechanical delamination of the panels is enough for bulk recycling, high-value recycling would require more sophisticated recycling facilities, such as chemical or thermal delamination techniques.

Considering a Solar PV waste management roadmap where the country has full technical capability for recycling and material recovery by 2040, the report proposes an incremental approach to developing the recycling technology – i.e. adopting bulk recycling technology in the beginning and slowly transitioning to high value recycling by 2040.



Furthermore, the landscape for solar waste management is guided and influenced by a variety of supporting developments while a number of challenges in the current ecosystem threaten success of a solar PV waste recycling and recovery system. From drivers such as a positive regulatory push, mounting early-loss panel waste, increasing cognizance on the importance of conservation and circulation of precious materials used in the panels, have created an enabling ecosystem to build solar PV waste management systems in. However, barriers such as lack of sufficient recycling infrastructure and significant upfront investment cost to set it up, low volumes of panel waste, predominant presence of the informal workforce rivaling the formal sector for collection and treatment of the waste demonstrate the need for collective action and a transformative change in the sector to make such an EoL system viable. The drivers and barriers for solar waste management has been used to create a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis essential to consider for linking opportunities with actions.

S

Strengths

- India is rich in solar resource
- Cogeneration potential on agricultural lands
- Suitable application of distributed PV power systems.
- Solar energy helps meet rural electrification needs
- High positive brand value for solar energy
- Policy support for waste modules under EWM 2022.

W

Weaknesses

- Small scale of renewable energy economy
- Unsound solar energy infrastructure
- Developing foundation in the PV industrial chain
- Insufficient awareness about social and environmental benefits of solar PV
- Lack of an efficient recycling infrastructure

O

Opportunities

- Increasing PV installations
- High economic value for secondary material recovery
- Incentivising take-back, EoL recycling
- High eco-design potential increasing module lifespan
- Consumer awareness for proper solar waste disposal
- Later profits to cover initial costs

T

Threats

- Dominant position of fossil fuels
- Inefficient implementation of solar waste policies
- Potential economical impacts from solar PV development
- Discontinuity of energy policies
- Availability of cheaper energy resources

For the solar waste management system in the country to further mature, there are several recommendations which can be implemented, ranging from policy considerations to logistical change and waste management strategies. Some of the key recommendations are presented below, and further elaborated along with other suggestions in Chapter 5 of the report:

- Effective categorization of solar waste: Effective categorization of solar PV waste is instrumental to defining the recycling infrastructure and secondary market. Classification of PV waste as hazardous can put limitations on how these items are handled and processed, which could be detrimental to the recycling and recovery system. Although India has recently acknowledged solar PV waste as a separate waste stream under the E-waste (Management) Rules, 2022, clearer guidelines on how the collection and processing of PV waste are necessary to ensure the proper handling and establishment of an efficient end-of-life (EoL) value chain for solar waste.

- Adopting mandatory Extended producer Responsibility (EPR) scheme to manage solar PV module waste: Similar to the EPR frameworks that exist for other waste streams in the country, solar waste should also come under the ambit of EPR, bringing with it an opportunity to set up a funding model for co-regulatory or mandatory approach through a consultative approach wherein producers, the government and the EoL management actors come together to define the precise fiscal mechanisms for the system.

- Develop and deploy metrics to measure compliance with solar-centric regulations and ensure these metrics are value-based and not volume-based: By making the measurement metrics value-based and not volume-based in nature, the regulations can promote high-value recycling over bulk-recycling thereby, incentivizing proper recovery and management of all materials, particularly the critical materials in PV modules.

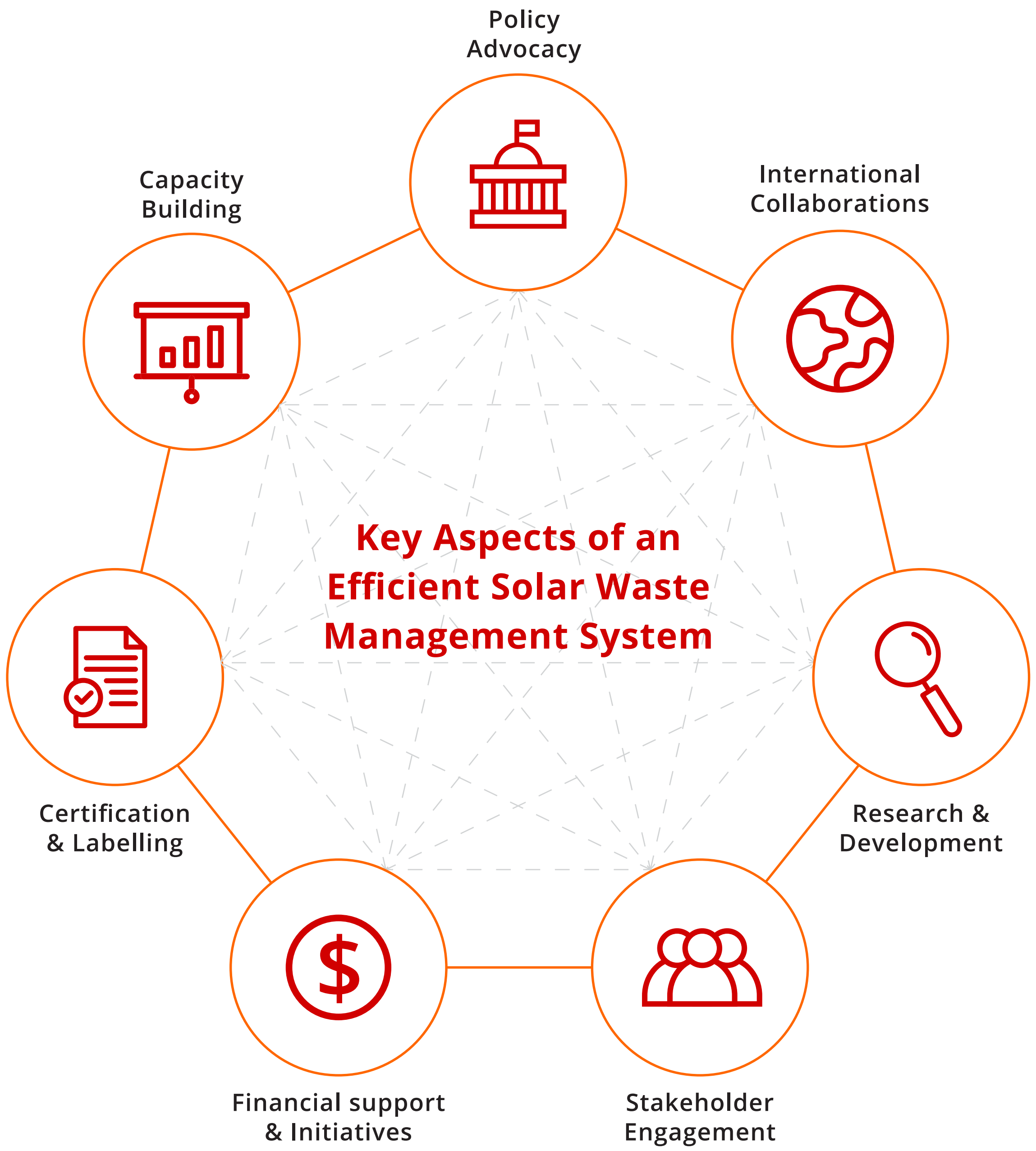
- Coupling landfill restrictions and product stewardship schemes: This is an effective intervention to promote collection and recycling activities, which will not only mitigate environmental pollution but also stimulate the growth of a domestic recycling sector, leading to improved waste management practices and resource conservation.

- Developing mobile recycling plants to maximize waste inflow: Pilots can be established which can explore potential solutions for avoiding the economic and environment burden associated with excess transportation.

- Implementing robust and innovative means of avoiding pilferage during storage and handling of solar waste, including robust labelling and tracking systems for every PV module and ensuring secure shipment processes.

- Promoting the use of Mechanical delamination for treatment of PV module waste for recovery of high volume materials can help increase availability of bulk recycling units in the country – which is crucial especially in the first few years of a formal solar PV EoL management system

Strategic recommendations have also been provided for policy makers and for the International Solar Alliance (ISA) to capitalize on their role as facilitators in the move towards a circular economy driven and efficient waste management sector. The development of a national strategy for solar waste management in India and the 'facilitator' role of the International Solar Alliance (ISA) are interconnected through nine key aspects crucial for an efficient end-of-life solar management system. The following infographic represents these key aspects.



In conclusion, international agencies in the solar waste sector, like ISA, plays the crucial role as a facilitator in the development and implementation of an efficient solar waste management strategy in India. By addressing key aspects such as policy advocacy, international collaborations, certifications and labelling, financial support and incentives, research and development, stakeholder engagement, capacity building, and circularity, India has an opportunity to effectively manage the growing volume of solar waste in the country.

01

The ‘rising’ solar sector in India

Trends, highlights and current market conditions of the Indian solar sector.

In 2015, The Paris Agreement called for reduction of 45 percent global emissions by 2030 and reach a net zero scenario by 2050, to avoid the worst impacts of Climate Change[05]. A growing coalition of countries are pledging to limit temperature rise to below 2 OC, making the transition to a net-zero scenario more immediate. The energy sector, contributing three-quarters, holds the key to a decarbonized economy, largely based on renewable energy[06]. The global pathway to net-zero emissions by 2050 requires governments to strengthen and successfully implement innovative renewable energy policies. Solar energy is one of the ‘key pillars of decarbonization’.

Globally, solar PV systems has seen rapid growth over the last two decades. Cumulative global deployment of PV grew from 1.2 GW in 2000[07] to about 1046 GW in 2022[08]. Solar PV capacity additions remain on an upward trend globally, despite some slowed growth in 2020. Government actions and commissioning of projects (under the JNNSM project - discussed in Section 1.3) have boosted the solar economy in key markets like the US, Europe, and India.

In the last few years, India has become a fertile ground for renewable energy development, bolstered by ambitious targets and progressive policies. Solar energy, especially, has seen rapid development which remains on an increasing growth trend. In 2022, India recorded its highest annual solar PV installation of 13GW[09]. Solar PV resources in India holds the capacity to meet 94 percent of the country’s current electricity demand. The push for a low-carbon pathway has seen an increasing renewable energy share in the country’s energy mix.

Factors like simplicity of technology, public incentives, lowered electricity costs, and lowering manufacturing costs, have encouraged the development of innovative solar policies. Since its inception the Ministry of New and Renewable Resources (MNRE) has taken several initiatives to increase the deployment of solar energy in India such as performance-based incentives to distribution companies (DISCOMs)

[05] United Nations, Blog post on “For a livable climate: Net-zero commitments must be backed by credible action”, 2021. Accessed on: https://www.un.org/en/climatechange/net-zero-coalition

[06] International Energy Agency (IEA), Report on “Net Zero by 2050: A Roadmap for the Global Energy Sector. Accessed on: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

[07] IRENASTAT Online Data Query Tool, 2022

[08] IRENA, Renewable Capacity Statistics, 2023

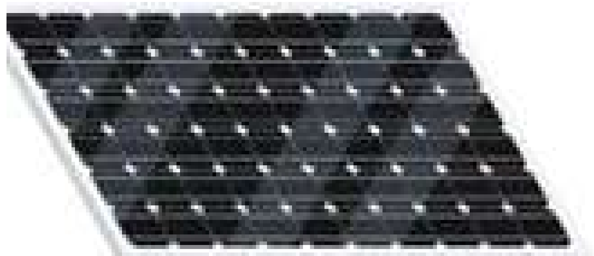
[09] PV Magazine, 2023. Accessed on: https://www.pv-magazine.com/2023/05/15/new-leaders-emerge-in-indias-2022-solar-market/

and consumers[10]. Supportive schemes like Central Financial Assistance and Viability Gap Funding (VGF) have reduced the financial risk for investors and developers of solar projects, significantly contributing to the rapid growth of the sector in the country.

1.1 A closer look at India's Diverse Solar Technologies

Most solar panels have an expected lifespan of about 20-25 years, although premature decommissioning is not uncommon . The lifetime of solar panels is determined by its technology. There are mainly three types of solar PV modules, predominantly used in India – monocrystalline, polycrystalline and thin-film. More than 95% of the market share is held by crystalline silicon PV panels in India, much like the global market share.

Monocrystalline Silicon PV Module



First generation solar panels made from a single silicon crystal. These panels have a higher efficiency than other types, reaching up to 20%. However, due to the additional cost and complicated process for creating pure silicon panels, these are more expensive than the other PV modules. It also causes silicon wastage. These have a lifespan of about 20-25 years.

Polycrystalline Silicon PV Module

First generation panels made from multiple silicon crystals. The panels have an efficiency of around 15-17%. They are easier to manufacture and are slightly cheaper than monocrystalline PV modules. These also have a lifespan of around 20-25 years.

[10] The Council on Energy, Environment and Water (CEEW), Policy brief on "Demystifying India's Rooftop Solar Policies", 2019. Accessed on: https://www.ceew.in/sites/default/files/demystifying-india-rooftop-solar-policies.pdf

Thin-film solar modules

Second generation panels, only marginally less efficient than the traditional panels. These are made up of thin-film solar cells formed of amorphous silicon, Cadmium Telluride (CdTe) or copper indium gallium selenide (CIGS) cells. These are commercially significant in utility-scale photovoltaic power stations, building integrated photovoltaics or in small stand-alone power system. CdTe modules are one of the fastest growing segments of commercial module production, attributed to the ease of its assembly and their low manufacturing process costs. CIGS modules represent the current most efficient alternative for large-scale, commercial thin-film cells . CIGS cells are relatively less non-toxic when compared to toxic cadmium used in CdTe cells[11].

However, these have the lowest efficiency of around 8-15% and power output and have a lower lifespan (~10 years).

1.2 Exploring the Growth and Current Status of PV Installations in India

Globally, India stands among the top five countries with the highest solar PV installations. India has seen a massive exponential growth in solar PV Installations over the last decade, especially since 2015. The installed capacity increased from a mere 0.98 GW in 2010 to about 63.15 GW in 2021. Figure 1 shows the PV installation trend over the last decade, since 2010[12].

When it comes to installed PV capacity in Indian states, two broad categories are seen – resource-rich states and resource-deficit states. Figure 2 shows the state-wise distribution of solar PV installations. The six resource-rich states, accounting for about 77 percent of the installed PV capacity have been highlighted. Rajasthan has the highest installed capacity with about 14 GW of installed capacity, followed by Gujarat and Karnataka with 7.8 GW and 7.6 GW, respectively.

[11] http://cleanenergywiki.org/index.php?title=CIGS,_CIS,_CdTe
[12] Renewable Energy Capacity Statistics 2023

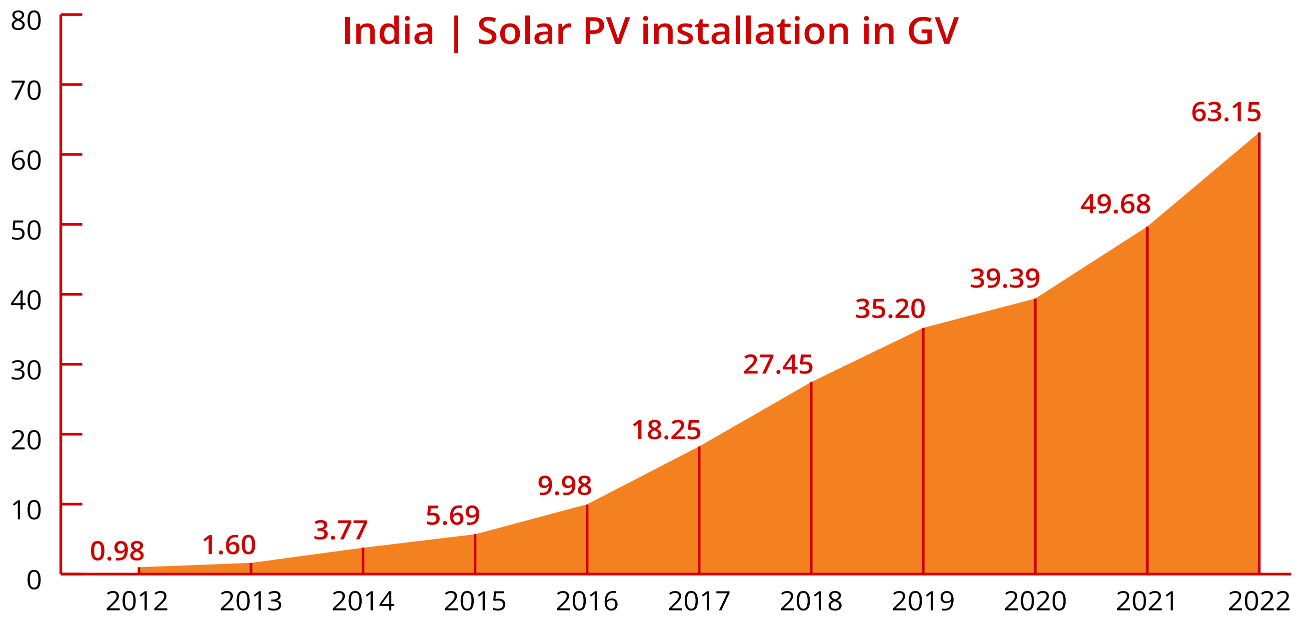


Figure 1: Solar PV installation in India (2010-2022)

Around 90% of annual PV module installations are supplied through imports, as shown below in Figure 2. Domestic PV production capacity in India includes 2.5 GW of PV cell and 11 GW of PV module manufacturing[13]. Currently, only 50% and 28% of the cell and module domestic capacity are utilized to satisfy annual demand. Moreover, there are no existing polysilicon and ingot/wafer production facilities in India. To achieve energy security, it is essential for at least 60-70% of manufacturing capacity addition to meet the annual demand. In the wake of the COVID-19 pandemic, the Government of India has laid out a vision for Atmanirbhar Bharat (Self Reliant India), which is expected to encourage domestic production of products in the solar PV value chain in the country.

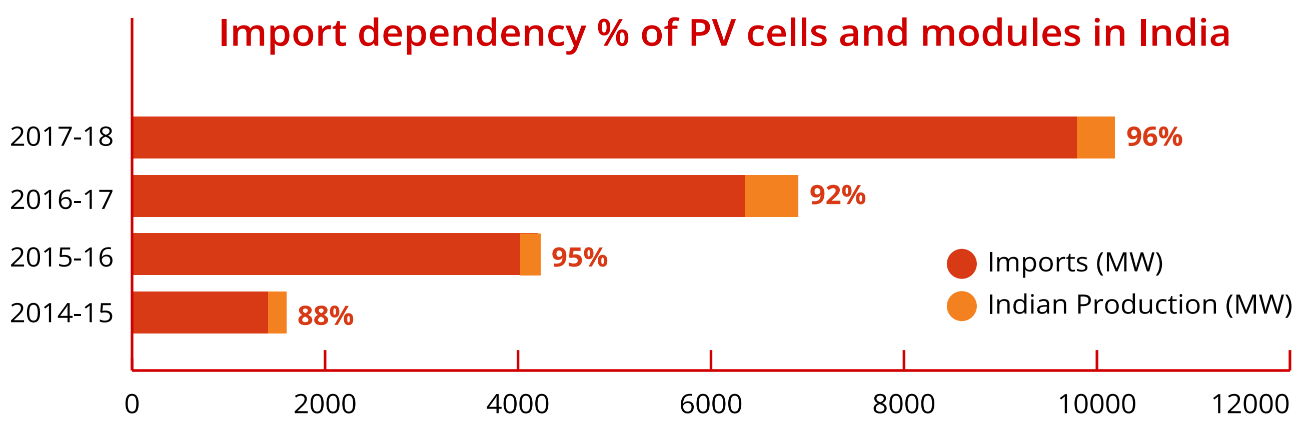


Figure 2: Import dependency of PV cells and modules in India

[13] CEEW, "Making India a Leader in Solar Manufacturing", 2022. Accessed on: https://www.ceew.in/cef/solutions-factory/publications/CEEW-Making-India-a-Leader-in-Solar-Manufacturing.pdf

1.3 Policy Support in driving the growth of Solar PV in India

In 2013, NITI Aayog (then known as the 'Planning Commission') initiated a stakeholder-driven analysis of the opportunities and barriers to rapid deployment of renewable electricity in India, titled 'India's Renewable Electricity Roadmap 2030'. This led to a 'roadmap' document in 2015 which proposed strategic interventions to meet the 175 GW RE target. The roadmap concluded that India needed new policies, programs, and operational rules to enable power flows from point of generation to load centres, ensure fair compensation to generators, and offer reliability of supply to consumers at affordable prices. Following this, several national and state-level schemes and incentives were notified for the growth of the solar sector in India.

The Jawaharlal Nehru National Solar Mission (JNNSM) or the National Solar Mission (NSM), was launched in January 2010 as a joint initiative of the Central and State Governments. The target was initially set at 20 GW by 2022. Later in 2015, the solar installation target was revised to 100 GW by 2022[14]. In August 2021, the Government increased the target to 300 GW for 2030.

Solar Energy Corporation of India Ltd. (SECI), an MNRE-owned company, has been established to facilitate the implementation of the JNNSM. It is the only Central Public Sector Undertaking company dedicated to the solar energy sector. The company is responsible for implementation of several government schemes including the Viability Gap Funding (VGF) schemes for large-scale grid-connected projects under JNNSM, the solar park scheme and grid-connected solar rooftop schemes[15].

Development of Solar Parks and Ultra Mega Solar Power Projects

MNRE introduced the scheme for Development of Solar Parks and Ultra Mega Solar Power Projects in 2014. The scheme had an initial target of setting up at least 25 solar parks and 20 GW of solar installed capacity within five years starting from 2014-15. The target was later revised to 40 GW by 2022 through the MNRE's order in 2017. Timeline for achieving the target was later extended to 31 March 2024[16]. The Indian Renewable Energy Development Agency (IREDA) was assigned as the implementing agency for solar parks which were under construction as well as upcoming ones. Solar Energy Corporation of India Ltd. or any of its joint venture companies will be assigned as the Solar Power Park Developer (SPPD).

[14] MNRE website

[15] PSU Connect Website

[16] MNRE, Office Memorandum, 2021. Accessed on: https://mnre.gov.in/img/documents/uploads/file_s-1644301947805.pdf

MNRE also provides Central Financial Assistance (CFA) incentive of up to INR 25 lakh[17] per solar park for preparation of a detailed project report (DPR). Further, CFA of up to INR 20 lakh per MW or 30 percent of project cost (including grid-connectivity loss), whichever is lower is given on achieving milestones under the Scheme. Financial assistance can be accessed by submitting proposals to MNRE/SECI.

The Grid connected Rooftop Solar Programme for achieving cumulative capacity of 40,000 MW from Rooftop Solar (RTS) Projects by 2022, provides CFA support. CFA covers 30% of the benchmark cost for general and 70% CFA for North East and Special Category States for residential, social and institutional sector.

The Viability Gap Funding (VGF) is designed to provide capital support to public-private partnership projects, to make them financially viable. VGF makes it easier to recover costs and provides a financially attractive return for the private sector[18]. VGF support has been used to provide incentives to project developers in the solar energy space in India. A 2000 MW Grid-connected Solar PV Power Projects is currently being set up under Batch-III of Phase-II of JNNSM with VGF support provided to project developers based on their bid.

The scheme provides Viability Gap Funding (VGF)[19] support of INR 5050 crore for solar power projects, with an upper limit of INR 1.0 crore/MW for the open category and INR 1.25 crore/MW for projects in the Domestic Content Requirement (DCR) category. It also includes a Payment Security Mechanism of INR 500 crore to enhance business stability, with 100% VGF released on project commissioning and a gradually reduced Bank Guarantee. This ensures lesser financial risks for project developers and makes solar projects more financially viable.

Solar Park scheme

This Scheme aims to set up to set up several solar parks across the country, each with a capacity of solar projects generally above 500 MW. The Scheme proposes to provide financial support from the Government to establish solar parks to facilitate necessary infrastructure development for new solar projects. The Government supports eases access to land, transmission and evacuation lines, access roads, etc. in a focused manner.

[17] Conversion rate: USD 1 = INR 82.85; INR 1 lakh = INR 100,000; INR 1 crore = INR 10,000,000

[18] Ministry of Finance, Government of India, Public sector funding assistance for PPPs. Accessed on: https://www.pppinindia.gov.in/toolkit/ports/module1-pse-ps-fafp.php?links=rfpee1d#:~:text=Viability%20Gap%20Funding%20(VGF)%20is,return%20for%20the%20private%20sector

[19] MNRE, Implementation of scheme for setting up of over 5000 MW Grid Connected Solar PV Power Projects with Viability Gap Funding under Batch-IV of Phase-II of the JNNSM. Accessed on: https://mnre.gov.in/img/documents/uploads/72f420e1cfa448ecbb6934e939ec0f96.pdf

Production-lined incentive (PLI) Scheme

In the Union Budget 2022-23, the government allocated INR 19,500 crore (USD 2.57 billion) for a production-linked incentive (PLI) scheme to boost the manufacture of high-efficiency solar modules. SECI received an allocation of INR 1000 crores (USD 132 million) to develop the RE sector in India[20].

State-level Policy Support

The MNRE has assigned each State a Solar capacity target based on their potential to produce solar power, including land area and days of sun per year[21]. Several states have formulated solar-specific policies and initiatives to drive the growth of the sector[22]. Specific policies in selected key states have been listed below.

Andhra Pradesh launched their Solar Power Policy in 2015 and pioneered solar parks under the Solar Energy Corporation of India (SECI) scheme. The State has further utilized the Solar Park Scheme and established a joint venture developer company with the government of India – Andhra Pradesh Solar Power Corporation Pvt. Ltd. (APSPPCL)[23] to develop more solar parks in the State.

Maharashtra's RE Policy, 2015, focused on developing hybrid and distributed solar projects and provides various incentives (e.g., electricity duty exemption, capital subsidy, etc.) for selected technologies under this policy. The solar irrigation pump scheme for agricultural consumers targets installation of 500,000 lakh solar pumps. The State is also planning to install solar agriculture feeder-based projects near existing substations to reduce infrastructure costs.

Karnataka's Solar Policy (2014-21) drove capacity addition mainly through grid-connected solar rooftop projects and net-metering options. Key initiatives leading to high capacity include exemption from pollution control board clearance, ease of land acquisition for solar projects, reduction of supervision charges by Electric Supply Companies (ESCOMs) to 5%, etc.

Rajasthan developed a Solar Energy Policy in 2014, focusing on development of both large and small-scale solar plants. The State's Solar Irrigation Pumps Program planned installation of one lakh solar panels to provide more flexibility to farmers.

