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Enabling a Circular Economy in India's Solar Industry

Assessing the Solar Waste Quantum

Report | March 2024

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Enabling a Circular Economy in India's Solar Industry

Assessing the Solar Waste Quantum

Prepared by

Council on Energy, Environment and Water (CEEW)
and Ministry of New and Renewable Energy (MNRE)

In compliance to Point 2 in NITI Aayog's *Action Plan for Circular Economy - Solar Panels*
"Detailed Survey of Projects for Type, Make and Number of installed modules and waste generation rates to ascertain the waste already generated and forecasting amount of waste generation"

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Solar waste recycling is an important circular economy strategy that can bring various socio-economic benefits to the country.

Image: Goldi Solar

भारत सरकार
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GOVERNMENT OF INDIA
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Azadi Ka Amrit Mahotsav

Dinesh Dayanand Jagdale
Joint Secretary

Date: 18th March, 2024

Foreword

Circular economy and resource efficiency have emerged as critical enablers for realising a sustainable future. Over the last year, India has demonstrated global leadership in driving momentum and building consensus to promote responsible consumption and production of resources. This includes steering a global movement on Lifestyles for Environment (LiFE) and establishing a Resource Efficiency and Circular Economy Industry Collation (RECEIC) to catalyse on-ground action. These initiatives found their place in the G20 New Delhi Leaders' Declaration.

A circular economy could accelerate the clean energy transition by providing new avenues to supply these technologies and intrinsic minerals to meet the growing demand. Material recovery from RE technologies' waste shall help build local and resilient supply chains of critical minerals needed for India's clean energy transition. Circular economy strategies such as repair and remanufacture will extend the life of products and allow the reuse of functional components in new products. Embedding circularity principles in the product design stage has the maximum potential to reduce the reliance on critical minerals and design durable products.

The Ministry of New and Renewable Energy (MNRE) is actively working to create a circular economy in India's clean energy sectors, such as solar. In 2022, it submitted a detailed report on the Circular Economy in Solar Panels to NITI Aayog. It guided an action plan focusing on policy and regulations, market mechanisms and technical assessments needed to facilitate a circular solar industry in India. Solar PV cells and modules are now part of the Electronic Waste (Management) Rules 2022, issued by the Ministry of Environment, Forest and Climate Change, Government of India. MNRE is a member of the steering committee constituted under these rules and supporting the development of implementation guidelines. It is a crucial decade for the Indian solar industry, poised for four to three times growth in manufacturing and deployment, respectively. This provides an opportune time to become circular and maximise the environmental, economic and social co-benefits. The availability of India-specific data on various aspects of the circular economy will facilitate this transition.

The report, '*Enabling a Circular Economy in India's Solar Industry: Assessing the Solar Waste Quantum*', developed by MNRE and Council on Energy, Environment and Water (CEEW), under the NITI Aayog Action Plan for Circular Economy - Solar Panels, will contribute to the progress on solar waste management in India. The study builds on the primary data collated from project developers and shall serve as baseline data for India-specific solar waste estimates. The temporal and spatial waste projections provided in the report shall support the industry in planning investments, partnerships and development of waste management infrastructure.

I congratulate the CEEW and MNRE team on this timely report. I compliment CEEW for their in-depth analysis and detailed discussions with key stakeholders to develop these estimates. I hope the report's findings and recommendations will inform the discussions and decisions in creating a circular economy ecosystem in the Indian solar industry.

Jagdale

(Dinesh Dayanand Jagdale)

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Solar waste contains several critical materials such as silicon and copper which are crucial for India's clean energy transition.

Image: Goldi Solar

About Ministry of New and Renewable Energy (MNRE)

The Ministry of New and Renewable Energy (MNRE) is the nodal Ministry of the Government of India for all matters relating to new and renewable energy. The broad aim of the Ministry is to develop and deploy new and renewable energy to supplement the energy requirements of the country.