[20] India Brand Equity Foundation (IBEF), Renewable Energy Industry in India, 2022. Accessed on: https://www.ibef.org/industry/renewable-energy

[21] Engaging Indian States, Blog article on "Solar Performance Tracker", 2021. Accessed on: https://indianstates.csis.org/national-goals/solar-performance-tracker/

[22] NITI Ayog, State Renewable Energy Capacity Addition Roadmap – Action Plan 2022 and Vision 2030: Summary of findings. Accessed on: https://www.niti.gov.in/sites/default/files/energy/Executive-Summary.pdf

[23] APSPCL website

Telangana announced a Solar Power Policy in 2015 and has made substantial achievements through it including in solar pumps and solar rooftop segments. key incentives leading to high solar capacity additions in the state include exemptions from electricity duty, VAT, wheeling and transmission charges (for captive use) within the state, PCB clearances, etc.

Punjab launched a New and Renewable Sources of Energy (NRSE) Policy in 2012, under which, targets have been assigned for each PV technology. The overall RE target for the State is 10 percent by FY 2022. Further, Punjab launched a Solar Rooftop Policy in 2012, which was conducive to development and had defined guidelines/procedures. Incentives provided under this policy include 100% exemption of electricity duty, VAT, exemption of NOC for solar PV projects from PCBs, etc.

1.4 Solar Market Maturity in India: A Brief Snapshot

India's solar market has predominately grown over the last ten years. As described above, the last decade has seen a remarkable increase in installed solar capacity, surpassing 40 GW in 2021, against the original goal of achieving 20 GW capacity by 2022[24]. This growth can be attributed to market-friendly policies, such as long-term power purchase agreements (PPAs), viability gap funding, and tax incentives, which have attracted domestic and international investment in solar projects.

India's solar market maturity is reflected in its consistent capacity additions and declining solar tariffs. One prominent trend in the Indian solar market is the focus on utility-scale solar installations. Large-scale solar parks and projects, often spanning hundreds of acres, have been developed across the country. These projects benefit from economies of scale, resulting in lower costs and increased efficiency. The Solar Energy Corporation of India (SECI) and state governments play a crucial role in facilitating land acquisition and providing a conducive environment for utility-scale solar developments. Another significant trend is the increasing adoption of rooftop solar installations. The government has implemented policies and financial incentives to promote rooftop solar, including net metering and group net metering schemes. This has encouraged commercial and industrial establishments, as well as residential consumers, to install solar panels on their rooftops. The rooftop solar segment offers numerous advantages, such as reducing reliance on grid power, lowering electricity bills, and contributing to environmental sustainability.

[24] As covered in the previous section, India's solar journey gained momentum with the introduction of the Jawaharlal Nehru National Solar Mission (JNNSM) in 2010. The mission aimed to promote the use of solar energy and set a target of achieving 20 GW of solar power capacity by 2022. This target was subsequently revised to 100 GW under the ambitious "National Solar Mission Phase-II" launched in 2015.

Technological advancements have played a pivotal role in the growth and maturity of the Indian solar market. The focus has been on enhancing solar panel efficiency, durability, and cost-effectiveness. Other factors such as economies of scale, and increased competition among solar panel manufacturers have also contributed to the declining prices. This cost reduction, coupled with various financial incentives and subsidies offered by the government, has made solar energy an economically viable option for both utility-scale and rooftop installations.

Key players in the Indian solar market include both domestic and international companies. Adani Green Energy, Tata Power Solar, Azure Power, and ReNew Power are among the leading Indian renewable energy companies with a significant presence in the solar sector. These companies have diversified portfolios, spanning project development; engineering, procurement, and construction (EPC), and operations and maintenance (O&M) services.

International players have also made substantial investments in the Indian solar market. Companies like SoftBank Group, Canadian Solar, and Trina Solar have entered partnerships or established subsidiaries to tap into the growing opportunities. Collaborations between domestic and international players have led to the transfer of technology, knowledge exchange, and the implementation of best practices in project development and operations.

In addition to project developers, various other stakeholders contribute to the maturity of the Indian solar market. These include equipment manufacturers, EPC contractors, financing institutions, and research organizations. The government bodies responsible for policy formulation and regulation, such as MNRE and the Central Electricity Regulatory Commission (CERC), also play a vital role in fostering the growth and stability of the solar sector. Initiatives such as the National Solar Mission and the International Solar Alliance, have further catalysed market maturity and help attract investment. The adoption of innovative technologies, such as floating solar and hybrid solar-wind projects, is likely to gain momentum in the coming years, ensuring optimal utilization of resources and improving grid stability.

Despite the growing solar market size in India, the sector is facing an imminent solar waste problem, with a steady stream of premature decommissioning. As the solar sector rises, waste from the industry has become an urgent concern that requires immediate attention. The next chapter will take a closer look at the existing solar waste management sector in the country. A solar waste forecast exercise has also been performed for India, which gives a quantitative outlook towards the upcoming solar waste scenario in the country.

02

Growing Solar PV Waste Challenge

Predicted Volumes and Regulatory Landscape

The rapid adoption of solar energy has brought with it the impending challenge of solar PV panel waste management, given the sheer scale of solar installations in India. Not only do PV panels contain toxic materials such as lead which are health and environment hazards if improperly discarded, they also contain rare and valuable materials which are lost due to lack of adequate recycling and recovery facilities.

Solar panels have an estimated useful lifespan of 20-25 years before they are considered waste (from here on out referred to as the 'Regular loss' scenario). However, global evidence demonstrates that this waste stream already started accumulating, due to faulty or damaged panels which need to be discarded in the early part of their lifecycle (from here on out referred to as the 'early-loss' scenario). Existing PV modules are also getting replaced with newer, more efficient modules, rendering the older models out of service and thus, adding to the waste volumes.

Over the last few years, there have been numerous studies highlighting the looming solar PV waste problem. Back in 2016, IRENA projected the global solar PV waste production to reach 60-78 million tons, as shown in Figure 3[25].

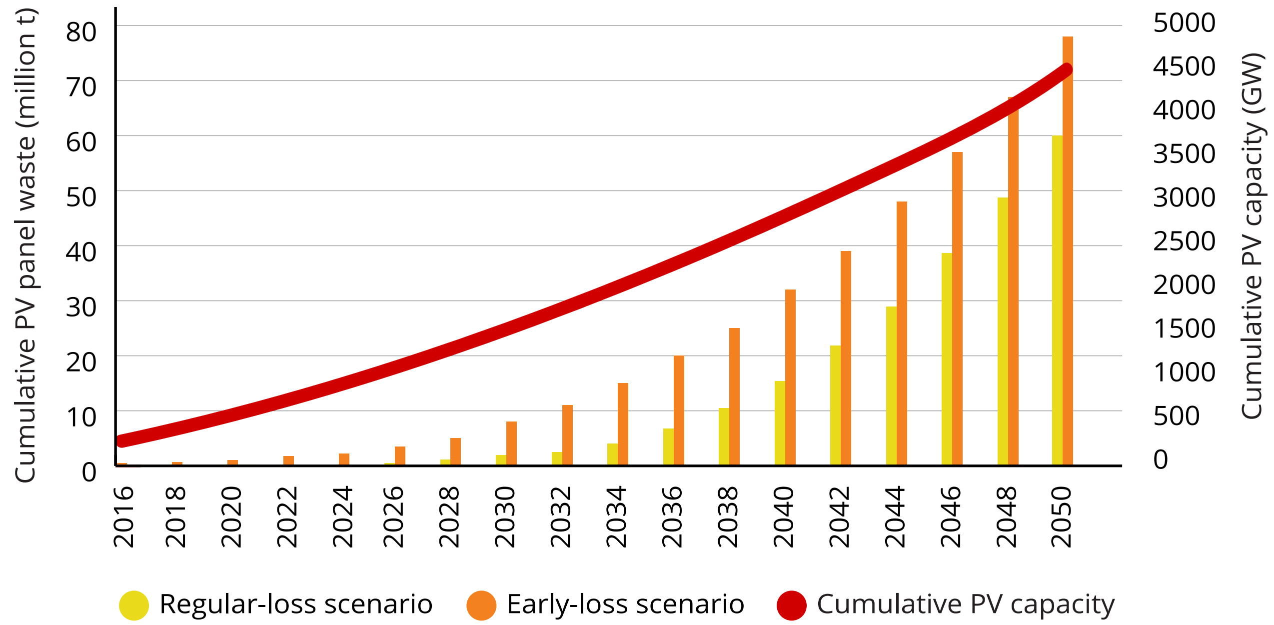


Figure 3: Estimated cumulative global waste volumes (million tons) of end-of-life PV panels

[25] IRENA, "End-of-Life Management: Solar Photovoltaic Panels", 2016. Accessed on: https://www.irena.org/-/media/-Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

The regular-loss and early-loss waste estimates for the top five countries in 2030 and 2050 (shown below[26]) also indicated that Asia is expected to see the highest volume of waste solar panels, due to the presence of global leaders in installations, namely, China, Japan, and India (Table 1).

Table 1: Top 3 Asian countries in waste projections by 2030 as per IRENA, 2016

Year 2030		
Scenario	Regular Loss	Early Loss
China	200,000	1,500,000
Japan	200,000	1,000,000
India	50,000	325,000

The solution to an efficient solar PV module waste management system lies in the recycling of photovoltaic materials, yet the substantial volume of units approaching the end of their lifespan or already non-functional poses a significant challenge. Most countries and companies are ill-equipped to handle such numbers, leading to a recycling rate of only approximately 10% of the total amount of PV units worldwide. This low rate can be attributed to insufficient organization and management for carrying out the recycling process effectively. Moreover, materials like silicon, obtained through recycling, are perceived to have limited value due to their widespread availability. Consequently, the disposal of waste in landfills is often considered the most cost-effective option. However, it is worth noting that recycling can potentially recover up to 80% of the weight of a photovoltaic cell. This will also reduce the amount of lead leaked into the environment through unmonitored disposal.

2.1 The Growing Solar Waste Problem in India

As the Indian solar sector started developing after 2010, there is some time before the solar waste management becomes alarming. However, considering the 'Early loss' scenario mentioned in the previous section, faulty or damaged solar panels have already started adding to the waste volumes. Preliminary analysis estimates that cumulative solar waste in FY21 was about 285 kilotonnes from the early loss of

26 IRENA (End of life management) accessed on https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

installed 40 GW grid-connected solar capacity[27]. In the absence of compliance obligations, early loss panels may end up in informal waste treatment sector. This may endanger unskilled informal workers and lead to the loss of critical secondary materials.

The following table summarizes the forecasted PV waste volumes for India by 2030 through various studies.

Table 2: Forecasted PV waste volumes for India by 2030

Source	Forecasted volume range (cumulative kilotonnes)	Methodology & Key Assumptions
IRENA[28]	50 to 325	• Installed capacity (GW) of the region was converted to weight/volumes (t) across the years based on the material intensity trends for a silicon PV panel. • Probability of failure across life cycle was taken based on an analysis of the literature and expert judgement. • Weibull distribution was used to forecast the PV waste. Shape factor was assumed to be the probability of failure whereas the scale factor was assumed as the life time of PV panel (30 years).
EU TCP: Energy[29]	11.2 to 34.6	• The mass of PV waste generated due to early failures or damages (i.e., during transportation, installation and operation) was alone derived in this study. EoL waste was not considered. • Assumptions were made regarding PV module weight, PV annual replacement rates, and PV modules damaged during transportation and construction. • Multiplication of the forecasted capacity by the annual replacement rates resulted in the waste volumes.
Bridge to India[30]	200	•'BRIDGE TO INDIA – Early loss' scenario assumes higher than average global early life loss scenarios based on higher incidence of poor quality and site accidents in India.

27 Council on Energy, Environment and Water (CEEW), Policy brief on "How India can manage Solar Photovoltaic Module Waste Better, 2021. Accessed on: https://www.ceew.in/sites/default/files/ceew-study-on-photo-voltaic-solar-panel-waste-management-disposal-india.pdf

28 https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

29 https://www.cecp-eu.in/uploads/documents/events/pv-waste-management-report-25-01-2021.pdf

30 https://bridgetoindia.com/backend/wp-content/uploads/2019/04/BRIDGE-TO-INDIA-Managing-Indias-Solar-PV-Waste-1.pdf

Further, batteries have an expected life between three to ten years depending on their chemistry. Early loss of batteries can be attributed to several factors, such as improper handling during transportation and installation, and operational factors like overheating, deep discharging, and fluctuating surrounding temperature[31].

2.2 Solar PV waste hotspots in India

As of 31 May 2023, the total Solar installed capacity in India has reached 67.8 GW. An overview of the total installed capacity across the country is provided in Figure 4.

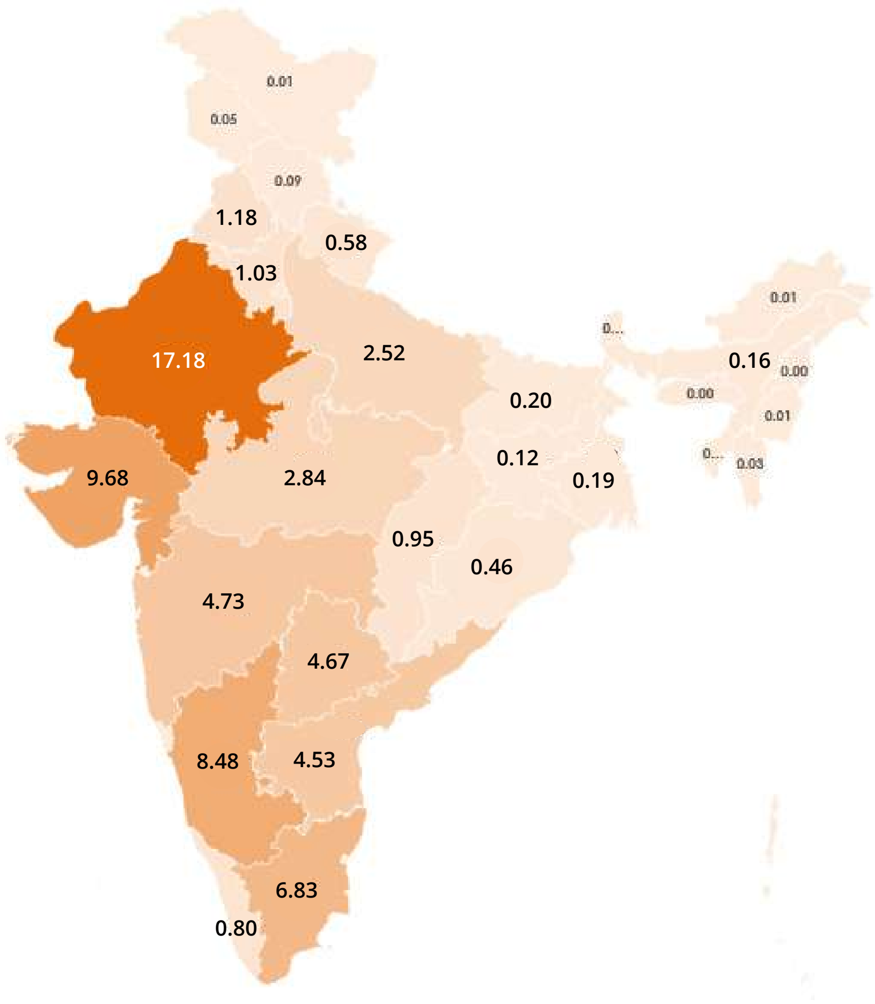


Figure 4: Total solar installed capacity in India[32]

[31] TERI, Blog post: Managing India's clean energy waste: A roadmap for the solar and storage industry, 2020. Accessed on: https://www.teriin.org/article/managing-indias-clean-energy-waste-roadmap-solar-and-storage-industry

[32] MNRE, State-wise installed capacity of Renewable Power as on 31.05.2023. Accessed on: https://mnre.gov.in/img/documents/uploads/file_s-1686304505453.pdf

Utility-scale power plants comprise more than 90% of the total PV installations in the country. The state of Karnataka has the highest share of Utility-scale PV installations at 21.6%, followed by Rajasthan at 15.2% and Tamil Nadu at 12.1%. It can be expected that in either regular or early loss scenarios, these states will see the highest generation of solar PV waste. Moreover, the advantage of such large installations of Utility -scale PV plants is that the bulk of future waste generation is centralised with respect to these plants' locations compared to the possibility of extremely distributed sites due to rooftop PV and off-grid solar.

With respect to rooftop installations, Gujarat leads with 23.8% of the total 3.088 GW installations in India as of August 2020, followed by Rajasthan at 11% and Maharashtra at 8.3%, as seen Table 3. Therefore, emphasis must be given to these states to track rooftop installations and update registries so that future PV takeback programs can benefit from it.

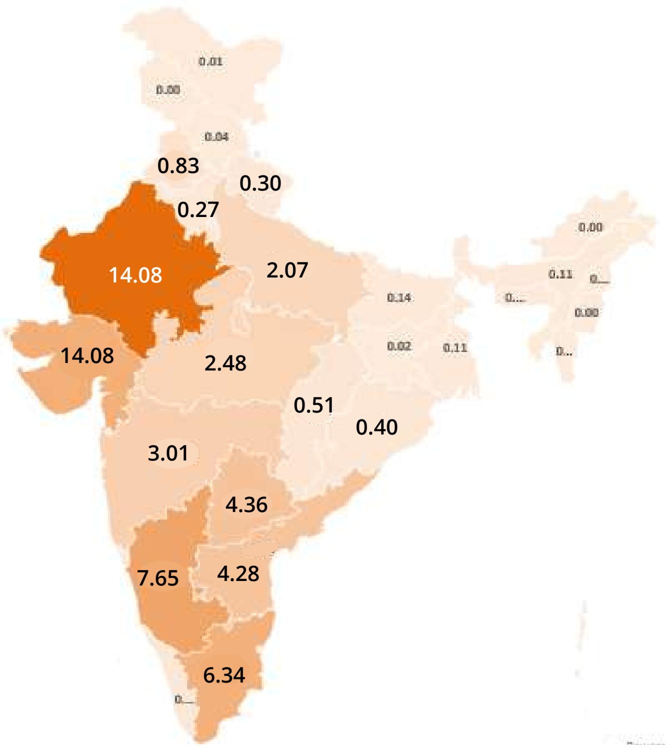
Apart from solar PV panels, India has experienced a rising adoption of other solar products in recent years. Solar lighting products like solar lanterns, street lighting and home lighting systems and water pumps are especially prevalent in rural areas with limited grid connectivity. Lighting products are widely used in states like Uttar Pradesh Bihar and Jharkhand, while water pumps find application in agricultural states like Rajasthan, Haryana and Chhattisgarh.

State-wise distribution of different types of solar installations (and hence the hotspots from a waste perspective) are given in the following table. The state-wise installation capacity for 2022 has been used to identify the major hotspots for solar waste generation in the future[33]. Hybrid RE systems combine multiple renewable energy sources, such as solar, wind, and biomass, to create an integrated and more reliable power generation system, optimizing energy generation and enhancing grid stability. This is a relatively new system in India and is still at an early stage of implementation. Currently, India has an installed capacity of 1.89 GW for hybrid solar, mainly in Gujarat and Rajasthan.

[33] MNRE, State-wise installed capacity of Renewable Power as on 31.05.2023. Accessed on: https://mnre.gov.in/img/documents/uploads/file_s-1686304505453.pdf

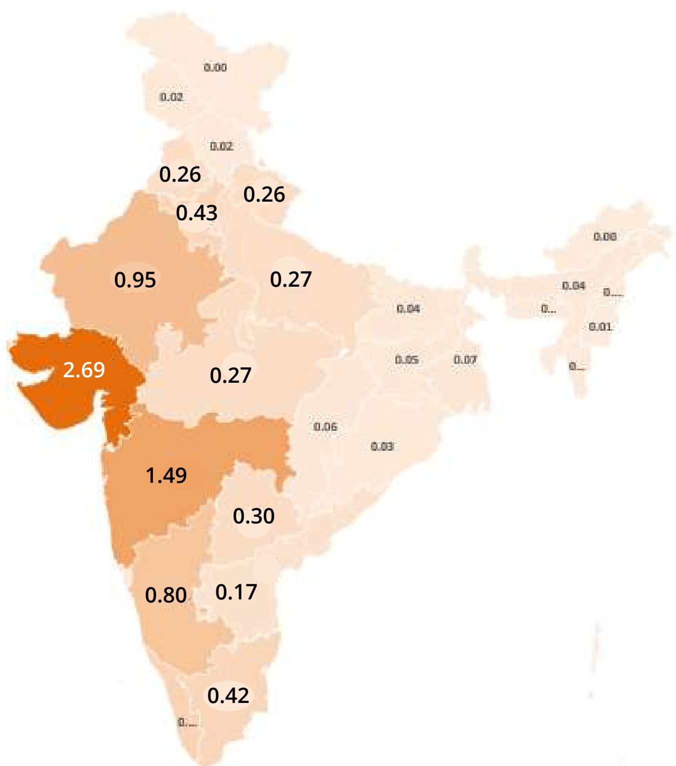
Table 3: Hotspots for solar installation, state-wise

Utility Scale Solar Hotspots



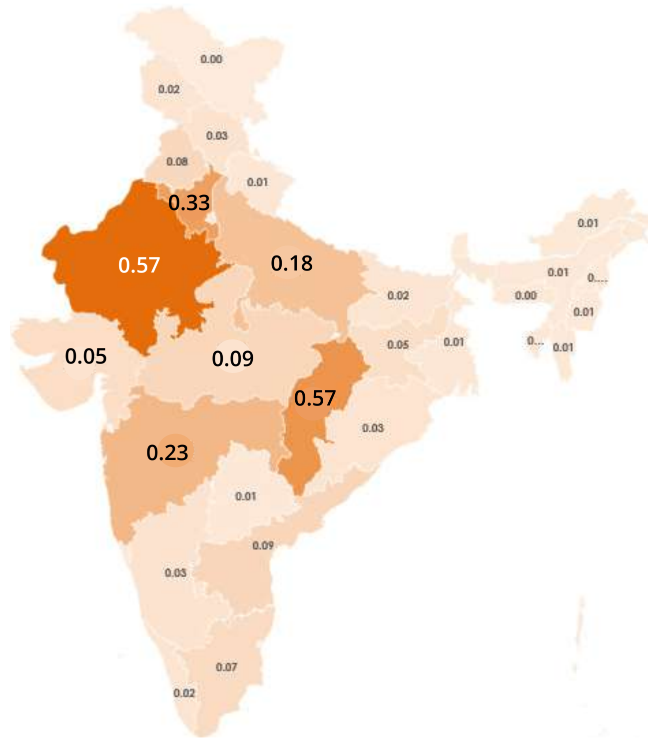
Utility Scale Solar Hotspots		
Total installed capacity	54020.5 MW
Hotspots	**Rajasthan,** Gujarat, Karnataka, Tamil Nadu
Percentage of total solar installation	79.6 %

Rooftop Solar Hotspots



Rooftop Solar Hotspots		
Total installed capacity	9497.9 MW
Hotspots	Gujarat, Rajasthan, Maharashtra, Karnataka
Percentage of total solar installation	14 %

OGS / Solar Pump Hotspots



OGS / Solar Pump Hotspots		
Total installed capacity	2410.2 MW
Hotspots	Rajasthan, Haryana, Chhattisgarh
Percentage of total solar installation	3.6 %

Remarks: Driven by the Kusum scheme, the OGS and the solar pumps hotspots are in the agricultural states in the country

2.3 Hazards from Solar PV Waste

Although most of the materials used in PV panels are non-hazardous, it's crucial to recognize the presence of valuable and potentially hazardous materials within these panels. These materials, although a small part of the overall composition, need careful handling due to their potential environmental and health impacts. Lead found in PV modules can cause gastrointestinal symptoms, severely damage the brain and kidneys, and may cause reproductive effects. Antimony is at par with arsenic in terms of toxicity and can cause problems with lungs, stomach and heart to workers exposed to it in unsafe conditions. The following table, explores and evaluates the specific hazardous materials found in PV modules.

Table 4: Hazardous material content in PV modules

Type of PV module	Substance	Content of Polluting/Hazardous substance
c-Si PV module	Lead (Pb)	0.7 to 1 g/kg per module in solder
	Beryllium (Be)	0.15 to 2% in CuBe alloy to improve properties of Copper
	Antimony (Sb)	100-300 ppm in front glass of module
CdTe PV module	CdTe	0.7 to 1.4 g/kg of module
	Lead (Pb)	0.1 to 1 g/kg of module
	Beryllium (Be)	0.15 to 2% in CuBe alloy to improve properties of Copper
	Antimony (Sb)	100-300 ppm in front glass of module
CIGS PV module	CdS	0.03 g/kg per module
	Selenium (Se)	0.02 g/kg per module
	Antimony (Sb)	100-300 ppm in front glass of module

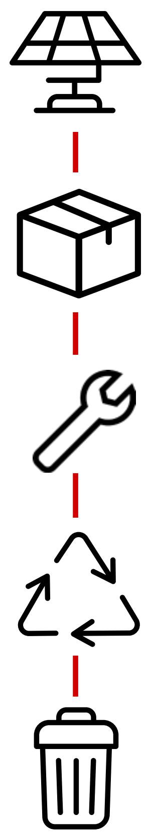
The Improper disposal or recycling of waste PV modules can lead to the release of these hazardous materials, potentially contaminating soil, water sources, and ecosystems. It is essential to establish effective waste management systems and adhere to regulatory guidelines for the safe handling and disposal of waste PV modules. Risks from specific components of the solar PV module is given in the following table.

Table 5: Major risks from different components of solar PV modules

Fraction	Composition	Source of Risk
PV cell	• Silicon (Crystalline) • Additives like Gallium, Boron, phosphorous • Cadmium, Lead (Thin Film)	Exposure to lead & cadmium
Aluminium Frame	• Aluminium	Injuries from improper handling

Fraction	Composition	Source of Risk
Glass	• Glass • Contaminants (e.g., Antimony)	Injuries from improper handling Exposure to contaminants
Plastics (Potentially containing Poly Vinyl Fluoride)	• Plastic • Fluorinated back sheets	Improper sorting and handling lead to unmonitored dumping in landfills Fluorocarbons, floricides, furans and dioxins released during recycling of fluorinated back sheets

Different stages of the EoL value chain for waste PV modules poses different hazards (Figure 5). Collection and take-back of waste modules at EoL is risky with workers often not taking any safety precautions. Transportation of waste PV modules also presents hazards. These modules can be large and heavy, requiring proper handling and secure packaging to prevent damage or accidents during transit. Dismantling and recycling stages also pose several risks.