The role of new and renewable energy has been assuming increasing significance in recent times with the growing concern for the country's energy security. Energy self-sufficiency was identified as the major driver for new and renewable energy in the country in the wake of the two oil shocks of the 1970s. The sudden increase in the price of oil, uncertainties associated with its supply and the adverse impact on the balance of payments position led to the establishment of the Commission for Additional Sources of Energy in the Department of Science & Technology in March 1981. The Commission was charged with the responsibility of formulating policies and their implementation, programmes for development of new and renewable energy apart from coordinating and intensifying R&D in the sector. In 1982, a new department, i.e., Department of Non-conventional Energy Sources (DNES), that incorporated CASE, was created in the then Ministry of Energy. In 1992, DNES became the Ministry of Non-conventional Energy Sources. In October 2006, the Ministry was re-christened as the Ministry of New and Renewable Energy.

About Council on Energy, Environment and Water (CEEW)

The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses **data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources**. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW has a footprint in over 20 Indian states and has repeatedly featured among the world's best managed and independent think tanks. Follow us on X (formerly Twitter) @CEEWIndia for the latest updates.

Solar cell and module producers should build necessary infrastructure and develop financing mechanisms for managing their waste.

Image: Goldi Solar

Contents

A granular, temporal and spatial mapping of solar waste is important to enable policy making and business decisions by the industry players.

Image: Goldi Solar

Executive summary

India needs around 292 GW of solar capacity by 2030 (CEA 2023). With the rapid deployment of solar photovoltaic (PV) technologies, concerns are building around solar waste management. Responsible solar PV waste management is critical for environmental, economic, and social reasons (Tyagi and Kuldeep, 2021). The discarded modules include minerals such as silicon, copper, tellurium, and cadmium, which have been classified as critical minerals for India by the Ministry of Mines (MoM 2023). Recycling solar waste to recover these materials will reduce import dependency and enhance India's mineral security. The Ministry of Environment Forest and Climate Change (MoEFCC) recently amended the Electronic Waste (Management) Rules to include solar cells and modules in their ambit (MoEFCC 2022). The Ministry of New and Renewable Energy (MNRE) has also identified solar PV recycling as one of the priorities thrust areas under the *Renewable Energy Research and Technology Development (RE-RTD) Programme* (PIB 2023a).

A granular estimation of solar waste would help policymakers and industry players make informed decisions regarding the required regulations and infrastructure deployment. Although some studies provide estimates for India's solar waste (IRENA and IEA-PVPS 2016, Suresh, Singhvi and Rustagi 2019), they rely on global databases to ascertain the waste at the end-of-life (EoL) of modules. A granular study that captures module degradation rates and replacement trends in Indian climatic conditions is crucial.

The study bridges the information gap in India-specific solar waste estimates by developing a comprehensive waste estimation model that provides the temporal and spatial distribution of solar waste. It further runs a comparative analysis across various scenarios by varying the module degradation rate and other available methodologies.