Solar PV EoL
Lack of proper consumer awareness leads to storing of smaller products in households, burying, burning, disposal into household waste or sale to informal collectors

Collection
Major risk during the transportation of waste modules like fires, improper handling and lack of safety mandates for informal workers pose safety risks

Dismantling
Improper recovery and packaging of critical materials, lack of sufficient safety precautions pose safety risks

Recycling
Major portion of waste solar PV modules handled by the informal sector, improper recycling leading to loss of valuable secondary materials

Final Disposal
Waste solar modules are usually sent to the landfill as it is relatively cheaper than recycling; this increases environmental burden of e-waste and leads to loss of valuable secondary materials

Figure 5: Risks from the EoL management of waste solar PV modules

The informal sector in India plays a substantial role in handling e-waste and PV panels currently, but it often operates outside of regulatory mandates and safety measures. This poses risks as it increases the exposure to hazardous components in waste PV modules. Additionally, the lack of proper disposal requirements leads to a significant portion of solar PV modules ending up in landfills. This not only exacerbates the social and environmental burdens of e-waste but also results in the loss of valuable materials, missing out on potential economic opportunities from secondary raw materials.

Regulations would be instrumental in developing and implementing solar waste management in India by providing a framework for responsible handling, disposal, and recycling of PV modules. Environmental protection, worker safety, and efficient utilization of resources are important aspects that upcoming regulations need to address in order to ensure a sustainable approach to managing solar waste.

2.4 Current Regulatory Landscape for Solar PV waste management in India

The increasing penetration of distributed solar PV resources in the Indian electricity sector has made it necessary to prepare for managing their waste. However, until 2022 there was no regulation or policy regarding the end-of-life management of solar PV panels. Without this regulatory oversight for solar PV waste management, most of the waste arising from early loss scenario ends up in the informal recycling sector, leading minimal recovery of critical raw materials (CRM). The newly issued E-waste (Management) Rules, 2022 is the first regulatory instrument to recognise solar PV waste as a unique waste stream and provides rules and a guidance framework to oversee its management. In addition, growing consciousness towards taking a more circular approach in solar PV is being pursued by NITI Aayog and key government stakeholders such as MNRE[34].

What does "Circular Economy" mean?

Popularized by the Ellen MacArthur Foundation, Circular Economy is a concept that proposes the decoupling of economic activities from the consumption of finite resources as an approach to tackle global concerns such as climate change, biodiversity loss, etc.

A Circular Economy has three foundational principles:
- Eliminate waste & pollution
- Circulate products and materials (at their highest value)
- Regenerate nature

Source: The Ellen MacArthur Foundation

[34] NITI Aayog press release from March 2021 https://pib.gov.in/PressReleasePage.aspx?PRID=1705772

Solar Waste as part of the "E-Waste (Management) Rules"

The "E-waste (Management) Rules", recently amended and issued on November 2, 2022, have laid down guidelines for the solar sector, by bringing the waste category under the purview of Extended Producer Responsibility (EPR). According to the regulations, which cover solar PV modules, panels and cells, every manufacturer and producer of solar PVs is required to register themselves on the MoEFCC online portal upload a list of the modules/panels/cells manufactured on the portal. They are also required to store the PV waste generated up to the year 2034-35, in accordance with the guidelines laid down by the CPCB and maintain an updated inventory of the waste on the portal. Recyclers of solar PV modules or panels or cells are also mandated for recovery of material, based on standards that will be set by Central Pollution Control Board.

The E-Waste Rules also cover the restriction of hazardous substances (RoHS) in Electrical and Electronic Equipment (EEE). It is applied to producers and distributors involved in the manufacture, sale, and processing of EEE or their components. The Rules restrict the use of lead (Pb), cadmium (Cd), mercury (Hg), hexavalent chromium and certain flame retardants (PBB, PBDE) in EEE appliances.

What is the EPR framework in India and its relevance for EoL solar panels?

Extended Producer Responsibility (EPR) is a vital waste management policy where manufacturers or their equivalents are held responsible for managing the waste resulting from their products. EPR frameworks offer three implementation styles - voluntary, co-regulatory, and mandatory - to encourage proactive waste reduction, proper recycling, and responsible disposal. Developing countries face unique challenges with EPR, as illustrated by India's learning process. Initially, EPR compliance was limited due to enforcement issues, neglecting collection as a crucial element, and competition from the informal sector. However, strengthened EPR measures in 2016, including collection targets and Producer Responsibility Organizations, led to improved producer accountability. Solar waste's inclusion in the amended E-Waste Rules in 2022 mandates producers to allocate funds for collecting and treating end-of-life PV waste, incentivizing eco-design practices and supporting public recycling efforts.

Hazardous and Other Wastes Rules

The Hazardous and Other Waste (Management & Transboundary Movement) Rules[35] implements the International Basel Convention in India. 'Other' waste includes those listed in Part B and Part D of Schedule III for import or export and includes all such waste generated originally within India.

[35] Ministry of Environment, Forest, and Climate Change, Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016. Accessed on: https://cpcb.nic.in/displaypdf.php?id=aHdtZC9IV01fUnVsZXNfMjAxNi5wZGY=

The Rules define hazardous waste as any waste which by virtue of any of its physical, chemical, biological, reactive, toxic, flammable, explosive, or corrosive characteristics. Crystalline silicon PV modules, which compose the great majority of the Indian installed PV fleet, when tested under the requirements of the Rules. In the newer PV modules, however, concentration levels of relevant metals, including mercury, arsenic, barium, cadmium, chromium, lead, selenium, and silver are below the limits defined by the Rules.

Glass used in solar panels often contain Antimony which has the potential to leach in wet landfill conditions. In 2019, the MNRE issued a draft blueprint acknowledging the concern of antimony leaching when solar glass is disposed of in uncontrolled landfills and gets crushed. Since solar PV was earlier categorized as non-hazardous waste under these Rules, the risk of improper sorting and solar glass ending up in uncontrolled landfills was higher. In lieu of the latest EWM Rules 2022, there is a need to update the current guidance present for different materials in solar PV modules.

CdTe solar panels have a higher concentration of cadmium and tellurium than prescribed limits of the Rules. These could be potentially leach out of panels if non-encapsulated CdTe solar modules are discarded in municipal landfills. However, the quantity of these panels is not high enough to make it a concern yet. CIGS PV modules are also listed as non-hazardous waste under these Rules, due to low concentration of selenium.

Batteries (Management and Handling) Rules, 2001

The Batteries (Management and Handling) Rules, 2001 currently only apply to lead acid batteries. Consumers are required to return spent batteries to designated collection points or authorized entities. Producers are obligated to collect 90% of lead acid batteries and establish collection points for end-of-life batteries. In August 2022, the the MoEF&CC notified the new Battery Waste Management Rules, 2022, after a round of updates following the public consultation stage. Lithium-ion batteries currently accompanying PV systems are covered under the scope of the new Rules, unlike the 2001 Rules.

Incentives for Recycling Infrastructure

Ministerial stakeholders have taken a more active role in implementing initiatives to enhance recycling infrastructure capacities. On March 3, 2022, the Ministry of Electronics and Information Technology (MeitY) introduced amendments to the Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS) Guidelines. These amendments make recycling facilities for precious metals from e-waste components eligible for incentives under SPECS. The amendment covers various e-waste components, including Li-ion batteries and printed circuit boards (PCBs). This step is expected to encourage private sector investments in solar waste recycling, with a minimum investment threshold of INR 2 crore.

Furthermore, solar manufacturers are obligated to comply with the Plastic Waste Management (Amendment) Rules, 2022, and the Solid Waste Management Rules, 2016, for managing their packaging waste and plastic waste from PV panels. Although the regulatory framework for addressing the growing volume of solar PV module waste in India is gradually developing, its implementation still faces challenges as producers and manufacturers adapt to the evolving focus on solar energy. While the emphasis remains on expanding solar power capacity as part of India's renewable energy drive, additional regulatory measures are necessary to ensure effective waste management practices.

2.5 Current solar PV recycling system

As mentioned in the earlier section, till November 2022, India did not have a dedicated policy for solar waste management. The new EWMR 2022, brings EoL solar PV modules under the purview of e-waste but does not yet mandate the EPR framework for its recycling. It tasks solar manufacturers to collect and store solar PV modules till 2034, due to lack of sufficient recycling infrastructure in the country at present. As per CPCB data, installed capacity for registered e-waste recyclers / dismantlers in the country is only about 0.4 million tonnes per annum, 22% of the estimated e-waste volume[36]. The actual capacity is lesser as many facilities are yet to start operations.

Currently India does not have a standalone commercial PV recycling plant. A pilot plant of 2.5 ton/day capacity has been developed as a part of Solar Waste Action Plan project by Sofies India and Poseidon Solar[37]. The pilot plant uses mechanical delamination technique and can recover close to 80% materials by weight. Lab scale models on thermal and chemical delamination techniques for PV panels have been report by IIT-Bombay[38] and C-MET[39]. The new Rules are anticipated to promote commercial-grade implementation of PV waste recycling, attracting private sector engagement and international funding support for building a robust recycling infrastructure.

The current recycling technologies available globally have been elaborated in the next chapter (Section 3.3).

[36] Bridge to India, "Managing India's PV Module Waste", 2019. Accessed on: https://bridgetoindia.com/backend/wp-content/uploads/2019/04/BRIDGE-TO-INDIA-Managing-Indias-Solar-PV-Waste-1.pdf

[37] Please refer to Section 5.4 for more information on SWAP project

[38] IIT Bombay, National Centre for Photovoltaic Research and Education (NCPRE). Access to website: http://ncpre.iitb.ac.in/ncpre/

[39] C-MET, Centre of Excellence (CoE) on E-waste Management, Solar Cells. Accessed on: https://www.coeonewaste.com/solar-cells.html

03 Looking at the scale of the challenge

Deep dive into Solar PV Waste Volumes

3.1 Opportunity for End-of-Life Management of Solar PV in India

Sustainable management of waste solar PV modules is crucial for material recovery. Each solar panel constitutes of not only abundant materials such as glass, aluminium and plastics, but also contains rare and critical raw materials (CRMs) such as Indium, Gallium, Selenium, etc. The material constitution of the different types of PV panes is given below:

Table 6: Material composition of PV panels by type.

Material	Crystalline silicon PV panel	Cadmium Telluride PV panel	Copper Indium Gallium Selenide PV panel	
Source:	**FRELP (2016)**[40]	**PVPS Task 12 (2020)**[41]	**PVPS Task 12 2020**	**Jungbluth et al.**[42]
Glass, containing antimony (0.01-1%/kg of glass)	70%	67.06%	94.56%	75.95%
Aluminium frame	18%	19.20%	2.03%	14.79%
Copper connector	1%	0.78%	0.078%	0.06%
Ethylene Vinyl Acetate (EVA) encapsulation layer	5.1%	6.6%	3.17%	4.4%
Polyvinyl fluoride +PET (Back sheet)	1.5%	2.305%	0%	2%
Silicon metal in solar cell	3.56%	4.36%	0%	0%
Silver	0.053%	0.025%	0%	0%

40 https://www.researchgate.net/publication/301693669_Analysis_of_Material_Recovery_from_Silicon_Photovoltaic_Panels
41 https://iea-pvps.org/wp-content/uploads/2020/12/IEA-PVPS-LCI-report-2020.pdf
42 http://esu-services.ch/fileadmin/download/publicLCI/jungbluth-2012-LCI-Photovoltaics.pdf

Aluminium, internal conductor	0.53%	0.32%	0%	0%
Copper, internal conductor	1.076%	0%	0%	0%
Solder (tin, lead)	0.053%	0.11%	0%	0.07%
Cadmium telluride	0%	0%	0.16%	0%
Indium	0%	0%	0%	0.017%
Gallium	0%	0%	0%	0.008%
Selenium	0%	0%	0%	0.034%
Molybdenum	0%	0%	0%	0.03%
Silicone product	0%	0%	0%	2.36%
Polyphenylene sulfide	0%	0%	0%	0.27%

Apart from CRMs, even materials such as Aluminium and Cooper need to be imported into the country to meet the demand by the solar industry. Other materials such as silicon wafers are also heavily reliant on imports (Figure 6). Silver, Poly Silicon, and low iron tempered glass for solar panels (solar glass) are the critical materials in India that are expected to be met through domestic manufacturing in the future.

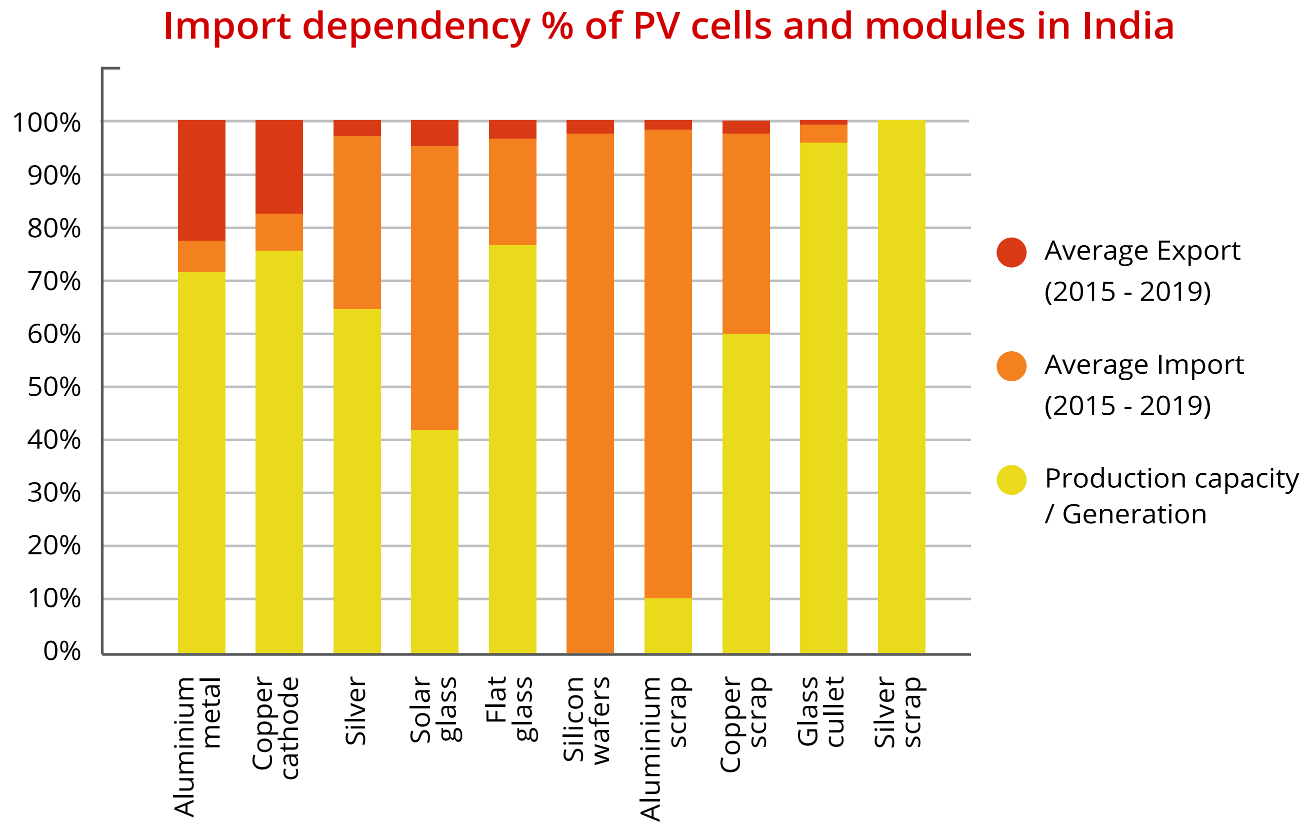


Figure 6: Production, Import & Export scenario in India for Upstream and downstream materials involved in PV module life cycle

Responsible management and recovery of the waste panels is essential in the recovery of these valuable raw materials and ensure a sustainable, long-term value chain. A robust closed 'loop' in the solar value chain can also help reduce import dependencies for the sector, thus making it more self-sufficient.

3.2 PV Waste Forecasting in India

Although there have been multiple PV waste forecasting studies in the recent years, it is important to understand – based on the current installation targets & latest data available – the size of the solar waste problem India is likely to face in the coming years. In this context, this section presents the solar PV waste forecasting exercise conducted for India, based on publicly available information. Multiple sources for cumulative PV installation targets have been used, varying from highly conservative to fairly optimistic, in order to provide a range of estimates.

3.2.1 Methodology for PV waste forecasting

The methodology for the Solar PV waste forecasting study can be summarized into the seven key steps summarized below. An Excel-based tool was also created for these calculations and has been shared as an annexe to this report.

1. Assessing the policies and market studies to understand the future PV targets
2. Scenario building based on the policy/ market study targets
3. Extrapolation of PV installation to achieve the said targets in respective scenarios
4. Material intensity targets (t/MW) - literature review and market studies
5. Converting PV installation annually from GW to tonnes
6. Calculating the failure probability used weibull distribution
7. Calculating annually forecasted PV waste

Step 1: Assessing the policies and market studies:

Five reputed sources were used as the basis for the forecasting study. These included - MNRE, India Energy Security Scenarios (IESS), and three scenarios by Solar Power Europe (SPE) Market Outlook – Low, Medium, and High. For each, the cumulative targets for the year 2030 were considered, as described below:

Table 7: PV installation targets by source

Source	Cumulative targets (GW)	
	Year 2022	Year 2023
Ministry of New and Renewable Energy (MNRE)	100	300
SPE market outlook (Low)	58.9	187.1
SPE market outlook (Medium)	71.4	287.4
SPE market outlook (High)	104	401.2
India Energy Security (IESS)	66	170

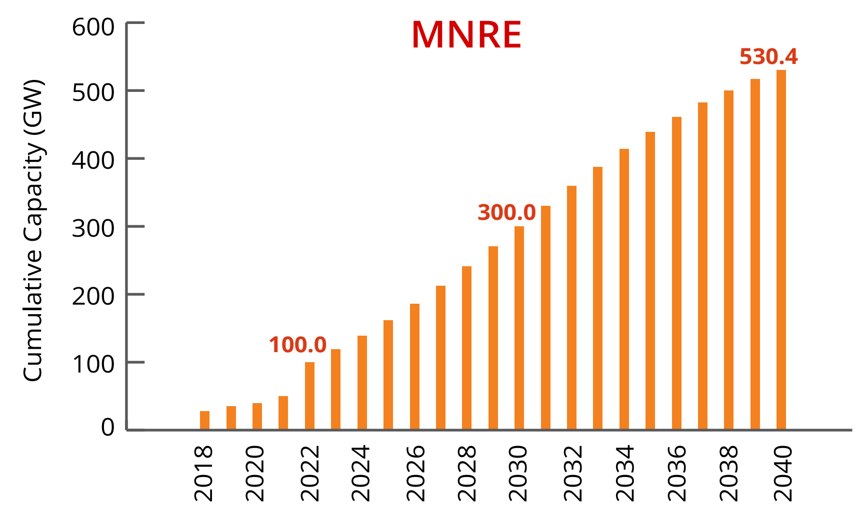
Step 2&3: Future PV installation projections according to the policy/market study targets

Based on Literature review, Logistic "S" shaped curve[43] was used to represent PV capacity addition, as it has been reported as the best fit for representing Solar PV installation trends.

$$Cumulative\ PV\ installation(Year) = \frac{L}{1 + e^{k(x_0 - Year)}}$$

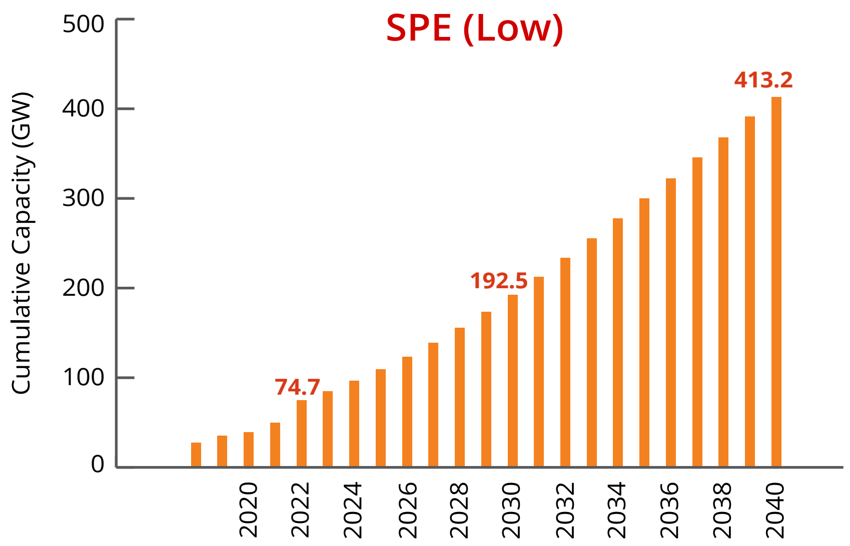
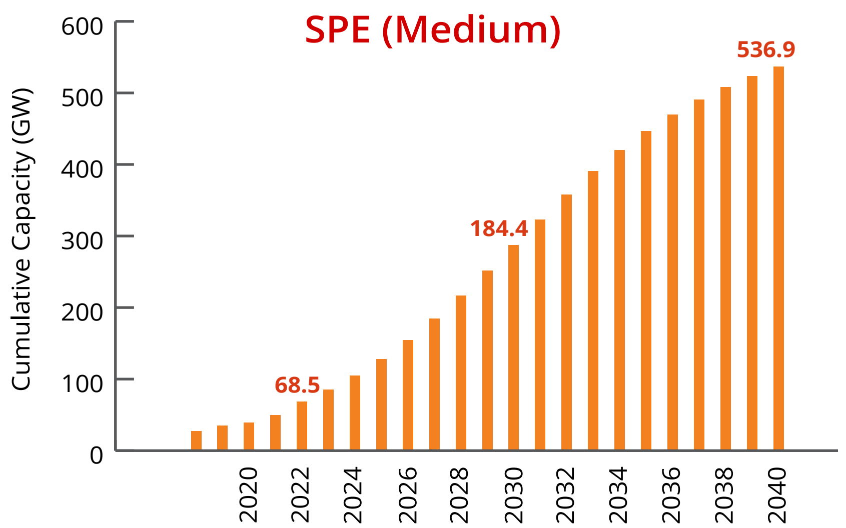
L	Maximum projected value of Cumulative PV capacity
k	Expected growth rate of PV installations
x_0	Year of maximum growth (mid-point of curve)
Year	Lifetime of PV panel considered

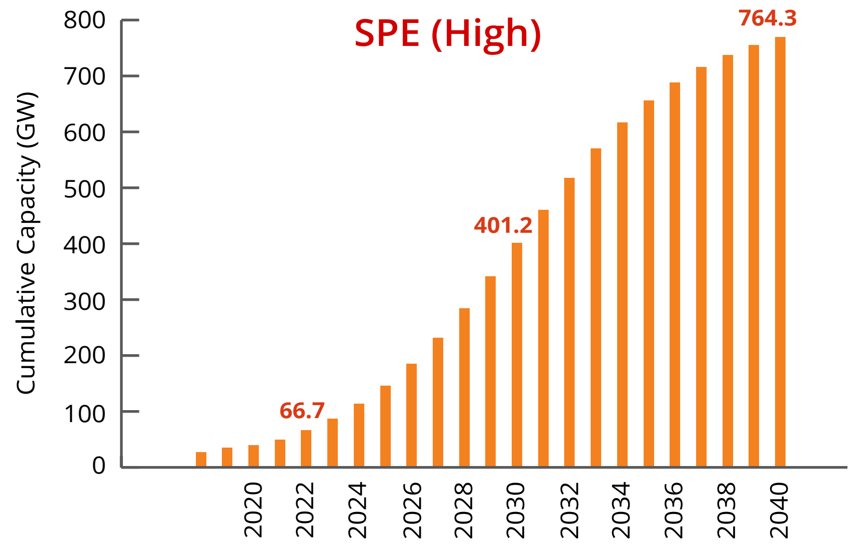
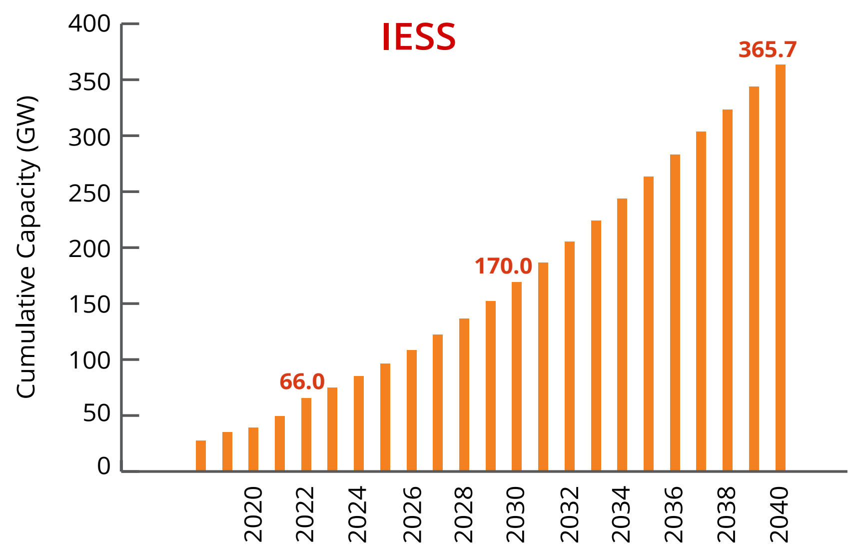
The projections for the sources identified have been depicted. Repowering has been considered in the following projections (i.e., solar PV capacity that has reached its EoL – 25 years, have been assumed to be fully replaced).

<table>
<tr><th>Source</th><th>Projection using logistic curve</th></tr>
<tr><td>MNRE</td><td>

Estimated cumulative capacities for the following horizon years:
2030 – 300 GW
2040 – 530.4 GW</td></tr>
</table>

[43] https://georgejetson.org/is-pv-capacity-growth-logistic/
https://www.researchgate.net/publication/303457109_Evaluation_of_the_main_energy_scenarios_for_the_global_energy_transition
https://onclimatechangepolicydotorg.wordpress.com/2019/02/06/rapid-growth-of-solar-pv-seems-likely-to-continue/

SPE (Low)	 Estimated cumulative capacities for the following horizon years: 2030 – 192.5 GW 2040 – 413.2 GW
SPE (Medium)	 Estimated cumulative capacities for the following horizon years: 2030 – 184.4 GW 2040 – 536.9 GW

SPE (High)	 Estimated cumulative capacities for the following horizon years: 2030 – 401.2 GW 2040 – 764.3 GW
IESS	 Estimated cumulative capacities for the following horizon years: 2030 – 170 GW 2040 – 365.7 GW

Step 4 & 5: Material Intensity targets

Material intensity indicates the specific mass of each raw or composite material per unit of installed capacity. Consolidated material intensity trends for a PV panel was identified through the sources[44] and the Medium density scenario (MDS) from the EU-JRC study was chosen for the analysis (Figure 7). However, the material intensity have been made a flexible input in the tool for future modifications.

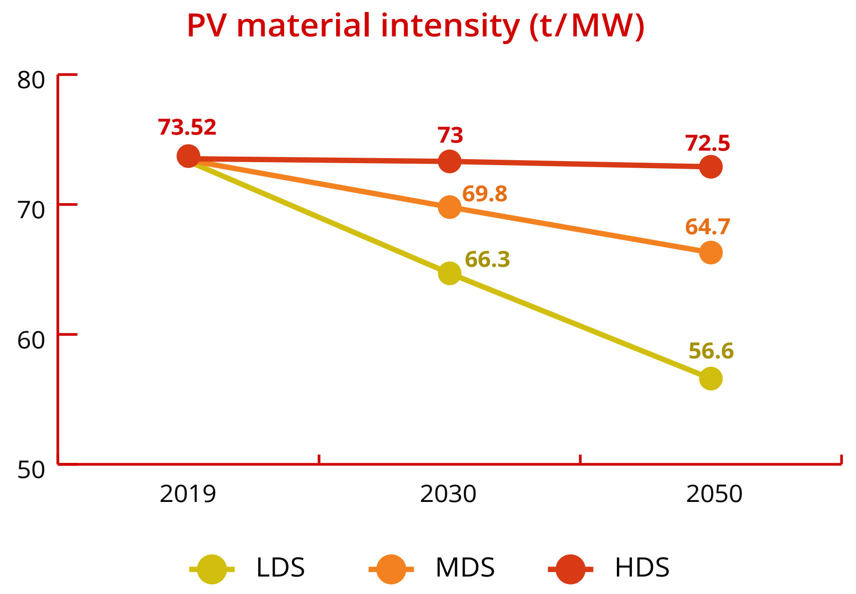


Figure 7: PV material intensity by scenario

Step 6: Calculating failure probability with Weibull

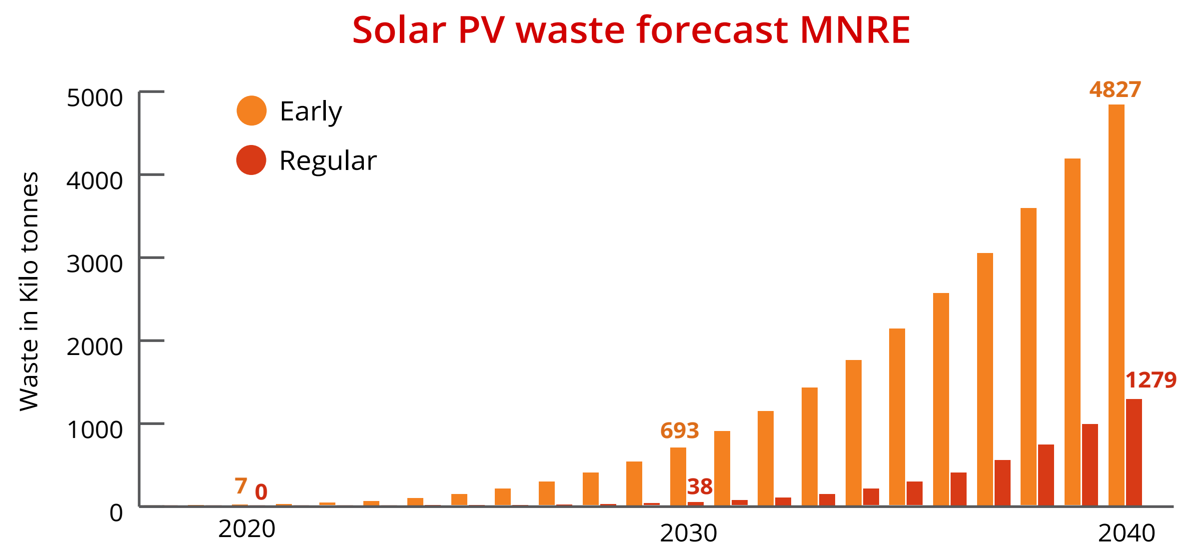
Scenarios are usually reported in the literature as early loss and regular loss. The shape factor is currently obtained by forecast studies from literature[45] of PV reliability studies.

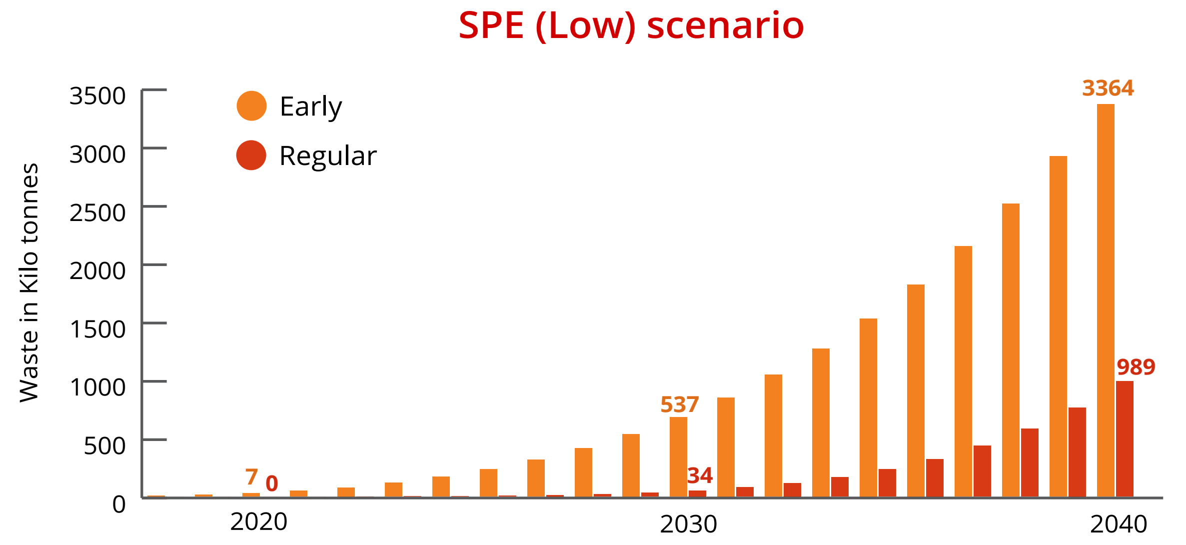
Scenario	Early Loss	Regular Loss
Shape factor α (obtained through accelerated testing and field data)	2.4928	5.3759
Average panel lifetime (would be made dynamic in the current study)	30-year	30-year
Probability of loss after 40 years	99.99%	99.99%
Waste due to damage during transport and installation phases	0.5% of PV panles	-
Waste within two years due to bad installation	0.5% of PV panles	-
Waste after 10 years	2% of PV panles	2% of PV panles
Waste after 15 years	4% of PV panles	4% of PV panles

[44] https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels
Carrara, S., Alves Dias, P., Plazzotta, B. and Pavel, C., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. Publications Office of the European Union, 2020.
[45] https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

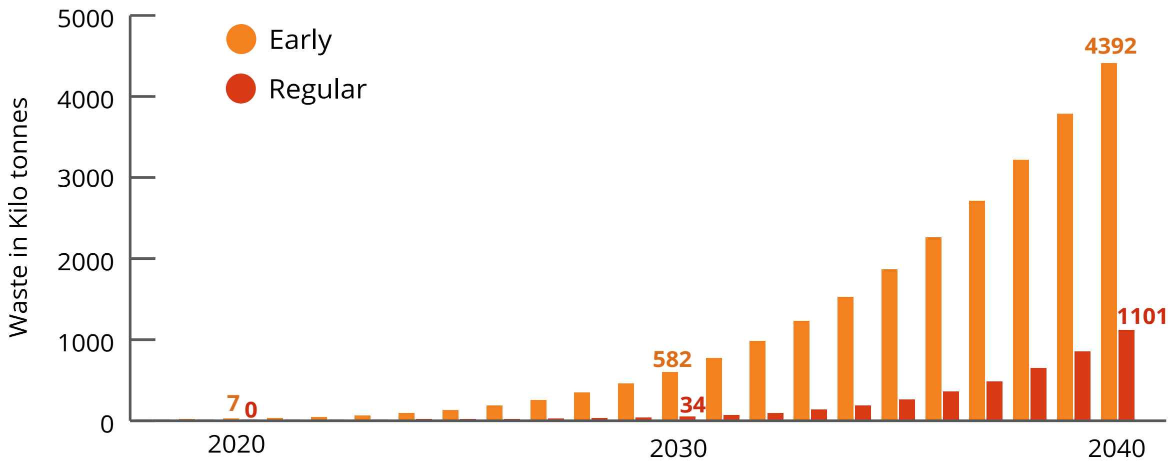
Step 7: Calculating annually forecasted PV waste volumes in India

On applying the failure probability to the converted installation capacity in tonnage, the annually forecasted PV waste volumes are obtained for both early and regular loss scenarios. The graphs below indicate the cumulative forecasted PV waste volumes based on MNRE, IESS and SPE's low, medium and high scenarios.

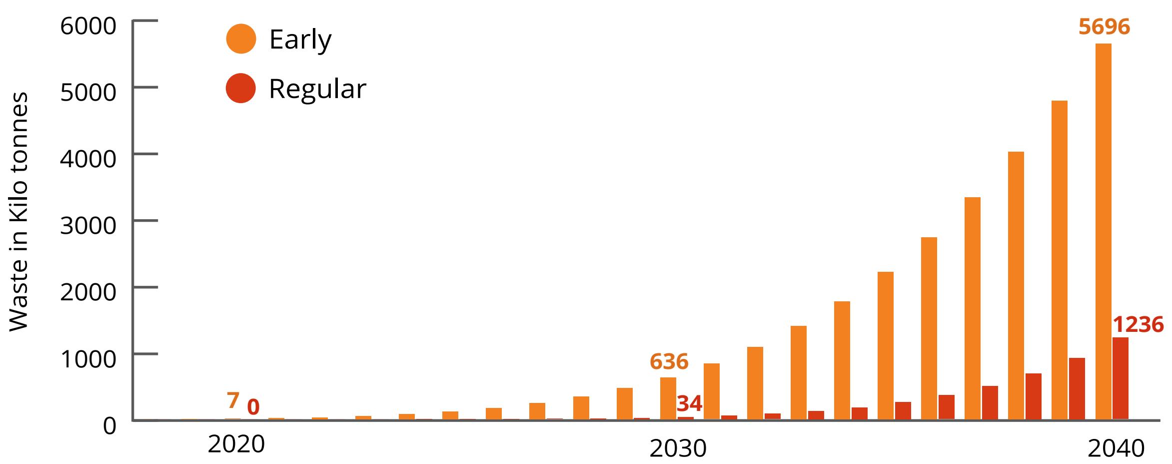




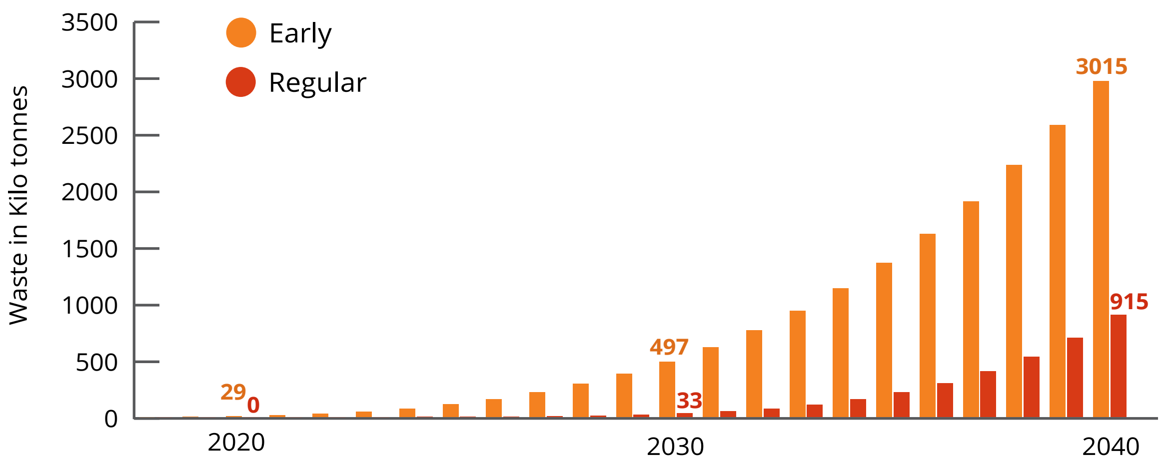
SPE (Medium) scenario



SPE (High) scenario



Solar PV waste forecast IESS scenario



The cumulative PV waste forecast numbers have been tabulated for the five different scenarios below (Table 8).

Table 8: PV forecast figures by scenarios

Scenario	Cumulative waste forecast (Kilo tonnes) by 2025		Cumulative waste forecast (Kilo tonnes) by 2030		Cumulative waste forecast (Kilo tonnes) by 2040	
	Regular scenario	Early scenario	Regular scenario	**Early scenario**	Regular scenario	Early scenario
MNRE	2	132	38	693	1279	4827
SPE (Low)	2	113	33	497	915	3015
SPE (Medium)	2	118	34	537	989	3364
SPE (High)	2	117	34	582	1101	4392
IESS	2	118	34	636	1236	5696

3.2.2 Waste forecast volumes for India

The forecast volumes determined based on the above-mentioned steps are presented in Table 8. As is clear from the table, different data sources as well as different loss scenarios results in variations of the project values for a particular year. The detailed calculation steps can be found in an excel document accompanying the report.

Table 9: PV waste forecast volumes by source

Source	Cumulative installation target (GW)			Cumulative waste projection (Million tonnes) by 2040	
	Year 2020	Year 2030	Year 2040 (projected)	Regular loss	Early loss scenario
MNRE	100	300	530	**1.3**	**4.8**
SPE (Low)	58.9	187.1	413	**1.0**	**3.4**

SPE (Medium)	71.4	287.4	537	**1.1**	**4.4**
SPE (High)	104	401.2	770	**1.2**	**5.7**
IESS	66	170	366	**0.9**	**3.0**

The MNRE scenario exhibits the highest waste volumes by 2040 in the range of 1.3-4.8 Million tonnes whereas the India Energy Security scenario exhibits 0.9- 3 Million tonnes by 2040. It must be noted that the India Energy Security scenario had the closest projection to reality in terms of PV capacity installed in 2022. SPE (High) scenario exhibits the highest PV waste volume by 2040 in the early loss scenario as the scenario assumes highest PV capacity installation from 2030. MNRE scenario on the other hand, assumes aggressive PV installation from 2022 itself, thereby exhibiting a higher regular loss based PV waste volumes by 2040.

The forecast volumes were then validated with the existing forecast studies as follows:

Table 10: Validated PV waste volumes

Scenario	Cumulative waste forecast (Kilo tonnes) by 2025		Cumulative waste forecast (Kilo tonnes) by 2030		Cumulative waste forecast (Kilo tonnes) by 2040	
	Regular scenario	Early scenario	Regular scenario	Early scenario	Regular scenario	Early scenario
MNRE	2	132	38	693	1279	4827
SPE (Low)	2	113	33	497	915	3015
SPE (Medium)	2	118	34	537	989	3364
SPE (High)	2	117	34	582	1101	4392
IESS	2	118	34	636	1236	5696
Study conducted by IRENA			50	325	620	2300

EU TCP study			11.2	34.6		
Bridge to India				200		

Higher waste volumes forecasted in the scenarios compared to study by IRENA can be attributed to the increased installations and projections of PV volumes in recent years as compared to 2016 when IRENA study was completed. EU TCP study only includes waste due to breakage, transportation and not the end-of-life waste volumes and bridge to India study is based on an empirical formulation and expert interviews on quality of PV installations in India.

3.3 Recycling Infrastructure and Technologies

PV recycling technologies have been researched since 1990s with the first patent being filed in 1995 for crystalline silicon PV panels. However, through the years, the emphasis on R&D in recycling has been on cadmium telluride (CdTe) PV modules due to the hazardous and rare earth material content – despite 95% of the market of PV panels being held by crystalline silicon PV panels.

In general PV recycling starts with removal of junction box and aluminium frame present in a panel. The most important step in PV recycling is the delamination of the panel to separate the solar cells, front glass, and the plastic layer (encapsulant, back sheet). The delamination techniques can be broadly classified as mechanical, thermal and chemical.

3.3.1 Mechanical delamination

Mechanical recycling method is used for complete photovoltaic modules[46]. Recycling process includes mainly mechanical and hydrometallurgical processing. PV modules are first crushed in the crusher and then shredded to the desired pieces of approximately 4 to 5 mm size. The PV module lamination is damaged in this way. The glass is separated from larger pieces of the laminate film due to the size of the milling cutter. Remaining parts of the laminate film are separated from the glass fragments in the vibrating network.

[46] Solar Waste Action Plan (SWAP) Report

Such processes exhibit low energy demand and easy integration with existing glass/metal/e-waste recycling infrastructure. Mechanical delamination is comparatively cheaper compared to the other technologies but lack in recovery of high value materials like silver, silicon, cadmium, lead etc which are present inside the solar cells.

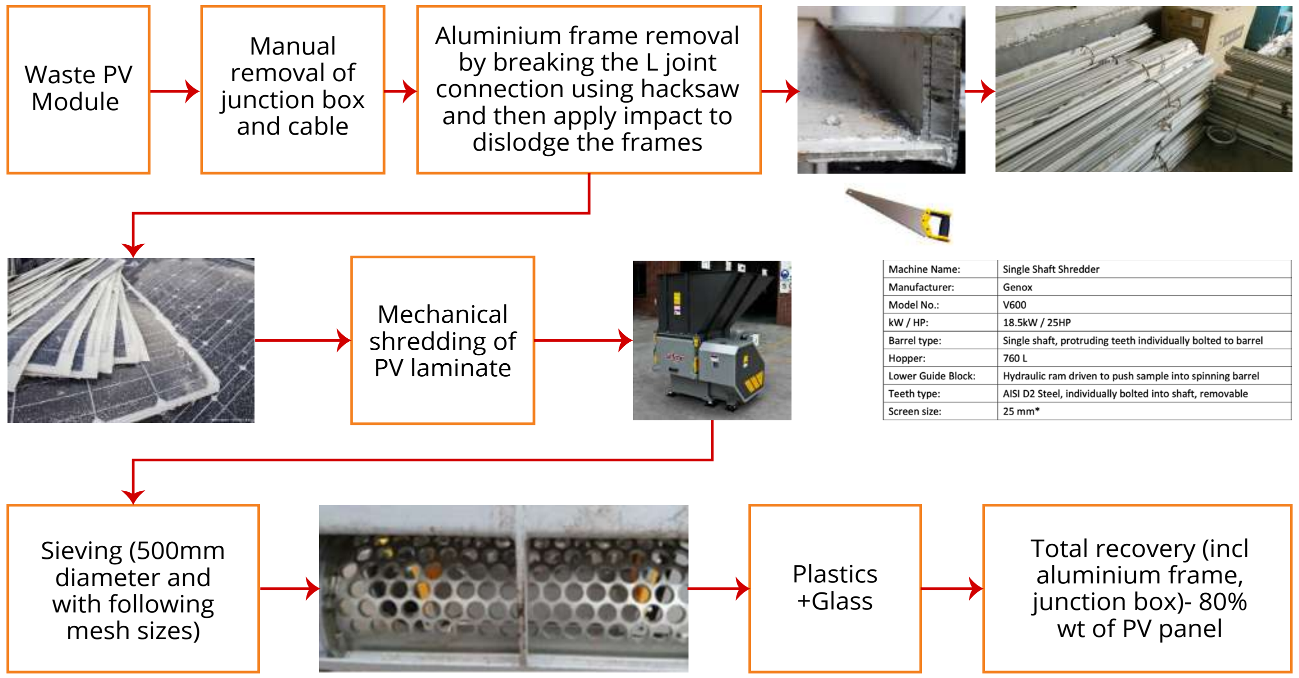


Figure 8: Mechanical delamination process

3.3.2 Thermal delamination method

Thermal delamination methods enable pure material stream recovery of glass and PV core containing silicon and metals as the polymer sheets undergo complete pyrolysis or burn off. The advantage therefore is higher material recovery from a PV panel compared to mechanical delamination. However, exhaust gas treatments are required which increases the investment cost. The back sheets of most PV panel contain fluorine which demands exhaust gas treatments owing to the combustion involved in thermal delamination.

This thermal delamination process can achieve recovery of 95% by weight of materials present inside PV panels. The extraction process involved in silver, lead and copper extraction is described in Figure below[47].

[47] Korea Institute of Energy Research

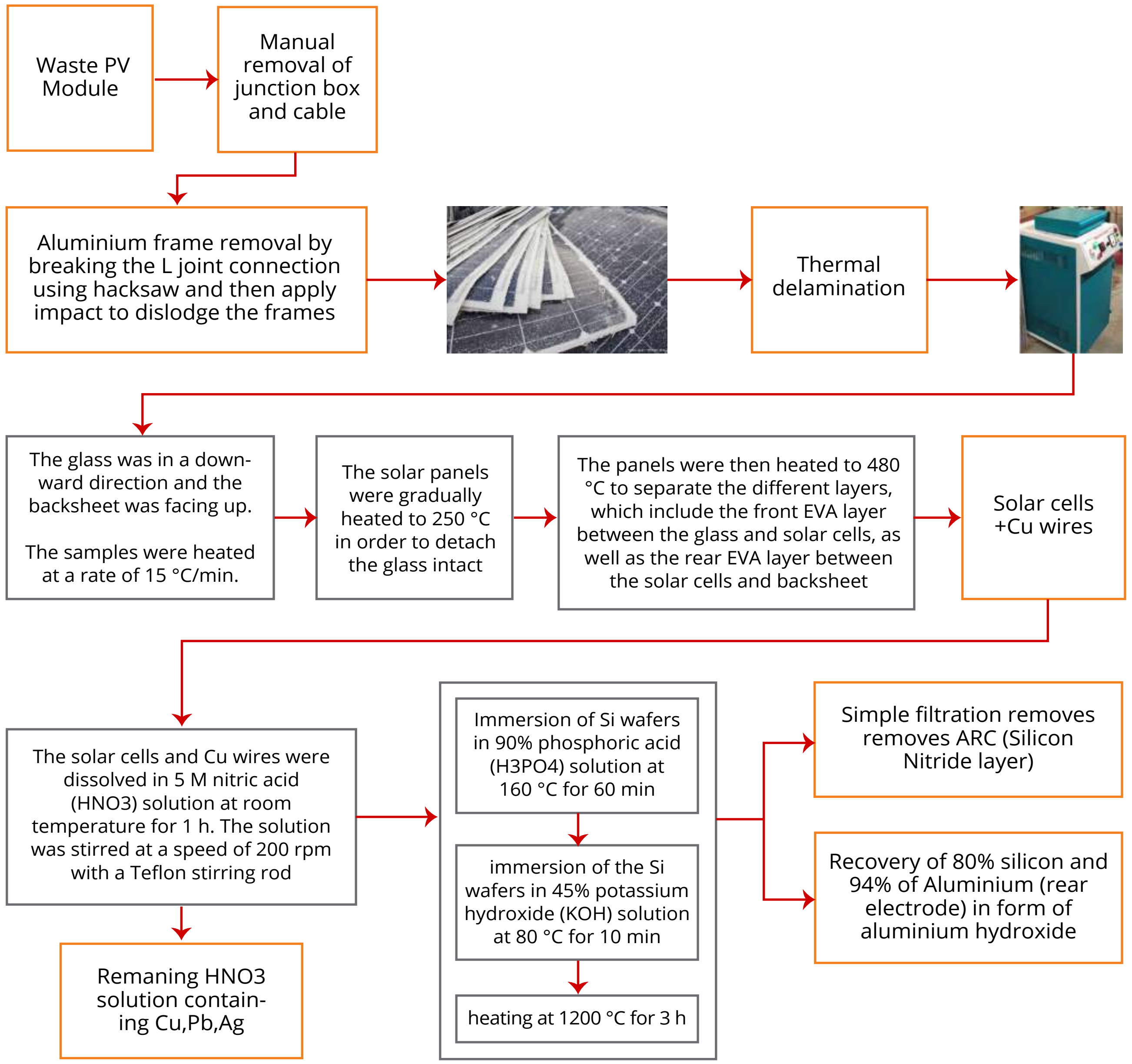


Figure 9: Complete material extraction from PV panels

3.3.3 Chemical delamination

Chemical delamination methods involve the dissolution of EVA in organic or inorganic solvents. The treatment time initially ranged in days, but dissolution under ultrasonic irradiance has enabled short dissolution times. Chemical delamination is still under the laboratory stage, and there is a need to understand the additional environmental impact due to the inclusion of chemical solvents.