A. Key findings

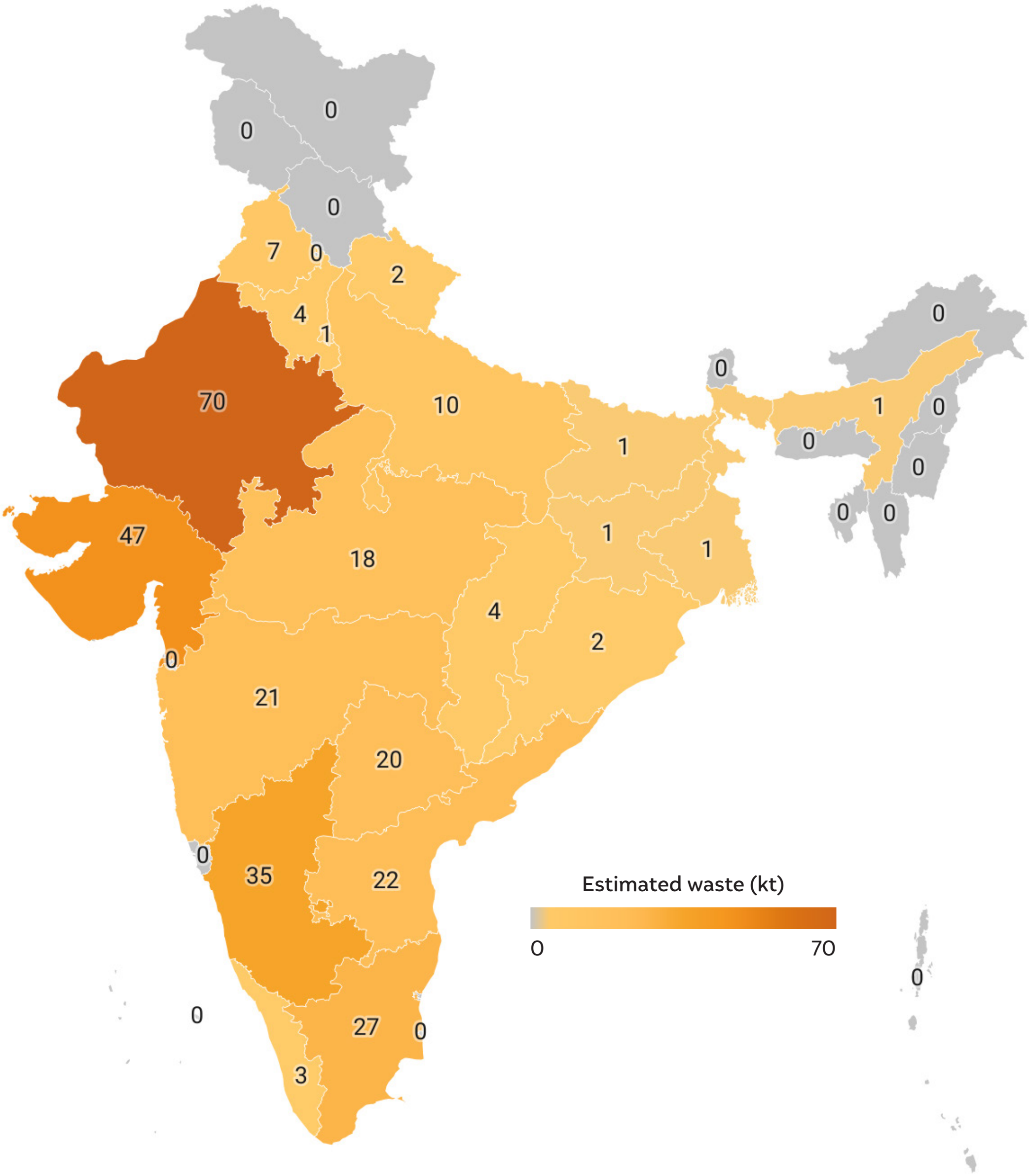
- India's installed 66.7 GW capacity, as of FY23, has generated about 100 kilotonnes (kt) of waste, which will increase to 340 kt by 2030 (Figure ES1). Around 67 per cent of this waste is expected to be generated in five states: Rajasthan, Gujarat, Karnataka, Andhra Pradesh, and Tamil Nadu.
- The cumulative waste from existing and new capacity (deployed between FY24 and FY30) will reach about 600 kt by 2030. Around 44 per cent of this will be generated from new capacities (Figure ES1). Similarly, the cumulative waste will increase to about 19000 kt by 2050; 77 per cent of which will arise from new capacities (Figure ES2).

B. Recommendations

- The MNRE should maintain and periodically update a database of the installed solar capacity (containing details such as module technology, manufacturer, commissioning date, etc.) for accurate mapping of plausible waste generation centres.
- The MoEFCC should issue guidelines for collecting and storing solar waste. Furthermore, it should also promote safe and efficient processing of stored waste.
- Solar cell and module producers should start developing waste collection and storage centres to adhere to the responsibilities assigned in the *E-waste Management Rules 2022*.