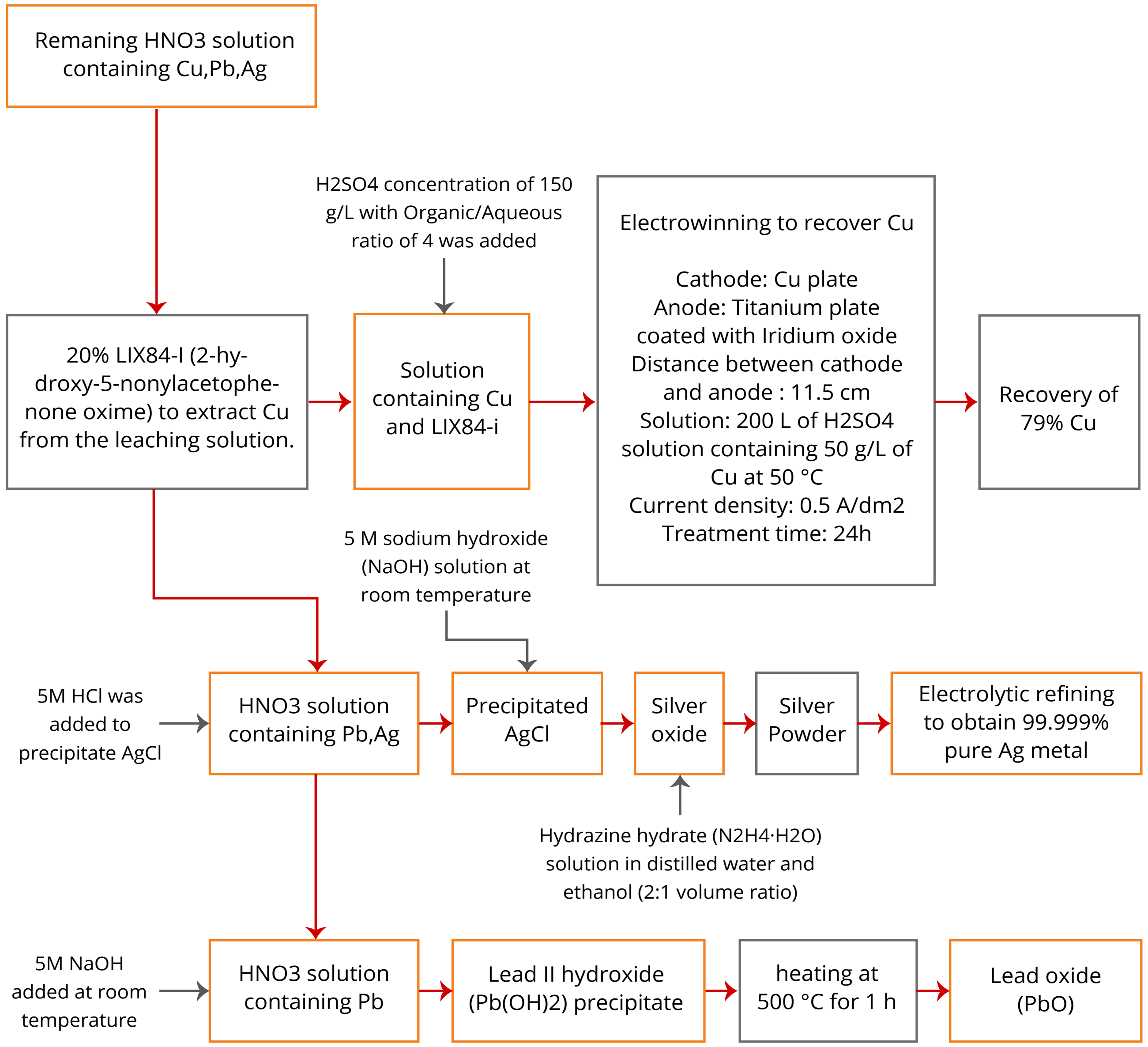
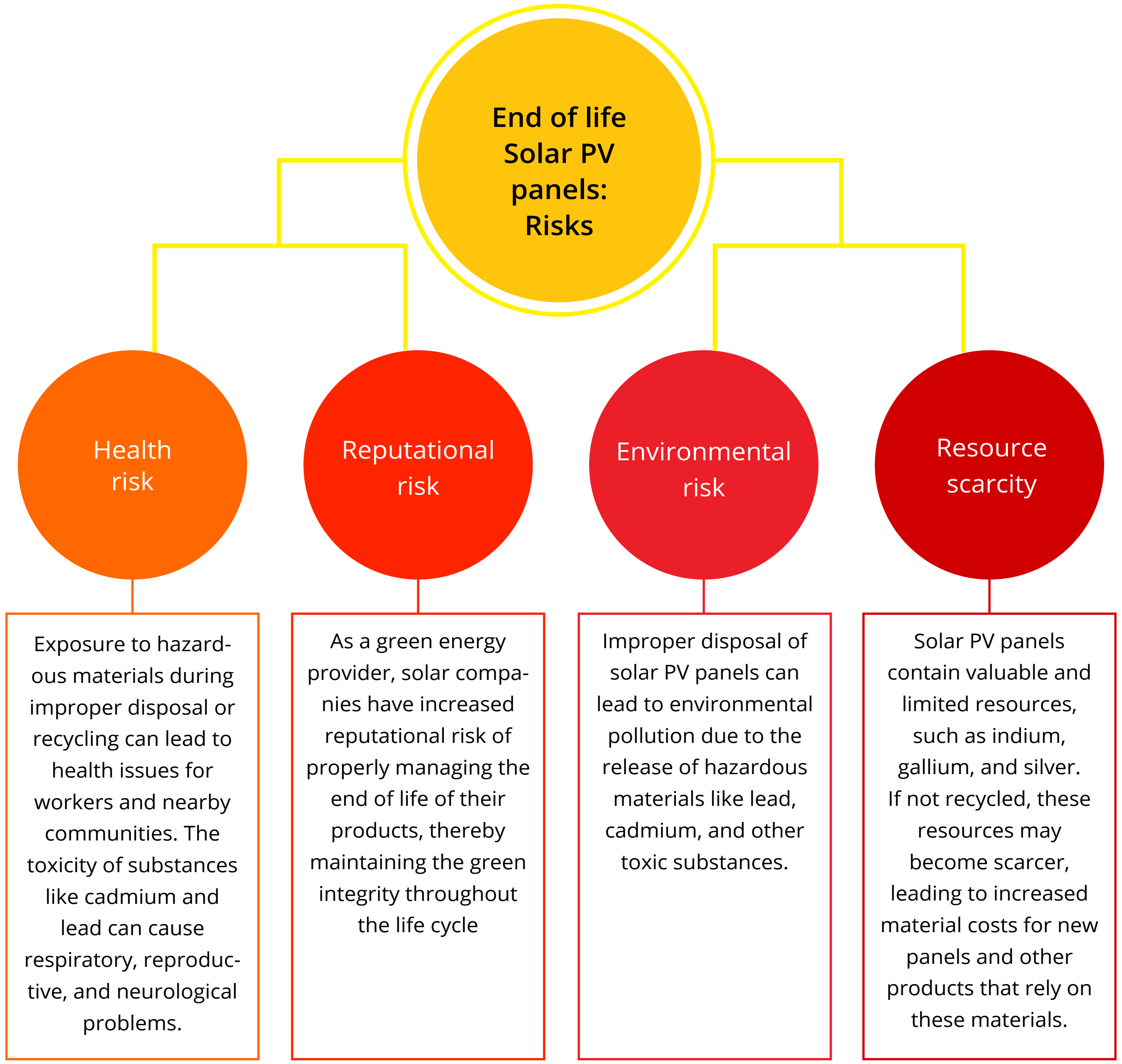


Figure 10: Extractions steps for copper, silver and lead from PV panels

A comparative table between the 3 recycling options is presented below.

	Mechanical delamination	Thermal delamination	Chemical delamination
Advantages	- Low Capital Expenditure - Proven at commercial scale	- Higher recovery rate compared to mechanical delamination - Validated in lab environment	- Higher recovery rate compared to mechanical delamination - Validated in lab environment - High purity recovered materials
Disadvantages	- Low recovery rate close to 75-80% by weight - High value materials like silicon and silver are hard to recover with mechanical delamination.	- Higher capital expenditure compared to mechanical delamination - Exhaust gas monitoring and treatment needed	- Disposal of used chemicals in industrial scale - Higher capital expenditure and operating expenditure than the other two delamination methods.

Various types of risks associated with the lack of operational solar PV recycling facilities at the end of life of a substantial volume of panels include:



3.4 Material volumes estimated for collection, recovery, and disposal

As mentioned previously, the global Solar PV market has been dominated by crystalline silicon modules, which accounted for 95% of the market share for the past five years. Thin film-based modules led by CdTe constitute the rest of the market. Demand for higher efficiency has made Monocrystalline silicon products overtake their multi-crystalline counterparts, with 66% of total market share in 2019 compared to 45% in 2018, as shown below. c-Si modules are expected to maintain their market share in the future owing to their higher conversion efficiencies and economies of scale.

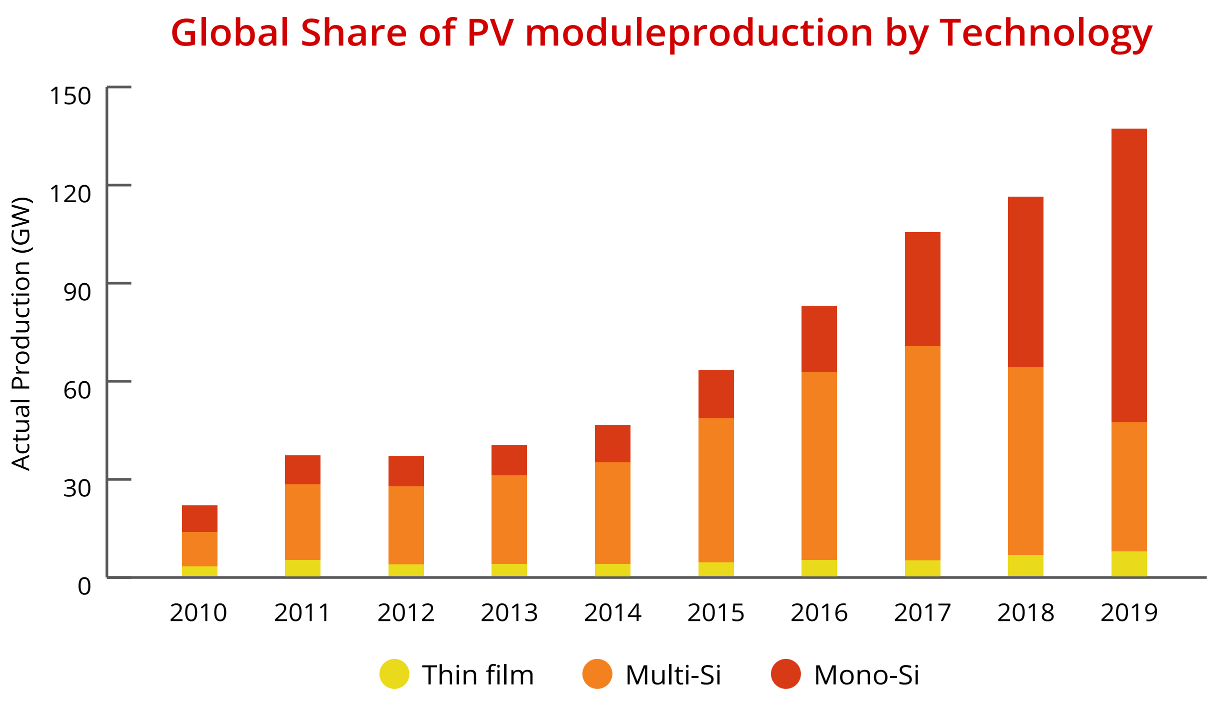


Figure 11: Global share of Solar PV production by Technology

Hence 95% of the waste volume can be assumed to be crystalline silicon and 5% to be CdTe module (as the market share of CIGS is almost negligible) for both historical and projected installations in India. To understand the potential for material recovery, two scenarios can be considered – bulk recycling, which refers to the recovery of major elements of PV panel alone by weight like Glass, Aluminium frame, copper from cables, and high-value recycling where even trace elements like copper, aluminium, silver present in a c-Si PV panel with close to 100% material recovery.

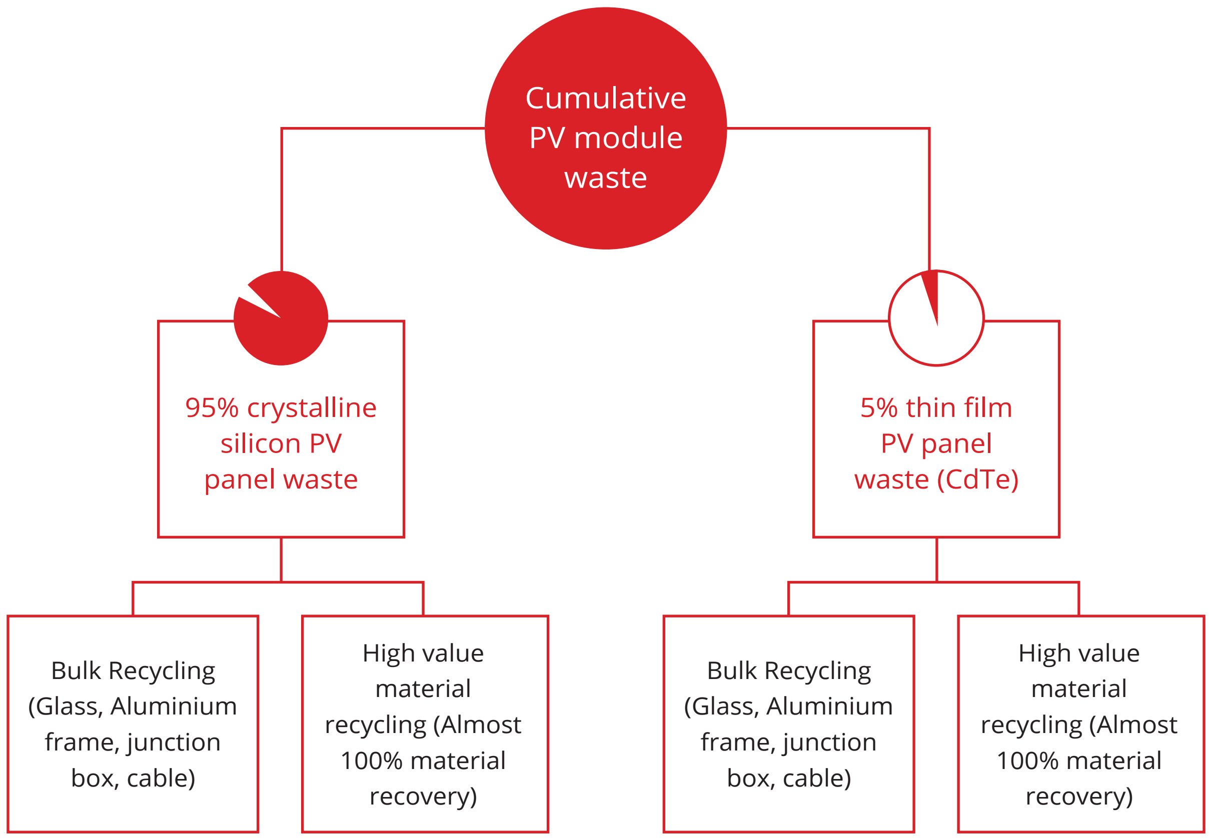


Figure 12: Material recovery scenarios by type of panel

For this analysis, material breakdown of crystalline silicon and CdTe panels are as given in section 3.1. The cumulative PV module waste volumes as per the MNRE scenario have been considered, as they exhibit the highest amount in the early and regular scenarios by 2040. Based on the MNRE waste forecast, the following material flows expected after end of life management (Figure 13).

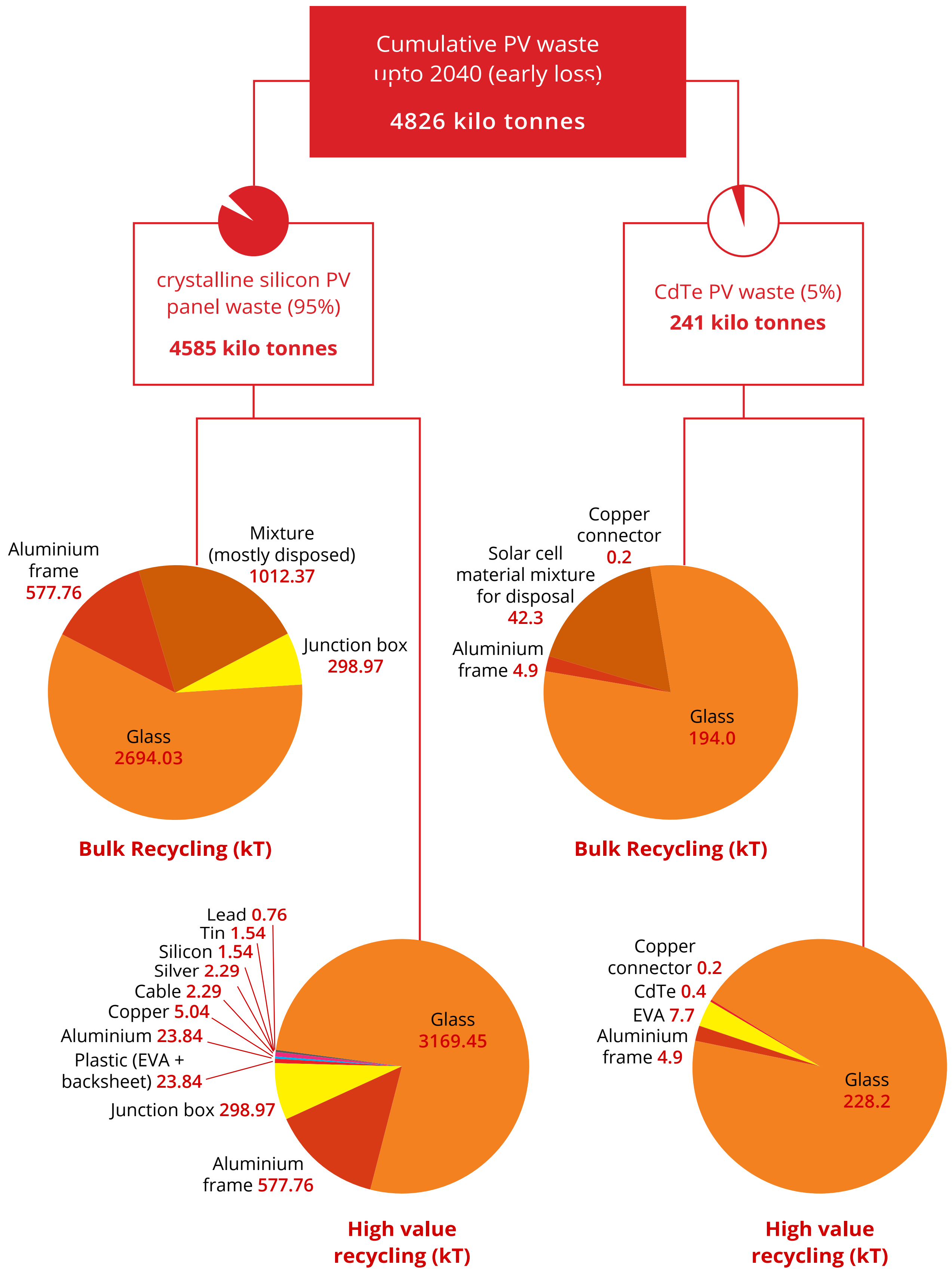


Figure 13: Material flows for early-loss scenario

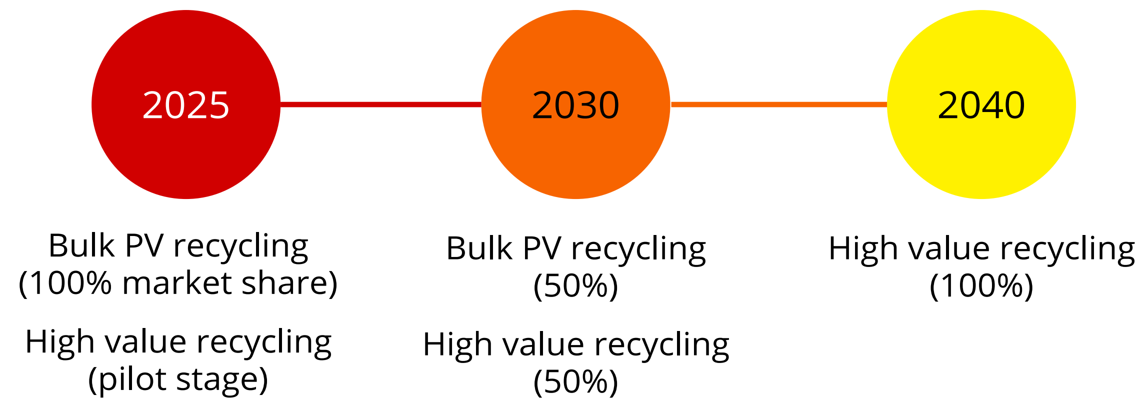
Using Bulk recycling, although more than 85% of PV panel waste by weight can be recovered, the scarce materials present in the solar cell which could also be hazardous aren't extracted and are usually disposed. This could prove to be a deterrent for realizing circular economy in the solar PV industry. Bulk recycling also recovers only 85% of glass by weight in panel, the remaining volume of glass gets contaminated with solar cell materials due to the mechanical delamination technique adopted.

On the other hand, high value recycling recovers close to 100% material and hence helps in circulating the recovered materials from solar PV waste with necessary quality back to the manufacturing loop. The detailed excel calculation and template provided with this report can be modified to include material intensity, recycling rate etc for future use.

Technologies relevant for the waste forecasted for India and recommended with description of their capacities required to handle the volumes generated in India.

Assuming conservatively the early loss scenario to prevail in India, an average of the projected waste volumes from the above scenarios suggest 120 kilo tonnes of PV waste by 2025, 590 by 2030 and 4260 kilo tonnes of PV waste by 2040 respectively.

The roadmap for PV recycling technology that would be suitable for India would be to adopt bulk recycling technology in the beginning and slowly transition to high value recycling by 2040.



High-value recycling refers to the recovery of even trace elements like copper, aluminium, silver present in a c-Si PV panel with close to 100% material recovery. In contrast, Bulk recycling refers to the recovery of major elements of PV panel alone by weight like Glass, Aluminium frame, copper from cables.

The mechanical delamination presented in the previous section is an example of bulk recycling and thermal, chemical delamination methods belong to high value recycling since they recover more than 95% of the constituted materials from waste PV panels.

For calculating the capacities of recycling plants needed, the annual waste volume forecast by 2025, 2030 and 2040 in the early loss scenario (average) is displayed below along with number of PV recycling plants needed. Given the geographical vastness of India, having decentralization with a significant capacity of 5000 MTA recycling plant[48] spread across the country would help to lower the logistical issue as compared to a large capacity plant located at select places.

Year	Annual forecasted PV waste volume (kilo tonne)	Number of PV recycling centres needed of 5000 MTA capacity
2025	120	24
2030	470	94
2040	3600	720

3.5 Value chain integration: Downstream management of recovered material

The prominent downstream recyclers associated with crystalline silicon PV waste products are glass manufacturers (flat glass, foam, fibre glass, container glass industries), Aluminium refiners or remitters, e-waste recycler (cable, junction box), copper refiners. Further, the services of material recyclers dedicated to processing silicon, silver, plastics, and lead would be needed based on the severity of high-value material recovery by the PV recycler.

Glass cullets:

The glass cullets generated from the PV recycling facility can directly be used in glass manufacturing. Usage of cullets in glass furnace reduces the energy demand and displaces the usage of equivalent primary raw materials. The various type of glass manufacturers like solar glass, flat glass, container glass, fibre glass, and foam glass can utilize the cullets based on descending order of quality.

Cullet usage in manufacturing varies according to the type of glass manufacturers, such as 40% for flat glass and 60% for container, fibre, and solar glass. The results,

[48] Capacity reference taken from standalone PV recycling plant available currently. eg: Veolia

establish a significant percentage of cullet contribution from PV recycling in the future for glass manufacturers. Assuming an expansion of glass manufacturing facilities and increased cullet usage in future production, it is possible to accommodate the cullet supply from PV recycling. India must accelerate the establishment of solar glass manufacturing facilities given the drive towards self-reliant PV manufacturing to realise the ambitious solar PV installation targets and the presence of only one major solar glass manufacturer currently. High-quality glass cullets from PV recycling can help solar glass manufacturing close the circular chain and improve resource efficiency.

Aluminium frame:

c-Si Solar PV panels usually contain AlMg3 anodized aluminium alloy frame for structural stability. Based on the PV recycling techniques, aluminium frames can be removed without contamination of other materials from PV panels. Hence, they can directly be remelted to form secondary aluminium ingots.

In the Indian context, currently, 90% of aluminium scrap is imported. Thus, Al frame scrap from PV recycling becomes a valuable waste stream with respect to the trade scenario and for energy demand reduction by displacing primary materials.

Plastic waste:

The plastics waste from PV panel that comprises ethylene-vinyl acetate, polyvinyl fluoride, polyethylene terephthalate needs to be investigated for secondary usage in other applications. Energy (thermal and electricity) can be recovered from burning the waste in a Waste to Energy (WtE) plant under a controlled environment. Exhaust gas treatment is necessary due to the presence of fluorine in the waste.

High-value recoverable waste

High-value PV recycling of c-Si panels could yield silver, copper, aluminium, silicon, tin, lead, plastics (EVA, PVF composites).

Recovery of quality silver from PV recycling can significantly contribute to silver production in the country. Copper and Aluminium from solar cells can add to the already recoverable streams from cable and frame of PV panels. Lead present in solder needs to be recovered to avoid disposal hazards. Although it has been indicated that exposure risk is under limits for the lead content present in a single PV panel, the disposal risk of a large volume of PV waste in a single location still needs to be studied. Also, the recovery of material from a resource efficiency perspective could be beneficial.

Silicon recovery from PV modules may be significant, with the current emphasis on circulating high-quality silicon back to solar PV production. Given India's push to establish polysilicon and silicon wafer production facilities, the recovery from the EoL panels would add significant energy demand reduction compared to the production with complete primary materials.

For Bulk recycling in Indian context the following downstream options are considered:

Table 13: Downstream vendors for solar PV waste

Glass cullet	Solar glass manufacturer; Flat glass manufacturer; Fibre glass; Foam glass (Decreasing order of quality expected)
Aluminium	Re-melters and refiners manufacturing secondary ingots
Junction box, cables	e-waste recycler
Plastics (Ethylene Vinyl Acetate +Tedlar (PVF)	Waste to energy plants (as input fuel); PVC pipe manufacturers (as filler material) [*Presence of fluorine in backsheets to be tested]
Fines (Glass + Silicon + Silver + Copper + Aluminium + Lead + Tin)	Sand casting; foundries; Clinker production

Detailed case studies on designing of Solar PV recycling efforts are given in Annexure 2.

3.6 Role of standards in EoL management of solar waste

Standards are required to regulate different fractions of the solar module waste stream and play an essential role in the responsible management of the waste, from regulating collection, sorting and handling to transport, treatment and disposal. This in turn can support a high-value recycling and reuse return from the waste panels and manage the environmental impact from this stream.

For instance, the European Committee for Electrotechnical Standardization (CENELEC) has developed standards and technical specifications for PV module collection, logistics and treatment which assists organisations in achieving effective and efficient treatment of waste PV panels. The 'TS 50625-2-4' and 'TS 50625-3-5' standards, amongst the TS 50625 series, specifically addresses the requirements for recycling and specifications for de-pollution of PV panels, respectively. They guide organisation in promoting increased high-quality material recovery and diverting PV waste away from operators whose facilities do not comply with the required local norms and documentation, while assuring protection of human health and the environment. Other standards also exist that go beyond just the downstream treatment of the panels and look at the entire life cycle of a panel, from manufacturing till disposal, as well as social indicators such as ethical practices. A notable example is the 'Solar Scorecard project' initiated by the Silicon Valley Toxins Coalition (SVTC), which ranks solar panel manufacturers based on several criteria including:

- EPR and takeback: Manufacturers and producers who set up a take back system for their customers instead of allowing their waste panels to exported to other countries.
- Supply chain monitoring and safety: Manufacturers and producers who set up systems to ensure their workers are protected from exposure to toxic chemical and other hazards during handling the PV modules (including suppliers and sub-suppliers).
- Undertaking life-cycle analysis: Manufacturers and producers who undertake life cycle assessment to identify and eliminate the use of certain hazardous chemicals and substances, wherever possible, from the manufacturing and treatment process.
- Disclosure: Manufacturers and producers who provide information related to their operations, necessary labour and health standards and guidelines which have been laid down and other sustainability-related information on an easily accessible, public platform.

Every year, SVTC publishes a 'Solar Company Scorecard' with names of the top 25 manufacturers and producers, who have been stringently rated and ranked, based on the above-mentioned criteria, and who best illustrate good practices and procedures for manufacturing and EoL management of PV modules.

Standards, which promote eco-design in PV modules, are also currently under development. These standards include a number of minimum requirements on aspects such as replacement of components, dismantling of modules and information which must be supplied by manufacturers on the potential to separate and recover various components in the modules.

End-of-life focused standards for PV modules can also reduce the overall treatment and management costs by making the modules easily reparable and recyclable, use and align with the existing market-based collection and recycling systems, enable solution pioneering and support policy adoption and implementation.

04 Navigating the Path

Drivers and Barriers in End-of-Life Management of Solar PV Modules

While a standalone commercial PV recycling plant in the country does not currently exist, there are several pilots underway, including the Solar Waste Action Plan project, which could recover close to 80% of the materials by weight. However, for the industry to become truly circular, several challenges and drivers need to be considered at different stages of the current linear supply chain for solar PV waste management. These are further elaborated in the following sections.

4.1 Drivers for a Solar PV EoL Management System

A thriving solar PV market, with waste panels: The solar sector has seen massive growth in installations over the past decade, which has helped provide the required push towards less grid and fossil fuel dependency. It is expected that the solar PV modules already installed would be decommissioned within the next two decades, leading to large volume of solar PV waste.

Circular economy for solar waste, as mandated by law: The Ministry of Environment, Forest and Climate Change and the Ministry of New and Renewable Energy have published the amended E-Waste Rules on November 2022, which brings the solar module manufacturers under the purview of EPR. They need to work with recyclers or recycle the EoL panels themselves to reclaim the raw materials, thereby enabling circularity in the solar waste industry.

Newer, more efficient modules: The new PV modules which are being introduced in the market are better designed and more efficient. In many cases, maintaining older solar units becomes relatively uneconomical before they reach the end of their useful lifespan, and it is cheaper to replace them with the updated versions. In which case, these decommissioned older models also add to the waste volumes.

Inferior quality panels adding to waste generation: Majority of the panels used in India are imported from countries such as China and Malaysia, since they are cheaper or similar-priced as the locally made panel process. Some of these panels have been found to be sub-par in terms of their quality and have shown other issues (such as inferior performance and mounting maintenance costs) that lead to an early loss/decommissioning scenario. Components of these panels are also not up to the mark in terms of quality, resulting in breakage and damage and thus to increased waste generation.

Conservation and recirculation of rare materials: PV system installations are likely to continue growing exponentially to satisfy the future energy demands. Therefore, there is an additional burden on raw materials needed for manufacturing the panels. Urban mining of waste PV panels can be an additional source for raw material creation for PV panel production. Additionally, end of life management of the waste PV panels, can help to alleviate a part of the raw material demands for domestic production in the future.

High secondary material recovery value from waste PV modules: Improper management of solar waste can lead to the loss of a lucrative revenue stream. The market for recycled solar panel materials is expected to grow exponentially in the coming decade, leading to the creation of a new economic stream. By 2050, the International Renewable Energy Agency (IRENA) predicts[49] that the recovered materials from solar panels could have a global value of up to $15 billion.

Maintaining green integrity of PV modules: Given the PV systems have been portrayed as a green alternative to the fossil fuel sources, there is an additional need for the technology to be completely sustainable even in end-of-life stage to maintain the green integrity. This might enable a more sustainable adoption of end-of-life management for PV panel compared to other sectors.

4.2 Barriers for a Solar PV EoL Management System

Unavailability of proper implementation of regulations or standards: Policies for solar waste management are still at a very nascent stage. As a result, there is a lack of proper collection, reuse, and recycling PV modules in India. Without any dedicated policy or incentives, PV modules will be treated the same way as equipment destined for disposal. Moreover, while there are several economic incentives and initiatives to drive solar energy growth in the country, the same cannot be said for the incentives provided for researching and setting up recycling infrastructure for solar PV.

Lack of sufficient recycling infrastructure and technical knowhow to manage this growing waste stream: One of the barriers to effective solar waste management in India is the lack of sufficient recycling infrastructure to handle the growing waste stream. While the Indian government has started recognizing the increasing need for solar waste recycling infrastructure, it is still in the early stages of development. The current infrastructure is not adequately equipped to handle the volume of solar waste generated, posing challenges in the proper disposal and recycling of end-of-life solar panels.

[49] Urban mining is the process of recovering valuable resources and materials from electronic waste and discarded consumer products in urban areas.

Further, a large percentage of the EoL management, including recycling, is done by the informal sector in country which lacks in skills, technical know-how and technologies required for handling hazardous materials. The involvement of the informal sector in solar PV recycling is also a hindrance in promoting circularity in the sector.

Lack of investments in setting up recycling infrastructure and overall low profitability from recycling: Setting up a recycling facility for managing solar PV waste requires a significant upfront investment input, which without a clear return-on-investment proposition, can be seen as a daunting prospect.

It is also important to remember that solar module recycling is still not a commercially attractive venture. Most of the recycling performed in the country is mechanical in nature, wherein the panels' copper wiring, plastic junction boxes and aluminium frames are physically removed, and the glass, silicon and metals are all shredded into a mixture known as the 'cullet', which can be used in industrial applications or as construction materials. The cullet is not very valuable, and it is unclear if there will be a market for all the recycled cullet that will be generated from recycling the panels. The total cost of recycling is estimated between USD 250-300/tonne, while the value of recovered material is only USD 45-130/tonne, depending upon the recycling technology used[50].

Low waste volumes of panels for recycling to take back and recycle PV modules: This can be attributed to the mild inflow of PV waste at present, making it difficult to set up infrastructure specifically for PV panel takeback and recycling.

For a recycling venture to be profitable, it needs a steady supply for waste panels per year (ideally between 2,000 to 3,000 tons), which is not guaranteed at this stage. And this number will increase in the case of silicon-based panels, which lack precious metals such as indium and gallium found in thin-film modules, thus the total value of the recovered material will be low.

Low processing cost for landfill and incineration of PV modules compared to recycling: Solar panels – particularly thin film modules – contain only tiny fragments of the valuable, precious materials mentioned earlier, which must be painstakingly taken apart in other to be recovered in a reusable manner. While there is recycling technology available for this extraction process, it is expensive and requires substantial investment. On the other hand, disposing solar panels into landfills is a much cheaper and cost-effective alternative, despite the potential negative environmental and social impacts.

[50] https://bridgetoindia.com/backend/wp-content/uploads/2019/04/BRIDGE-TO-INDIA-Managing-Indias-Solar-PV-Waste-1.pdf

Lack of consumer willingness to return EoL products: Especially in rooftop and off-grid solar sectors, consumer have been demanding incentives or monetary returns for parting with the waste products. Additionally, there is a general lack of awareness around recycling or other EoL treatment options for solar PV as the waste has not yet piled up significantly. Consumers may also prefer selling/giving their solar products to the informal sector due to their ubiquitous presence.

Predominant presence of the Informal sector: Due to the absence of specific regulation in India for PV panels, the informal sector has been actively involved in procurement of waste PV panels and extracting materials like aluminium, glass, silver etc. often in an unsafe way. Given their unsafe treatment practices, the informal recyclers can offer higher economic value for procuring waste PV panels as compared to formal recyclers who are unable to maintain economic feasibility for recycling PV panels at this current stage.

4.3 SWOT Analysis for an efficient EoL value chain

The drivers and barriers for solar waste management provides a roadmap towards efficient system in the country. A SWOT analysis has been performed for the current solar waste landscape in India (Figure 17), considering the drivers and barriers mentioned in the previous section. It evaluates the strengths, weaknesses, opportunities, and threats of the current solar sector in India.

S

Strengths

- India is rich in solar resource
- Cogeneration potential on agricultural lands
- Suitable application of distributed PV power systems.
- Solar energy helps meet rural electrification needs
- High positive brand value for solar energy
- Policy support for waste modules under EWM 2022.

W

Weaknesses

- Small scale of renewable energy economy
- Unsound solar energy infrastructure
- Developing foundation in the PV industrial chain
- Insufficient awareness about social and environmental benefits of solar PV
- Lack of an efficient recycling infrastructure

O

Opportunities

- Increasing PV installations
- High economic value for secondary material recovery
- Incentivising take-back, EoL recycling
- High eco-design potential increasing module lifespan
- Consumer awareness for proper solar waste disposal
- Later profits to cover initial costs

T

Threats

- Dominant position of fossil fuels
- Inefficient implementation of solar waste policies
- Potential economical impacts from solar PV development
- Discontinuity of energy policies
- Availability of cheaper energy resources

Figure 17: SWOT Analysis of Solar Waste Management Sector in India

The analysis provides the internal (strengths, weaknesses) and external (opportunities, threats) for the solar PV waste management sector under the present scenario. A balance is required between the internal and external factors to ensure that the solar PV EoL value chain management is very efficient and circular in design. A system which incorporates circularity principles is required to support a sustainable PV sector, where minimal waste is produced. For this, complementary actions are required. While incentives like the Production-Linked Incentive (PLI) scheme can drive India's manufacturing growth in the coming years, it needs to be complimented with operationalizing opportunities like recovery of critical secondary materials from waste PV modules.

With the inclusion of solar waste as a separate category of waste under the latest E-Waste Management Rules, 2022, the Ministry of Environment, Forests and Climate Change (MoEF&CC) is already acknowledging the growing concern of solar waste. Although the Rules are still in the early stages of implementation, growing consumer awareness can boost demand for sustainable solar waste management.
An efficient solar waste management also presents a significant economic opportunity. Incentivizing various stages of the end-of-life (EoL) value chain for solar waste can facilitate the development of robust recycling infrastructure. As solar waste recovery matures in India, its high value can turn the waste sector profitable, covering the initial costs of building necessary recycling infrastructure.

4.4 Case Studies – Assessing Current Initiatives for Solar Waste Recycling in India

First PV Recycling Pilot plant in India – Solar Waste Action Plan

The SWAP Pilot was initiated in February 2019 with an aim to design and test a blueprint for management of solar waste that can be as applicable in a developed as also a developing country context. The SWAP team successfully commissioned a recycling pilot facility exclusively for PV panels in Gummudipoondi at Poseidon Solar's facility in Chennai in August 2020. The pilot plant has been built to process 2.5 tons of PV panel waste per day through state of art recycling technology that neither utilizes chemicals nor generates process related waste whilst ensuring high material recovery. The adopted recycling technique allows for processing solar PV panel waste, independent of their type. Around 5 tons of PV module waste has already been processed in the pilot plant.

The SWAP pilot plant comprises of the processing stages as depicted in Figure 18 below. The process chart indicates the mass balance of the batch of PV panel waste processed in SWAP pilot plant, where green indicates the useful material stream and red indicates the separated stream for disposal.

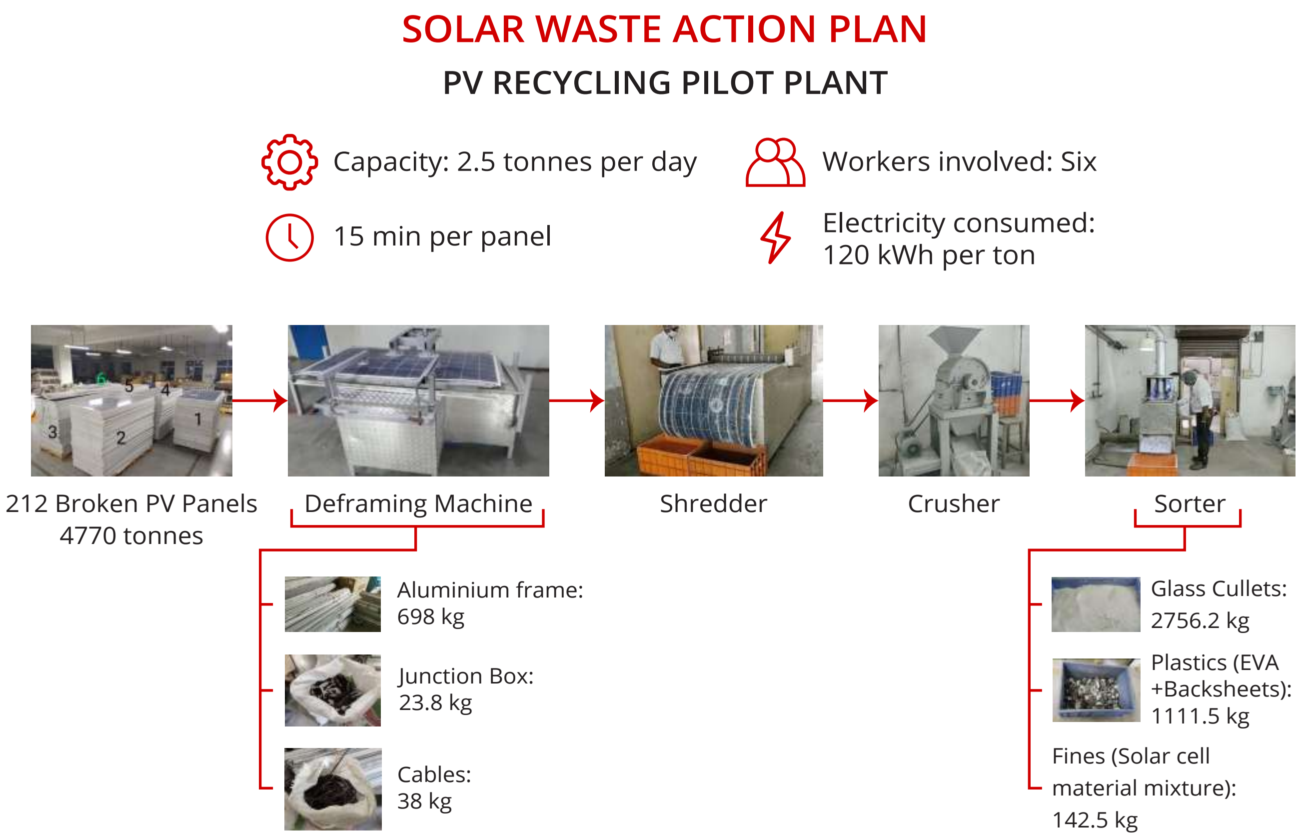


Figure 18:PV panel recycling/processing stages

The pilot plant had a 75% recovery rate from processing about 4770 kg of PV module waste. Materials recovered included glass cullet (~2750 kg), plastics (~1100 kg), and aluminium frame (698 kg). These materials are externally attached to the panels and can be directly processed downstream by the concerned recyclers. The recovered glass cullet was analysed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) through a metrology lab.

The preliminary results suggested that the glass cullet was successfully separated without mixing with lead, tin and silver content of the solar modules. Tempered solar glass contain antimony and alumina for structural stability which explain the presence of these materials. The presence of copper in the recovered cullet's is being investigated and process improvements have been suggested for complete separation of copper wires from glass cullet's using sieves. The SWAP pilot project also brought to light some challenges in the present solar waste management landscape in the country. These include the lack of a proper certification.

Partnerships for coordinated actions – The Centre of Excellence (CoE)

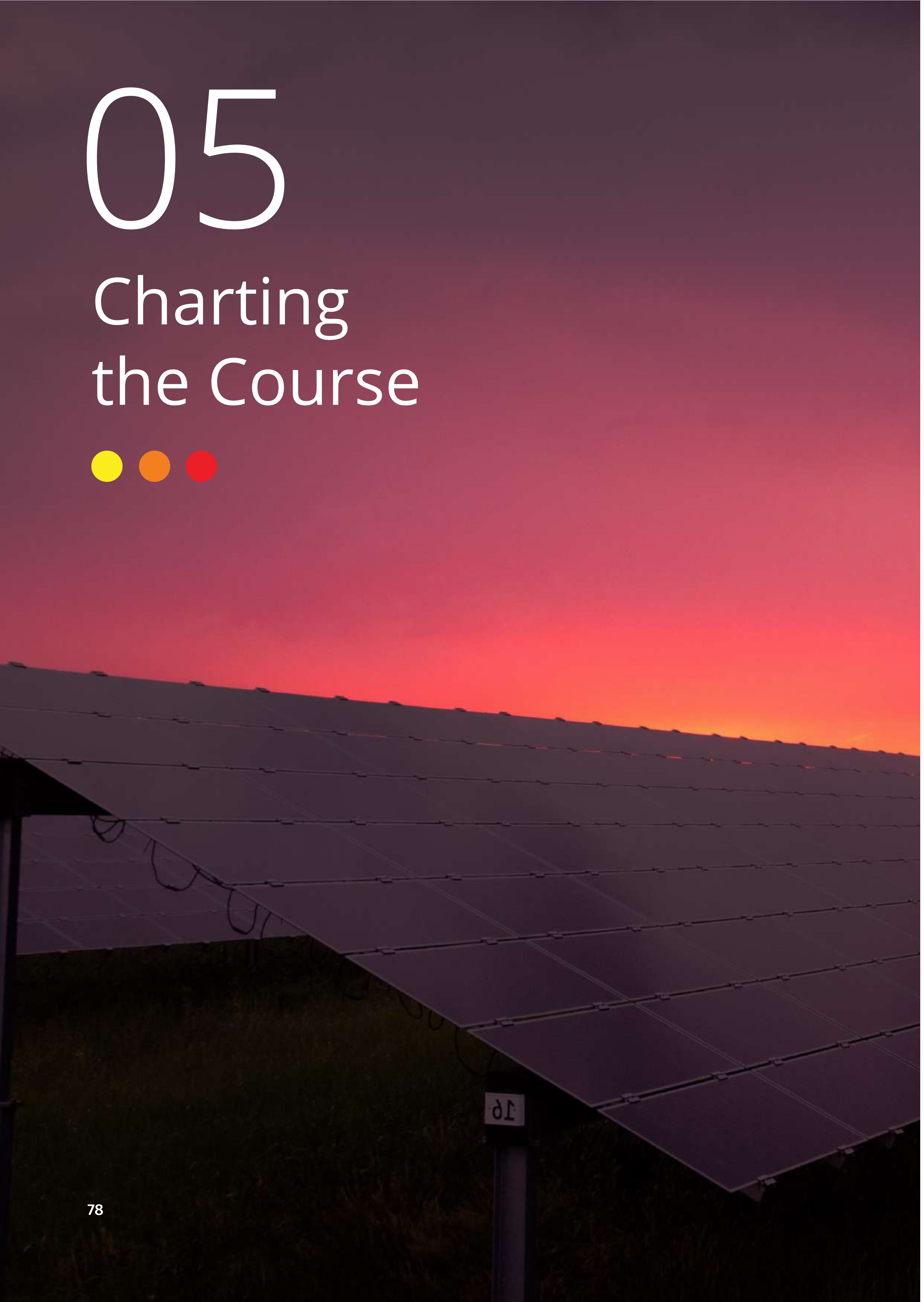
The Centre of Excellence (CoE) in E-Waste Management was established to create a self-sustaining ecosystem capable of processing India's e-waste. It is a joint initiative by Ministry of Electronics and Information Technology (MeitY), Govt of India in partnership with Government of Telangana (GoT) and the industry[51]. C-MET, Hyderabad laboratory, as a part of the CoE mission has initiated R&D activity to develop commercially sustainable recycling technology for end-of-life silicon solar modules to recover various metals including toxic and valuable materials. Further, C-MET Pune has established the hybrid solar cell (inorganic-organic materials based) fabrication set up and developed conceptual solar cell. Also, DSSC and perovskite solar cell materials are being developed under this activity[52].

A series of global case studies have also been provided in Annex 1

[51] COE, https://www.coeonewaste.com/aboutus.html#:~:text=Centre%20of%20Excellence%20(CoE)%20in,(GoT)%20and%20the%20industry.
[52] CMET, Accessed on https://cmet.gov.in/rd_materials_renewable_energy

05

Charting the Course



Strategic Recommendations for an Efficient Solar Waste Management System

Over the last few years, the consciousness towards the potent solar PV waste problem has grown alongside the country's installed capacity. However, despite several efforts in research and analysis, there has been limited action on the ground. Often seen as a problem for the future, solar PV waste was largely ignored in national dialogues on waste management until recently. Even the first (and only) recognition of the waste stream in the regulatory sense - the E-waste (Management) Rules, 2022 – recommends storage of PV panels as the key waste management technique and responsibility for manufacturers despite early-loss waste panels already making a case for formal management. In this context, taking a holistic and comprehensive approach to the solar panel lifecycle from manufacturing to EoL management is the need of the hour – since advancement in panel design and standardization of quality and performance can be crucial to ensuring minimization of early loss and even potentially the extension of a panel's lifetime.

Such a comprehensive approach needs to be catalyzed through a national strategy that is developed through a multi-stakeholder and collaborative process based on circular economy principles. This chapter provides recommendations on how this can best be realized.

5.1 Key Stakeholders in the Solar PV Waste Management Sector

The success of end-of-life management systems is contingent on responsible, collective action from key stakeholders especially under an EPR framework, which enshrines accountability of key actors as a core concept and guiding principle. Solar PV waste management is at the nexus of various sectors and impacts, and thus requires the participation of a milieu of stakeholders. The table below provides recommendations on the roles and responsibilities of key stakeholders in the sector.

Government Stakeholders		
Fraction	Composition	Source of Risk
Ministries (key)	Ministry of Environment, Forestry & Climate Change (MoEFCC)	• Nodal authority for issuing E-waste (Management) Rules and subsequent waste management rules • Waste management framework development (such as EPR)

		• Outlining key roles and responsibilities for different sector actors • Policy formulation & enforcement oversight • Supporting MNRE in the development of a national strategy for PV waste management
	State Pollution Control Board	• State-level enforcement authorities for waste rules • Ensure empanelment of formal & benchmarked end-of-Life management players • Ensure effective enforcement of the rules on ground through timely audits, data collection, etc.
Departments/ Agencies, etc. (support)	NITI Aayog	• Leading national-level discussions on Panel improvement & innovation (such as repairability, improved circular performance, etc.) • Work with MoEFCC & MNRE to develop guidelines for improved PV panes as well as panel repair/recycling
	Solar Energy Corporation of India	• Supporting effective implementation of sustainable practices in upcoming Solar projects, including circular design, effective EoL recovery process, etc.
	Producers (including manufacturers, sellers, importers)	• Ensuring compliance to EPR as set by the E-waste (Management) Rules including registering on the CPCB portal, storing decommissioned PV panels as per CPCB standards, and periodic reporting • Actively exploring opportunities for sustainability/circularity innovation in panel design including minimization of virgin material usage, improved efficiency, higher durability, easy repair & dismantling, etc. • Supporting the development of downstream value chain integration to encourage a closed loop system for critical raw materials
EoL Management Actors	Collectors, Dismantlers, Repairers and Recyclers (formal)	• Ensuring compliance to the E-waste (Management) Rules including registering on the CPCB portal, processing decommissioned PV panels as per CPCB standards, and periodic reporting

		• Ensuring safe, high-efficiency processing of PV panels with minimal impact on human health and the environment • Developing circular business models with industrial symbiosis where all outputs of the processing can be sold to downstream actors, thus minimizing dependencies on virgin material.
	Downstream actors (glass manufacturers, metalworkers, etc.)	• Work with collectors, dismantlers, repairers, etc. to buy their outputs, thus reducing dependencies on virgin material
Other Stakeholders		
National Stakeholders	National Academia	• Capacity building and adoption of Best Practices and developments in the sector internationally • Conduct local and national research to ensure a science-based approach is taken for determining policy decisions.
	Non-Governmental Organizations, Think Tanks	• Driving conversation around innovation in the Solar PV sector, including EoL management • Supporting a multistakeholder approach to sector development by helping build linkages between various stakeholders • Supporting knowledge transfer and skill building in the sector wherever possible
	Consumers/citizens (for rooftop PV - RTPV)	• (especially for roof-top solar) familiarising with awareness on best practices regarding RTPV maintenance as well as steps to take in case of decommissioning • Complying with the takeback policies as defined in the E-waste (Management) Rules, 2022. • Ensuring effective management of the waste and avoiding disposal through landfilling or incineration

Interna-tional Stake-holders	International Organizations, Funding agencies (bilateral/ multilateral donors (like the World Bank, IFC, GIZ etc)),	• Enabling the growth and development of EoL management system by initiating discussion among stakeholders, providing technical assistance and funding
	International solar agencies, associations, etc. (such as ISA, IRENA, etc.)	• Creating synergies across borders to accelerate the sharing of international best practices • Supporting the development of the national strategy for solar PV waste management • Supporting national and local government in designing and implementing the EoL management system by connecting with funders, providing technical expertise, and hand-holding support through knowledge collaterals such as toolkits, guidelines, etc.

5.2 Strategic recommendations for the Solar PV waste sector

In the context of India's thriving solar sector, the rising adoption of solar energy has propelled a remarkable growth in the number of solar PV installations. As these installations near their end-of-life phase, ensuring responsible management of resulting waste becomes imperative to safeguard the environment and public health. Further, to overcome the challenge posed by the lack of a well-established infrastructure for solar waste management, India envisions a comprehensive and integrated system including collection centers, recycling facilities, and effective mechanisms for treating hazardous components. This section presents strategic recommendations, designed to address systemic gaps and foster a circular approach to tackle the solar waste problem.

5.2.1 Policy/Regulations:

• Effective categorization of solar waste. A key policy recommendation is to classify PV modules as universal waste instead of hazardous waste to promote efficiency in the system. The experience of California serves as a valuable lesson[53], where the initial classification of all PV panels as hazardous waste was later revised to universal waste.

[53] Please refer to Annex 1 for more details

Although India has recently acknowledged solar PV waste as a separate waste stream under the E-waste (Management) Rules, 2022, stronger policy support is necessary to ensure the proper handling and establishment of an efficient end-of-life (EoL) value chain for solar waste. By addressing the issue of categorization, India can lay a solid foundation for a robust and sustainable solar waste management system.

• Adopting mandatory extended producer responsibility (EPR) scheme to manage solar PV module: Although the EPR framework is being implemented for solar PV waste, the exact mechanism of how it will be implement is not fully clear. In this context, there is an opportunity to set up a funding model for co-regulatory or mandatory approach through a consultative approach wherein producers, the government and the EoL management actors come together to define the precise fiscal mechanisms for the system. It can be industry-funded or involve shared costs between consumers and industries. This funding can be collected upfront to cover uninstallation costs or as a service fee at the end-of-life stage, which can be incorporated into the purchase costs of PV modules and batteries, either covered by consumers or funded by industries.

• To ensure accountability, industry associations or Producer Responsibility Organizations (PROs) could be established to manage the funding in coordination with approved solar installers. However, it is essential to implement this funding model in a balanced manner that avoids uncompetitive prices for PV panels and Battery Energy Storage systems. Striking the right balance is crucial to ensure affordability and accessibility of solar technologies while effectively managing the end-of-life stage and promoting responsible waste management practices.

• The government plays a critical role in introducing and monitoring regulations and establishing an effective funding model & stakeholder engagement strategies for collection and recycling to achieve an optimal collection rate. incentivized by a supportive policy support framework. This will also improve communication between the formal and informal stakeholders in the process and make it more efficient in the long run.

• Industry participation is critical in implementing effective regulatory measures for waste management in renewable energy technologies like Solar PV in India. Regulations should mandate industry participation and set specific targets for product and material recovery rates. Establishing a sustainable funding model is essential to meet operational requirements and future needs. Collaborative efforts between local industries and the government are necessary to improve domestic recycling capability and capacity, given the restrictions on overseas waste exports. Without an effective end-of-life (EoL) management system for residential PV and Battery Energy Storage systems, valuable and hazardous materials could end up in landfills, stockpiles, or illegal dumping sites, leading to unintended and adverse environmental consequences.

• It is important to ensure that the metrics deployed for measuring compliance are value-based rather than volume-based: the inclusion of PV panels in the WEEE directive in the EU has promoted proper end-of-life management, it falls short in encouraging high-value recycling and complete material recovery. The current WEEE directive mandates targets of 85% recovery and 80% weight reuse/recycling for PV panels. However, this approach creates a loophole where recyclers primarily focus on recovering bulk materials like glass and aluminium,, which constitute over 80% of the panel's weight. As a result, high-value and hazardous materials like silicon, silver, lead, copper, cadmium, and tellurium, which account for less than 10% of the panel's weight, are not adequately recovered. In order to avoid this and ensure sustainable end-of-life management in India, it is crucial to establish individual 'material quotas' instead of relying solely on bulk recovery targets. This will incentivize proper recovery and management of all materials, including those of high value and environmental concern, while ensuring a steady stream of waste material inflow to completely utilize the recycling infrastructure in India.

• Coupling landfill restrictions and product stewardship scheme is an effective intervention to promote collection and recycling activities. A clear, consistent, and informative education and awareness that is accessible to diverse communities should form a major part of any EPR approach. However, incentives and recycler investments are required to develop domestic capability and capacity to avoid stockpiling issues. These comprehensive measures will not only mitigate environmental pollution but also stimulate the growth of a domestic recycling sector, leading to improved waste management practices and resource conservation.

• As discussed in this report, the management of PV panels is necessary not only to reduce the environmental and social impact due to disposal but also to mitigate the material supply chain risk which is undeniable given the volume of installation in future. India needs to identify the critical raw materials and assess the material security with respect to PV panel production, so as to set the material recovery targets accordingly for waste PV panels. By this way, urban mining can help in alleviating the raw material supply chain risks in the future.

• Develop a long-term recycling plan: Given the rapid development of the PV sector and short innovation cycles with respect to PV cell types, module designs and material improvement of PV technologies the future remains uncertain. PV technologies in the future are likely to be vastly different from existing technologies. PV waste recycling technology and capabilities would thus need to be agile and evolve along with the PV module technologies. Thus any PV waste management and recycling policy should provide adequate opportunity and incentives for technology innovation, and even promote (going forward) high-value recycling, as recovery at materials level will ensure a more complete reutilization of waste panels. PV manufacturing standards that promote complete separation of components (Design for recycling) can

play a crucial role in linking PV modules with recycling technologies and needs and capabilities of the recycling market.

5.2.2 Interlinkages between regulations and India's recycling market strategy

• India's nascent recycling infrastructure provides an opportunity to facilitate an open market system across the country. An open market approach offers advantages such as fostering competition, enhancing efficiency, and stimulating innovation in solar waste recycling. It attracts private investment, bringing additional resources and expertise to address the growing volume of solar waste. Flexibility allows diverse entities to enter the recycling industry, contributing to a resilient ecosystem. It also allows the recycling industry to capitalize on the vast informal sector presence in solar waste management. However, lack of regulations in an open market approach may lead to inadequate recycling practices, non-compliance, disparities in accessibility, and prioritization of short-term profits over long-term sustainability.

• Balancing market-driven efficiency with environmental and social responsibility is crucial. A well-regulated market with proper standards, certifications, and enforcement

01. Quality assurance across recycling processes

• Ensures recycling meets established industry standards and certifications
• Promotes responsible and safe handling of solar waste and ethical handling practices

02. Upstream and Downstream Linkages

• Fosters efficient material recovery, sustainable practices, and a circular economy approach, creating a healthy and profitable secondary resources market
• Encourages technological advancements for better and more efficient recovery

03. Transparent and streamlined reporting

• Enhances stakeholder accountability and improves monitoring for compliance authorities
Fosters public trust in the recycling sector

04. Long-term sustainability

• Ensure alignment of the recycling sector aligns with the country's environmental goals and commitments
• Provides equal opportunities to all participants in the recycling market, preventing monopolies and encouraging fair competition among various stakeholders

can serve as a middle ground, leveraging the benefits of competition while ensuring responsible recycling practices. A robust implementation framework should consider some crucial regulatory aspects to ensure that sufficient interlinkages are established between regulation and management. These aspects (represented in the following infographic), while ensuring proper e-waste management also ensures that the system is sustainable.

• India's solar PV waste recycling system is in its early stages, with regards to regulations, policies, mandates, and incentives. The new EWMR only categorises solar waste as e-waste and tasks solar manufacturers with collection and storage of PV modules till 2034, after which it will be recycled. This provides sufficient time for different stakeholders to develop the required recycling infrastructure in the country. Government involvement, alongside international organizations and facilitators, would be instrumental in developing a comprehensive regulatory framework, incentivizing responsible recycling, and supporting capacity-building efforts. Collaboration among various stakeholders can address challenges and foster the growth of a sustainable solar waste recycling industry in India.

5.2.3 Transportation/Reverse Logistics:

• Given the boom of the solar rooftop sector in India, mobile recycling plants may provide potential solutions for avoiding the economic and environment burden associated with excess transportation. A mobile recycling plant pilot was established as part of the SWAP project (mentioned in case study section). More such plants can provide quick recycling solutions to multiple cities across the country, followed by bigger plants based on solar waste generation levels in different States. These plants increase access to recycling and improves collection rates of solar PV modules, especially from households.

• Implementing an efficient backloading mechanism is crucial to link the end consumers with the recyclers and improve collection rate of solar products. To transport PV panels from remote areas to collection points more efficiently, a backloading mechanism can be implemented where non-food product carrying trucks returning empty or have available space can be utilized for dropping off waste PV modules at the designated recycling centres. This approach optimizes transportation resources and reduces emissions by maximizing the utilization of existing transport routes.

• The potential risk of pilferage in the solar waste management process should be addressed as early in the EoL management chain of waste PV modules. Insights from similar incidents in countries like Italy, should be referred where PV panels were illicitly transported to Asian/African countries and sold as second-hand panels. To mitigate this issue, it is crucial to implement specific measures tailored to the Indian context. This includes introducing robust labelling and tracking systems for every PV module and ensuring secure shipment processes. These actions will

significantly enhance transparency, traceability, and accountability throughout the solar waste management chain in India. By effectively addressing pilferage concerns, India can safeguard its solar waste resources and foster a more secure and responsible waste management ecosystem.

5.2.4 Waste Management Strategies:

• Despite the potential of promoting refurbishment activities for PV panels, developing refurbishment capability domestically is expected to remain a challenge. This is because most PV panels are imported, whilst manufacturers have different product standardisation and design which will add complexity into the refurbishing process.

• Landfill disposal, stockpiling, and illegal dumping of PV panels and Batteries will contribute to high externality costs as both technologies consist of a considerable number of heavy metals. These externality costs include the opportunity cost of land and costs related to land pollution. Potential leachate of heavy metals in the landfill will also trigger direct costs for the government trough the need to prevent and manage the leachate as well as amenity costs, and potential costs associated with the fire prevention activities that could arise due to fires resulting from the stockpiling.

• PROs may also work together with the government and industry associations to incentivise industries or scheme participants to undertake circular business model to ensure that PV and Battery systems can be collected at the end-of-life cycle. Examples include product-as-service, lease, and deposit-refund. These types of business models should be managed by PSOs or industry associations to ensure that they are sustainable.

• Mechanical delamination is currently the widely adopted PV recycling technology in commercial scale globally as opposed to chemical and thermal delamination which provides purer and more efficient material recovery. This is because Thermal delamination faces the issue of emission control while scaling up of chemical delamination involves significant use and discharge of chemical effluents. Thus, as an initial step in system development, mechanical delamination is perhaps the best approach, with a potential introduction of other technology types in future depending on innovation, cost & recovery needs.

5.3 Solar PV Waste Strategy for India

The development of a national strategy for solar waste management in India and the 'facilitator' role of the International Solar Alliance (ISA) are interconnected through nine key aspects crucial for an efficient end-of-life solar management system. The following infographic represents these key aspects (Figure 19).

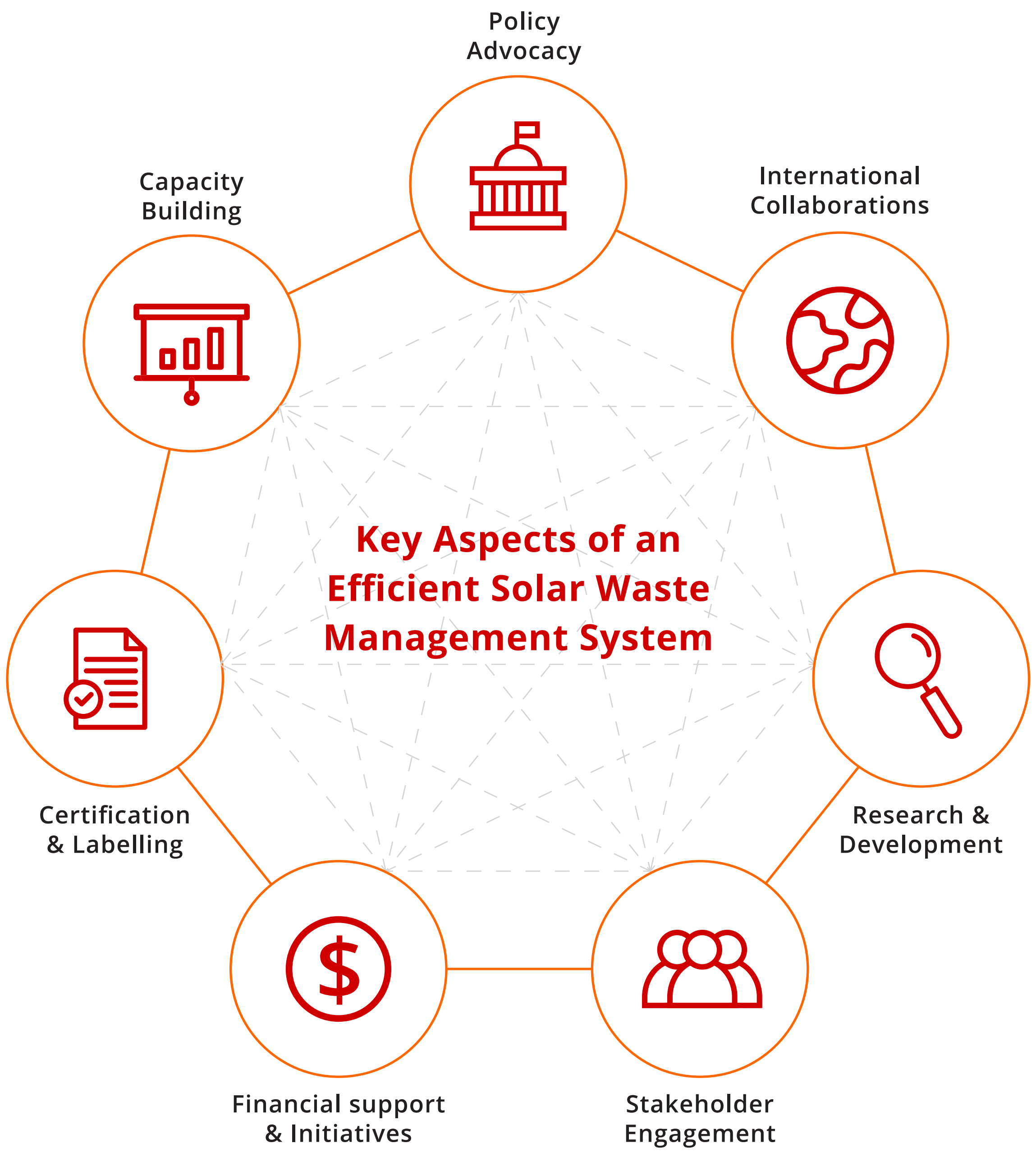


Figure 19:Key Aspects of Efficient Solar Waste Management System

These key aspects are also interconnected and complementary of one another and would need to be addressed while strategizing for the solar waste sector in India. Each of these components is essential in transforming the solar waste management system and addressing the challenges associated with solar waste. By implementing recommendations for each aspect, India can establish a comprehensive framework that promotes sustainability, circularity, and effective management of solar waste, while also benefiting from international collaborations and advancements in research and development.

5.3.1 Recommendations for Policy Makers

India's rapid growth in solar installations has highlighted the urgent need for a national strategy for solar waste management. With the increasing number of solar PV modules reaching their end-of-life stage, it is essential to establish a comprehensive framework to address the challenges associated with their disposal and recycling. A national strategy would enable the development of standardized practices, regulations, and infrastructure for efficient and environmentally responsible management of solar waste. Such a strategy would not only mitigate environmental risks but also unlock the economic potential of valuable materials within PV modules, promoting a circular economy and sustainable growth in the solar sector. A national strategy for India needs to encompass various aspects of the complete EoL value chain. Some key components which should be included are given in the following recommendatory steps.

India's national strategy for solar waste management should encompass various aspects to effectively manage the rapidly increasing volume of solar waste. Here are some key components that could be included:

> *"Unlike other policy instruments that focus on specific points in the EoL value chain, the EPR-based E-Waste (Management) Rules, 2022, is well-placed to address all environmental concerns of solar PV products and their EoL management. However, its implementation at the required scale requires the distribution of physical and economic responsibility and significant awareness and capacity building. Considering the lack of consumer knowledge about the environmental attributes of solar products in India, it will be crucial to steer both producers and consumers towards more environment-friendly behavior."*
> *- Legal Expert*

Policy Advocacy and Support: Develop comprehensive policies and regulations specifically addressing solar waste management, including guidelines for collection, transportation, recycling, and disposal. Ensure that these policies are in line with international best practices and standards. Based on India's current policy framework, the EPR mechanism will be most suited for assigning accountability to stakeholders in the EoL value chain. Strengthening the EPR framework to hold solar equipment manufacturers responsible for the entire lifecycle of their products, including the collection, recycling, and safe disposal of end-of-life solar panels will be instrumental in improving the solar waste management strategy for India. This approach will also encourage manufacturers to design products with recyclability in mind to lengthen product lifecycles and delay waste generation, giving time for the required recycling facilities to be established. A well-organized collection and disposal network for solar waste, including designated collection centres and recycling facilities is required to be set up across the country. Collaborate with waste management agencies and local municipalities to ensure efficient collection and disposal processes.

Research and Development: Promote research and development initiatives focused on improving solar panel designs, materials, and manufacturing processes with an emphasis on recyclability and minimizing waste generation (i.e., implement eco-design principles in panel manufacturing). Encourage collaboration between academia, research institutions, and industry to drive innovation in solar panel recycling technologies. Integrating R&D into the national strategy for solar waste management can contribute to efficient handling of PV waste and promote a sustainable, circular economy in the solar industry. Transitioning to a circular model will also help reduce dependency on virgin materials.

However, this transition will require a major reorganization of the existing value chains, starting from an institutional organization of collective knowledge and know-how, through collaboration between different stakeholders, to address challenges associated with experience, resources, capabilities, good/best practices, risks, and strategies. Legislative backing will be required with long-term targets to increase recycling and reuse and reduce landfilling and economic incentives for this shift (including taxes for landfilling), wherever possible. Another key aspect will be the creation of markets for secondary raw materials, which can be created, stimulated, or regulated by economic incentives/policies. Therefore, the policies will also need to address the volatility associated with secondary material prices.

> *"Learning from the experiences and potential gaps in the implementation of the e-waste management model in India, and in order to reduce the environmental, economic and social impacts on the eco-system surrounding the collection, transportation and management of solar waste, the government could consider introducing policies that encourage actors across the entire value-chains to build and work in localised cluster-like models."*
> *- Expert from the E-waste management sector*

Stakeholder awareness and engagement: Launch a nationwide awareness campaign to educate the public, solar industry stakeholders, and waste management agencies about the importance of proper solar waste management and the potential environmental hazards associated with improper disposal. Encourage public participation in solar waste management initiatives through awareness campaigns, recycling drives, and community engagement programs. Promote the concept of a circular economy where the public is actively involved in recycling and reusing solar products.

Financial Support and Incentives: Introduce financial incentives such as tax benefits, subsidies, and grants to encourage the adoption of sustainable practices in the solar industry, including the proper management of solar waste. Provide support to recycling companies through incentives and subsidies to promote their growth and viability, for setting up robust recycling infrastructure which can handle the growing volume of solar waste and is equipped with advanced technologies for efficient and environmentally friendly solar panel recycling. Some examples of such incentives can also include co-funding a portion of the upfront cost required for setting up such a facility (such as the 'Scheme for promotion of manufacturing of Electronic Components and Semiconductors, by the Indian government, which provides a financial incentive of 25% to cover the capital expenditure for setting up modern recycling facilities for e-waste) and/or providing tax credits or reduction on the equipment required for the recycling operations (such as the state-level tax credits and reductions provided in the United States on machinery and equipment for setting up recycling facilities for solid waste including plastic, paper glass and other types of solid waste, which vary from 10 to 20 percent of the total installed cost of the equipment[54]). This can also encourage public-private partnerships for jointly setting up recycling infrastructure.

International Collaboration: Foster partnerships and collaborations with other countries and international organizations to share best practices, knowledge, and technologies in solar waste management. Participate in global initiatives aimed at developing standardized processes for recycling solar panels and reducing environmental impacts.

For policy makers there are additional components which need to be incorporated in a national strategy for solar PV module waste management. These include the following components.

Monitoring and Enforcement: Establish a monitoring and enforcement framework to ensure compliance with regulations and guidelines for solar waste management. Regular audits and inspections should be conducted to verify that manufacturers, recyclers, and other stakeholders adhere to the prescribed standards.

In addition, the National strategy should also focus on how to best incorporate a wide and expansive part of any waste management system in the country – the informal sector.

[54] https://archive.epa.gov/wastes/conserve/tools/rmd/web/html/rec-tax.html

• Capitalise on existing Informal sector networks in the waste eco-system: Integrating the vast informal network which exist in the country and capitalizing on their reach and infrastructure in waste management has several benefits including expanded reach and collection of waste, improved working and environmental conditions of the informal sector and increased scrutiny, monitoring and ultimately formalization of the sector. Formalization of the informal workforce also has the added benefit of increasing their tax revenue and promoting the establishment of local value chains, and local incomes from solar waste collection and processing. Informal workforce will also be able to access tangible benefits such as social security, health care and other essential items for a sustainable livelihood.

• Building partnerships between the formal and informal workforce will also impact the environmental impacts of the informal sector, via initiatives such as adoption of pollution control standards or targets for collection and recycling, following national guidelines for other waste fractions and other avenues for preventing contamination from uncontrolled and unsupervised recycling and treatment of solar waste.

• The steps towards formalization will include mapping and identification of the relevant stakeholders, setting requirements for the informal recyclers to take specific actions that will entitle them to participate in formal recycling, building their capacity through relevant trainings and access to basic tools and knowledge and other means of up-skilling to bring about a structural and permanent change in the way they operate. These steps will also need to be accompanied by a legal commitment through legislations which include the informal sector in the waste ecosystem, requiring the informal sector to achieve a legal, formal and a transparent relationship with the central, state, and local authorities and institutions.

[By implementing a comprehensive strategy that addresses these aspects, India can effectively manage solar waste, minimize environmental impact, promote sustainability in the solar industry, and contribute to a cleaner and greener future.]

5.3.2 ISA's Role in Solar Waste Management Transformation

This sector can benefit from the contribution of international facilitators such as ISA. The International Solar Alliance (ISA) can play a significant role in facilitating better management of solar waste in India and other regions.

How does ISA help in the development of the solar sector?

ISA accelerates de-risked solar investments, lowering costs for member countries while driving innovation and investments. It also enables member countries in finding suitable bilateral and multilateral funding, making large-scale solar applications possible. It acts as an incubator for studies for Common Risk Mitigation Mechanism (CRMM) for solar power generation projects in solar rich countries and further facilitates stakeholder consultations, workshops, and forums for member countries to foster enabling environments for solar energy projects. As one of the founding members and resource-rich countries, India has taken the lead for setting up ISA and its institutions. Guided by the Framework Agreement, ISA aims to mobilize investments of more than USD 1,000 billion by 2030.

Here are some actions the ISA could take:

Policy Advocacy and Support: The ISA can work with governments across its different regions to develop and implement policies that promote responsible management of solar waste. This can involve encouraging the adoption of regulations and guidelines for the handling, collection, and recycling of solar panels and other components, facilitating lessons from the more advanced regions (in the solar waste management context) to the developing ones.

Stakeholder Awareness and Education: The ISA can initiate awareness campaigns to educate governments, industries, and the public about the importance of proper solar waste management, including PV and off-grid solar (OGS) waste found in most countries around the world. This can include sharing information about the potential environmental impacts of improper disposal and the benefits of recycling solar components. ISA can provide funding support for development of a toolkit for member countries to score their solar waste management strategy and drive actions based on the scale of market maturity of the system.

Research and Development: Through its networks and collaborations, and by including stakeholders such as manufacturers and OEMs, the ISA can focus on research and development to explore innovative technologies and processes for the recycling and safe disposal of solar waste. This can include funding research projects (including functional pilots), collaborating with academic institutions and industry experts, and facilitating knowledge sharing among member countries. In countries like India, they could explore the use of companies' CSR funds to facilitate and run such pilots in collaboration with international experts.

Capacity Building: The ISA can support capacity building efforts in member countries by providing technical assistance, training programs, workshops and webinars and knowledge-sharing platforms. This can help develop the expertise and infrastructure required for effective solar waste management, including recycling facilities and collection networks. Lessons learnt in one region can be shared through cross-regional collaboration and by building capacity of local experts. As part of the capacity building measures

International Collaboration: The ISA can encourage international collaboration among member countries and other stakeholders to share best practices and experiences in solar waste management. This can involve organizing workshops, conferences, and forums where experts can discuss challenges, exchange ideas, and develop joint initiatives.

Certification and Labelling: By partnering with suitable agencies, the ISA can establish certification standards and labelling mechanisms for solar products that promote recyclability and environmentally responsible manufacturing processes. This can incentivize manufacturers to design products with easier recyclability and provide consumers with information to make sustainable choices.

Financial Support: The ISA can explore financial mechanisms such as grants, subsidies, or low-interest loans to incentivize the establishment of solar waste recycling facilities and infrastructure. This can help address the financial barriers associated with recycling and encourage the growth of a sustainable solar waste management sector.

In conclusion, the International Solar Alliance (ISA) plays a crucial role as a facilitator in the development and implementation of an efficient solar waste management strategy in India. By addressing key aspects such as policy advocacy, international collaborations, certifications and labelling, financial support and incentives, research and development, stakeholder engagement, capacity building, and circularity, the ISA can support India in effectively managing the growing volume of solar waste. Through its expertise, knowledge sharing, and collaborative initiatives, the ISA can contribute to the formulation of comprehensive policies, the establishment of robust recycling infrastructure, and the promotion of sustainable practices across the solar industry. By working together with national and international stakeholders, the ISA can drive innovation, enhance transparency, and ensure the proper management of end-of-life solar panels, leading to a more sustainable and environmentally friendly solar energy sector in India.

Annex 1: Global Case Studies

Germany

Electrical and Electronic Equipment Act (ElektroG) implements the European WEEE Directive 2012/19/EU in German law. It regulates the placing on the market, the return and the environmentally friendly disposal of electrical and electronic equipment. The law first came into force in 2005 and was amended in 2015 (ElektroG2) and 2022 (ElektroG3).

Scope:

In the scope of application of the Electrical and Electronic Equipment Act, electronic (electronic) devices for operation with an AC voltage of no more than 1,000 volts or DC voltage of up to 1,500 volts are in principle, which meet the following requirements (§ 3(1) ElektroG):

• Devices that require electrical currents or electromagnetic fields for their proper operation,

• Devices for generating, transmitting, or measuring electric currents or electromagnetic fields.

Solar panels are included in this category as an electronic product.

Financial Mechanism

Two types of financing mechanisms are present for meeting EPR obligations in Germany – Business-to-Business and Business-to-Consumer.

Business-to-Business (B2B)

In a B2B scenario, the producers are given flexibility in selecting funding/financial mechanisms. The Producers can reach a mutual agreement with the consumers for compliance through types of agreements that may include upfront recycling payments, recycling service contracts, and outsourcing to third-party etc. The consumers may also opt to use the same mechanism as a B2C consumer. Producers are the sole financers, with the businesses procuring the solar panels becoming “customers” in this scenario[55].

[55] UNDP, 2021

Business-to-Consumer (B2C)

Financers include all stakeholders involved in the value chain. In Germany, two levels are defined:

• Level 1 defines the cost related to collection system operation and instantaneous collection and recycling of PV waste products (i.e., old PV installation before being included in the scope of the law). Level 1 costs are covered using Pay as You Go (PAYG) system for all market players based on their current market share. If a producer exists from the market, its market share will be taken up by the other market participants along with the responsibility for financing collection and recycling. In over to finance for a situation in which all the market participants exit the market, each level 1 market participant pays an annual premium for insurance by name last man standing insurance.

• Level 2 ensures sufficient financing mechanism for future collection and recycling of PV module which are introduced in market today i.e., after inclusion into the scope of the law. 2 The costs are calculated by Shiftung EAR (clearing house) taking into consideration the average lifetime, the return quota at municipal collection points, and the treatment and logistic costs.

Cost responsibility =Basic amount for registration (PV panel tonnage put on the market) x presumed return rate (%) x presumed disposal costs (EUR/t)

Disposal/treatment costs for residential PV panels have been presumed by Stiftung EAR for the year 2021 as 245 EUR/tonne[56].

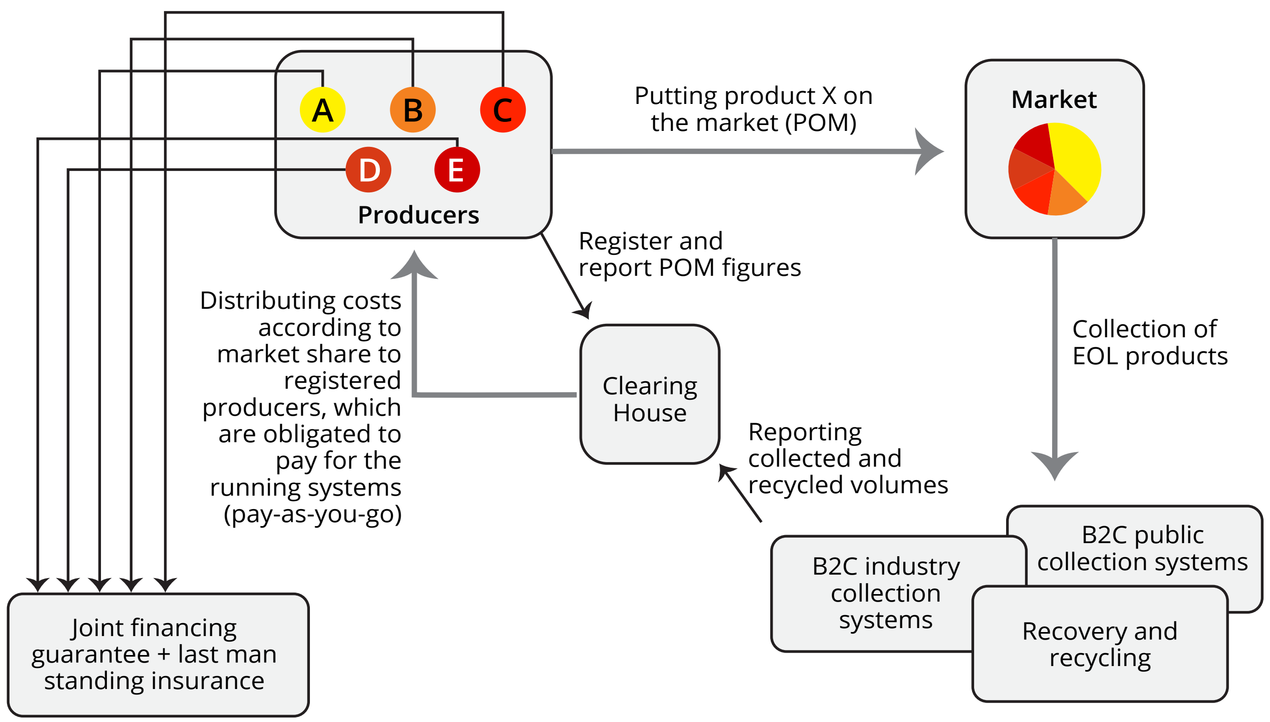


Figure 20:Collective Producer Responsibility scheme for End-of-life management of Business to Consumer (B2C) PV panels

56 https://www.stiftung-ear.de/en/topics/elektrog/producers-ar/pbs-rules/pbue/regulations-guarantee-amount

Obligations:

Manufacturers, importers and, in the case of direct sales, also foreign providers must first register with the joint agency, Stiftung EAR, for all brands and types of equipment before they are allowed to offer the corresponding electrical or electronic equipment for sale in Germany for the first time or to place it on the market. Financial guarantee security must be proven annually for B2C devices. For B2B products, the professional properties must be substantiated, and a take-back concept must be presented. As part of an active registration, extensive administrative activities such as regular quantity reports must be carried out. Products must be labelled correctly, and information provided to consumers.

Large dealers with at least 400 square meters of shop, storage or shipping space must take back old electronic devices and have them disposed of at their own expense. This also includes online trade and, from July 2022, food retailers with a total sales area of 800 square meters or more. In addition, further information, registration and reporting obligations arise. If electrical or electronic devices are sold directly to users in other European countries, additional WEEE solutions must be set up in the various countries. Online retailers from third countries are obliged to use authorized representatives.

Penalty:

Manufacturers, importers and dealers who violate the ElektroG expose themselves to the risk of various penal sanctions. At the administrative level, fines of up to EUR 100,000 and other sanctions such as the confiscation of profits are threatened. Under private law, there is a risk of warnings from competitors and possible claims for damages. In general, there may be a ban on sales until compliance with the ElektroG is established.

Italy

In Italy, earlier in accordance with the Ministerial Decree on 5 July 2012, the manufacturers of panels must adhere to a system or consortium for panels recycling at the end of life to demonstrate the sustain- ability of these systems. Guarantor of Electric Services (GSE) has published information on procedures and documents to be submitted by the systems or consortia to demonstrate their suitability. After the publication of the list of suitable systems or consortia, which occurred on March 2013, manufacturers of panels used in PV plants of the 4th and 5th Conto Energia which came into operation after 1 July 2012, must provide an attestation of adhesion to a consortium or system to be granted feed-in tariffs[57].

57 Photovoltaic waste assessment in Italy

An information system named PVCERT[58] was established to provide accessible data and information on the PV systems installed. It collects and makes accessible the certificates and attestations of photovoltaic panels and inverters, particularly about their quality and the identification of manufacturers and/ or importers of these components into the Italian market.

Legislative Decree 49 of 2014, implementing the EU directive on WEEE, has effectively imposed the obligation to dispose of photovoltaic panels. It also indicated that producers and / or distributors of the equipment itself are responsible for end-of-life management, in proportion to the quantity of new products placed on the market, through the organization and financing of collection, transport, treatment and recovery systems as illustrated in Figure 21 below.

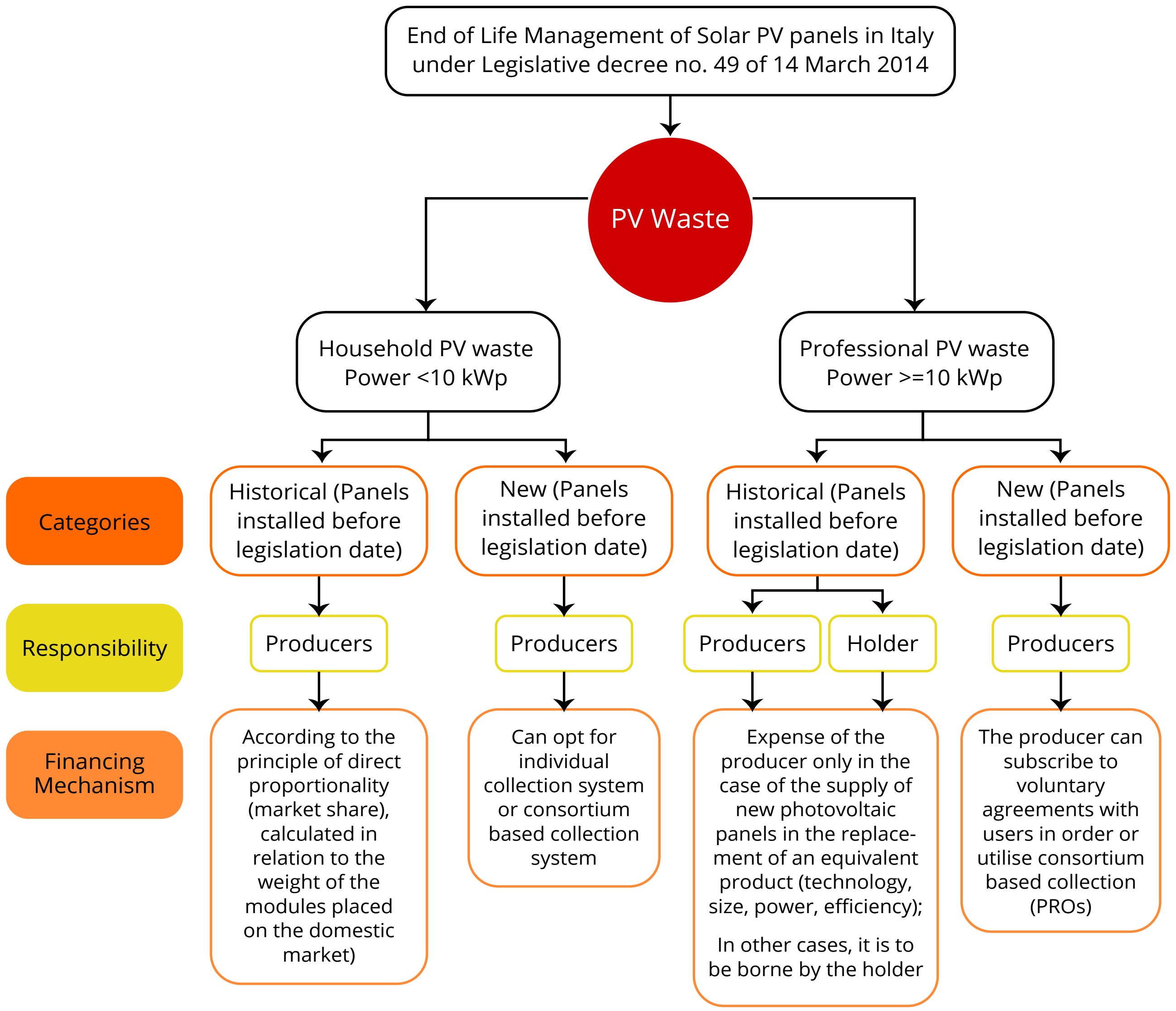


Figure 21: General overview of provisions in Legislative decree no.49/2014

[58] http://www.fotovoltaicosulweb.it/guida/certificare-pannelli-solari-e-inverter.html

For plants with incentives (feed in tariff) in the Energy Bills, two different management methods are active according to the date of entry into operation, type of plant and belonging to the Energy bill: the first follows the provisions of Legislative Decree 49/2014; the second, on the other hand, follows the provisions of the Technical Regulations published by the GSE for plants with incentives pursuant to the fourth and fifth Energy Bill.

About costs, for the beneficiaries of the incentives of the I, II, III Conto Energia there is a quota withheld by the GSE, aimed at guaranteeing complete coverage of the management costs foreseen for the disposal of the photovoltaic modules. end of life. This quota is determined based on the average costs of joining the Consortia and the estimate of the costs attributable to the collection, transport, adequate treatment, recovery, and disposal of photovoltaic WEEE. The fee withheld by the Energy Services Manager is 12 euros per panel for domestic solar panels, while for professional photovoltaic modules it is 10 euros per panel. These sums, held as collateral, will then be reimbursed after the Manager's checks on compliance with the obligations envisaged for management and disposal.

The Legislative Decree number 118 of September 3, 2020[59] makes producers of photovoltaic EEE responsible for the financing and management of WEEE retroactively, that is, regardless of whether the equipment was placed on the market before the entry into force of this new legislation, or if the equipment is of domestic or professional origin. The legislation recognizes the validity of financial guarantee instruments that may have been activated by producers for the end-of-life management of photovoltaic panels placed on the market before the entry into force of this legislation. In the case of photovoltaic panels placed on the market after the date of entry into force of this new legislation, producers must set aside an amount necessary to cover all costs necessary for the proper management and disposal of such equipment, which is to be deposited in a trust account established according to applicable legislation. The trust thus established is operated and managed by a trust guarantee system, which is collectively managed, and that covers up to 20% of the total amount of the costs associated with the financing provided by producers obliged to finance the photovoltaic WEEE.

The United States of America (USA)

Washington

Photovoltaic module stewardship and takeback program

This was created under Senate Bill 519 (2017) to promote a sustainable local renewable energy industry through modifying tax incentives. The program requires PV

[59] https://www.loc.gov/law/foreign-news/article/italy-implementation-of-eu-legislation-on-the-recycling-of-electrical-equipment-and-batteries/

module manufacturers to finance and implement a takeback and recycling or reuse stewardship plan for PV modules sold after July 1, 2022, at no cost to the owner manufacturer, distributor, retailer, or installer may sell or offer to sell PV modules within or into Washington unless the manufacturer has submitted and obtained approval for a stewardship plan from the Washington Department of Ecology (Department).

Scope:

• PV modules used for residential, commercial, or agricultural purposes that are installed on, connected to, or integral with buildings

• Freestanding off-grid power generation systems such as water pumping stations, electric vehicle charging stations, solar fencing, solar-powered signs, and solar powered streetlights

• PV modules that are part of a system connected to the grid or utility service

Draft Manufacturer Plan Guidance for the Photovoltaic Module Stewardship Program

The Washington State Legislature passed Senate Bill 5939 to promote a sustainable, local renewable energy industry through modifying tax incentives. One portion of the bill created Chapter 70.355 RCW (Photovoltaic Module Stewardship and Takeback Program) requiring manufacturers of photovoltaic (PV) modules to provide the public a convenient and environmentally sound system for recycling modules that were purchased after July 1, 2017.

This guidance document provides an EPR policy for PV waste management- Manufacturers are required to finance the takeback and recycling system at no cost to the owner of the PV module.

California

California had classified PV panels as hazardous waste under SB 489 regulation in 2015. The Department of Toxic Substances Control (DTSC) proposed changes in hazardous waste program to classify PV waste as universal waste which was approved by EPA in 2020. The new regulation is expected to be passed by office of administrative law by October 2020. These regulations include notification, reporting, transportation, storage, and handling requirements that are less stringent than California's hazardous waste management norms.

The regulation in California gives the best-case example of including solar PV waste in the category of universal waste. This ensures that PV panels are subject to the more stringent norms for universal waste.

New York

The New York State Senate passed Senate Bill S2837B "Solar panel Collection Act" in July 2018 which is currently awaiting approval of the assembly. The bill enacts the "solar panel collection act" which would require solar panel manufacturers to collect used panels and requires educational outreach related to establishment of collection goals and reporting.

The SB 942 would require manufacturers selling solar modules in the state to implement a collection and recycling program at no cost to the system owner and creates a landfill ban.

Australia

Australia currently does not have any dedicated policies for EOL management of solar panels/cells/modules. However, a few scoping studies have been done in different regions of Australia to understand the current scenario of solar waste in the continent. A summary of the studies have been provided below:

Victoria

A scoping study was done for application of EPR framework for solar PV recycling. The study assesses option to progress a national product stewardship approach, through stakeholder identification, consultation and a feasibility assessment for photovoltaic (PV)systems, including panels, associated inverter equipment and energy storage systems (ESS) reaching end-of-life in Australia.

New South Wales (NSW)

A scoping study for photovoltaic panel and battery system reuse and recycling fund was completed by UTS Institute of Sustainable Futures & Equilibrium Consulting. It aimed to identify and provide detailed case studies on the most promising reference processes and facilities from Australia and overseas for collection, reuse and recycling of PV panels and batteries that could become options for an industry in NSW. This review focuses on c-Si PV panels and LIB as these technologies have the largest market share.

Northern Territory (NT)

A study on End-of-Life Management of Solar PV Panels was done by Regional Development Australia, Northern Territory. The purpose of this study was to quantify the nature and extent of the Northern Territory's solar photovoltaic (PV) waste and to explore how end-of-life (EOL) management planning could be used to mitigate both the environmental threats posed by solar waste as well as offset the potential costs of managing this waste in the future.

China

China has the highest installed capacity of solar PV across the world, as of 2021. Despite being at the top of manufacture and installed capacity of solar power, it has no specific legislation in place. In fact, PV panels are not even included in the WEEE products processing directory of the Waste Electrical and Electronic Product Recycling

Management Regulation. However, the country has a National High-tech research and development (R&D) Programme for PV recycling and safety disposal research, which will set the foundations for future regulation. R&D investments are in fact often a successful incentive for increased circularity and better end-of-life management.

Annex 2: Case Studies on Solar PV Waste Recycling

Recupero integrale pannelli fotovoltaici / Full Recovery End of Life Photovoltaic (FRELP) – PV Recycling Process Study[60].

FRELP project was carried out by SASIL S.p.A through funding from the European LIFE+ program. The project concentrated on developing technology for full recovery of mono and polycrystalline silicon PV panels. The project ran between 2013 and 2016. FRELP stands for Full Recovery End of Life Photovoltaic panel. The phases of the project were as follows:

I) Robotic mechanical detachment of aluminium profiles, glass connectors and PV sandwich
II) Thermal combustion of the Eva to recover metallic silicon and other metals
III) Acid leaching to separate silicon from other metals by filtration
IV) Electrolysis to recover copper and silver and acid water neutralization treatment.

The project successfully demonstrated the overall treatment technology envisaged in phases I, II, III and IV and proved that the adopted technology is economically and environmentally sustainable. The FRELP project was discontinued in April 2016 as the availability of photovoltaic panels at the end of their life was insufficient to ensure the sustainability of the prototype. Phase I allows the recovery and enhancement of 88% of the total weight of the mono and / or poly crystalline silicon photovoltaic panels with a negative impact of the sandwich alone, which represents 12% of the weight. The economic return of phase I could be achieved with a quantity of only 2,000 t / year of panels, equal to one work shift. The economic return of phases II, III, IV, on the other hand, requires a minimum of 7,000 t / year of panels as the processing cycle is foreseen continuously, 24 hours a day.

60 ENEA-Socio Economic Study (In Italian)

Process Parameters and Snapshot:

Pilot plant Capacity	1000 kg/hr of PV waste
Projected Capacity for expansion	7000 kg/hr
Number of employees involved	8
Designed for Panel	Silicon PV panel up to (2x1) meter dimensions

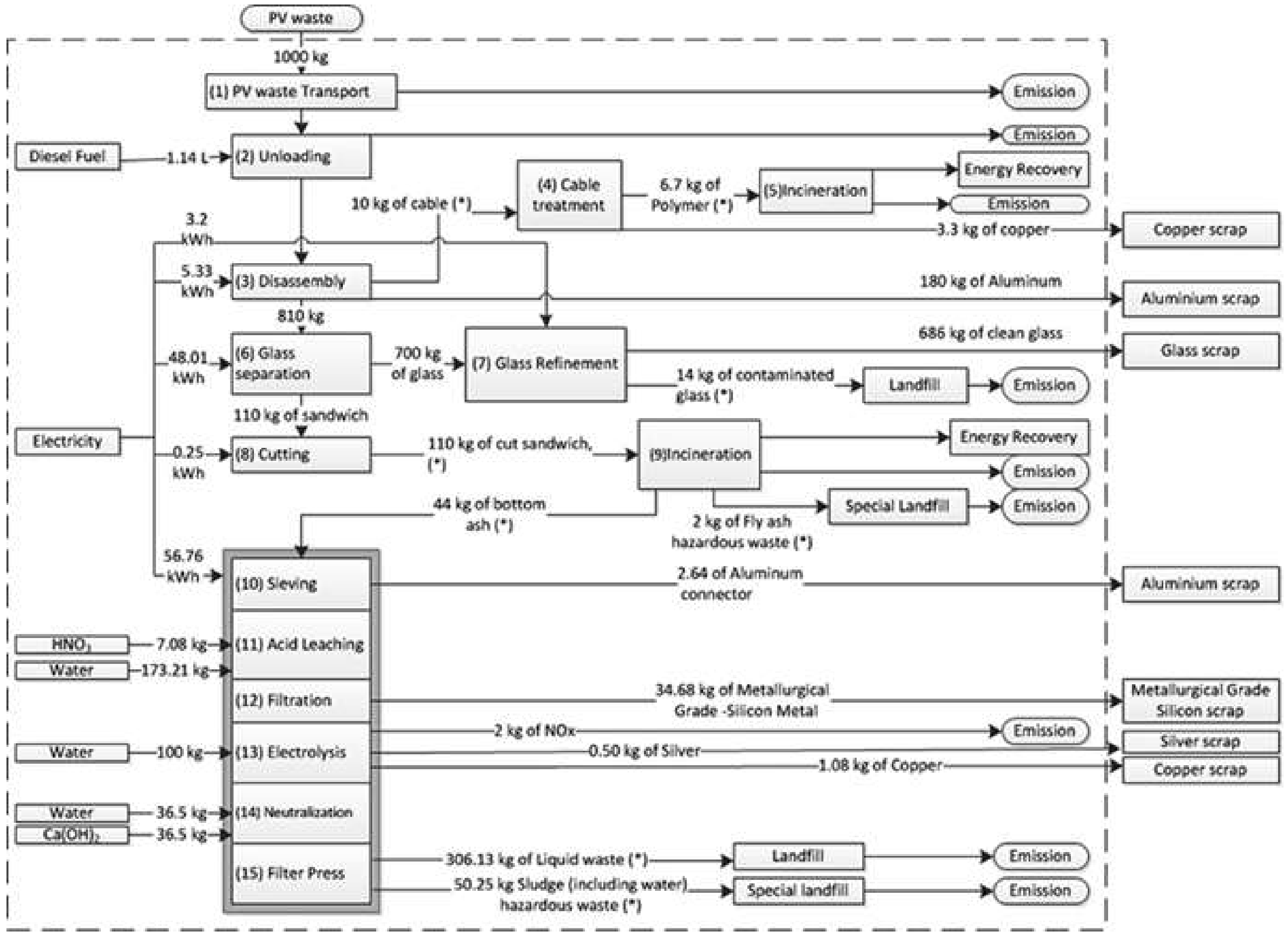


Figure 14: Process parameter and flow chart of FRELP PV Recycling process

Economic Analysis:

Cost (Mentioned as €/ton of PV waste)			
Investment cost (Land & Machinery):53 to 62 €/ton			
Assuming Incidence of a ten-year mortgage, at an interest rate of 4%. For Veolia: Machinery Investment cost for 4000 t/year plant was 1 Million euros whereas for FRELP with projected capacity 7000 t/year, the cost came up to 2 Million euros. Cost of land is assumed to be 1 Million euros.			
Production/Operation cost: 116 €/ton			
Input/Output	Quantity	Cost (€/ton)	Total cost
Electricity	113.55	0.2	22
Fuel	1.14	1.05	1
Water	309.71	0.002	1
Nitric Acid	7.1	1.6	11
Calcium hydroxide	36.5	0.9	33
NOx	2		
Landfill waste	320	0.11	35
Special landfill waste(hazardous)	52.25	0.24	13
Labour costs:100 to 190 €/ton			
Veolia estimates 10 to 19 employees in its pilot plant. Using the Veolia data and assuming an average gross salary of € 40,000 a year, we get an incidence of labour costs between 100 and 190 € / t.			
Transport cost: 42 €/ton			
Assuming 7000 tons/year plant; 438 loads per year; 2 crew members for transport and corresponding fuel prices			
Revenues:620 €/ton (Potential: 1240 €/ton)			

Material	Theoretical potential (kg)	FRELP (Sasil) (kg)	Economic value of recovered material (€/kg)	Total Revenue €
Glass	730	686.0	0.006	4.116
EVA	36.8	Combusted	0.7	0
PET Back sheet	2.7	Combusted	0.7	0
Aluminium	182	182.0	1.6	291.2
Silicon	40.3	34.7	0.8	27.76
Silver	1.7	0.5	490	245
Copper	6.7	4.4	5.3	23.32
Tin	0.8	Not recovered	15	0
Lead	0.4	Not recovered	1.9	0
Electric Energy (kWh)		69.1	0.2	13.82
Thermal Energy (litres of diesel equivalent)		13.7	1.05	14.385

First Solar – Thin film solar PV recycling

First Solar operates a commercial recycling facility for CdTe modules in Germany. Their CdTe PV module recycling technology is a combination of a mechanical and a chemical treatment (Figure 16). First Solar started operating their first version of this technology in 2006 in Germany (10 tons/day), with an updated second version of the technology operated in the United States and Malaysia in 2011 (30 tons/day), and an introduced third version of the technology in the United States in 2015 (50 tons/day)[61]. The third version of the technology is a continuous process, whereas the earlier versions are batch processes. The fourth version is expected to have a treatment capacity of 350 tons/day. In addition, mobile technology on a smaller scale to reduce the transportation cost is to be developed[62].

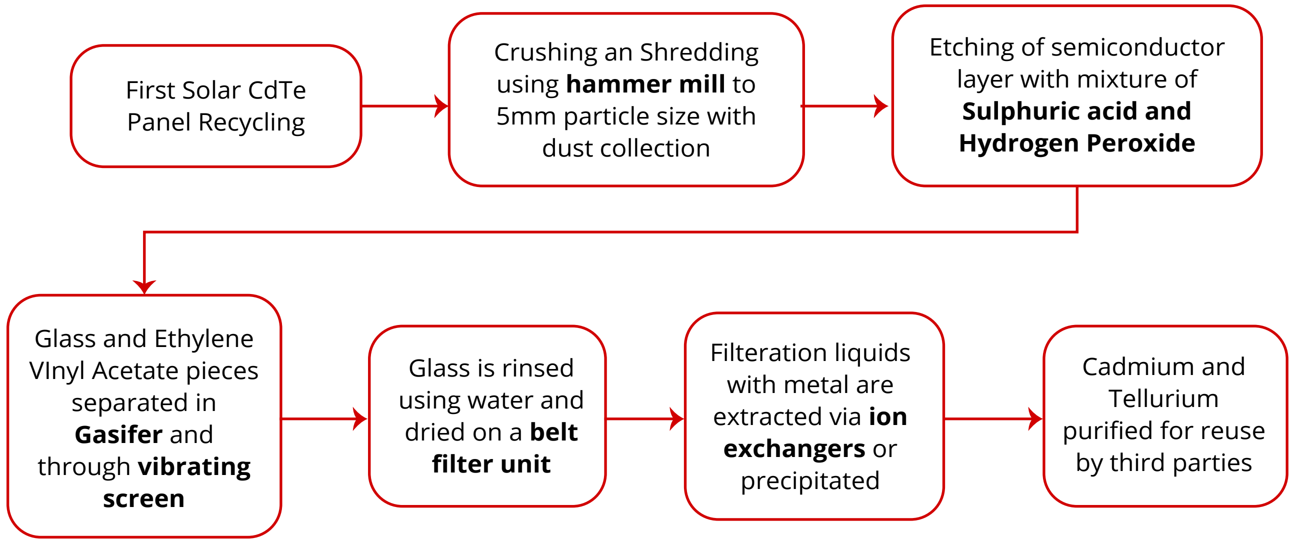


Figure 15: First solar recycling steps for CdTe modules

[61] IEA PVPS TASK 12 PV recycling trends
[62] IEA PVPS TASK 12 PV recycling trends

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This report has been developed by dss+ and was commissioned by
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