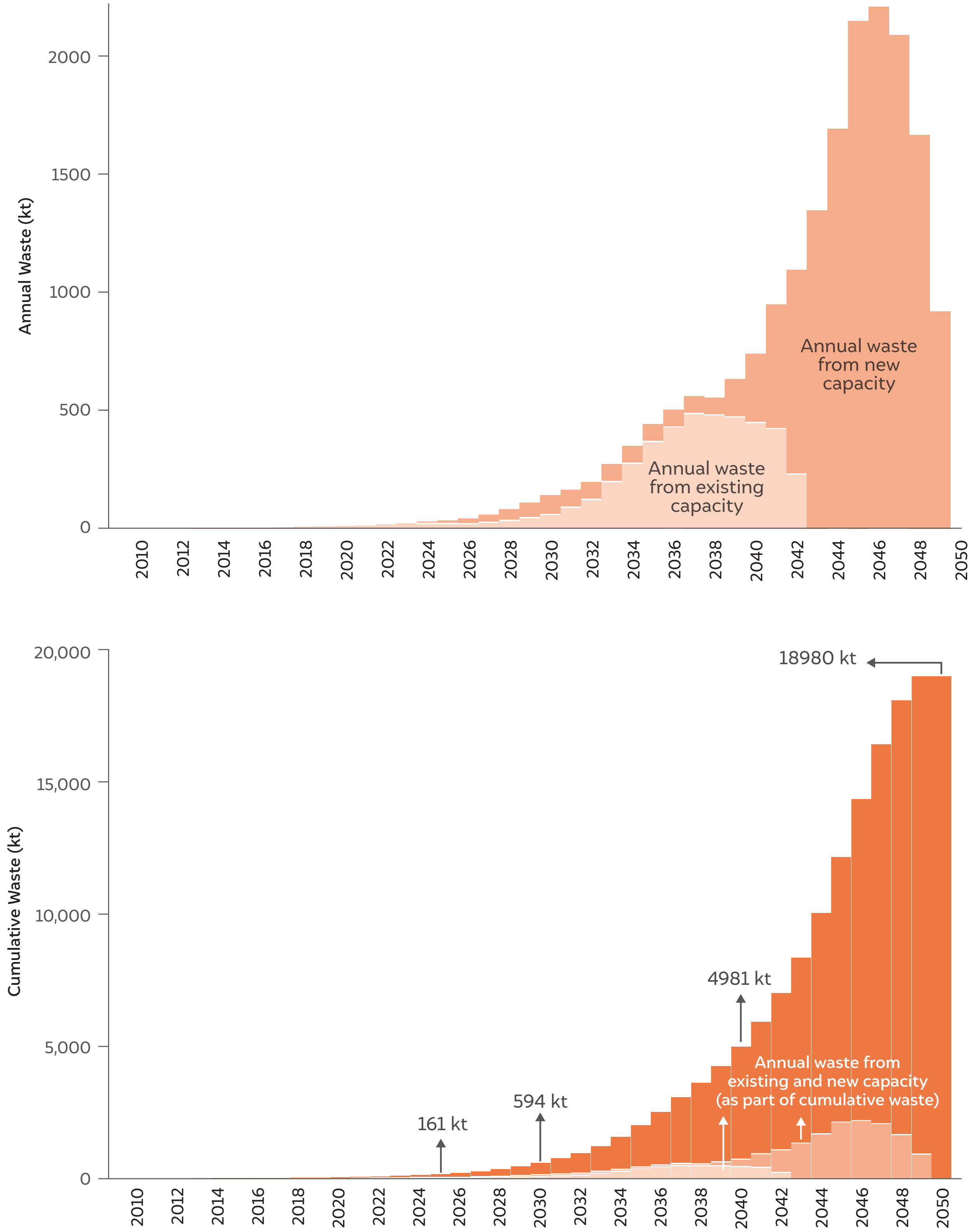

Image: Alamy

Figure ES1 **67% of the cumulative waste in 2030 is expected to be originating from five states**



Source: Authors' analysis

Figure ES2 **India's cumulative solar waste will increase 32 times between 2030 and 2050**



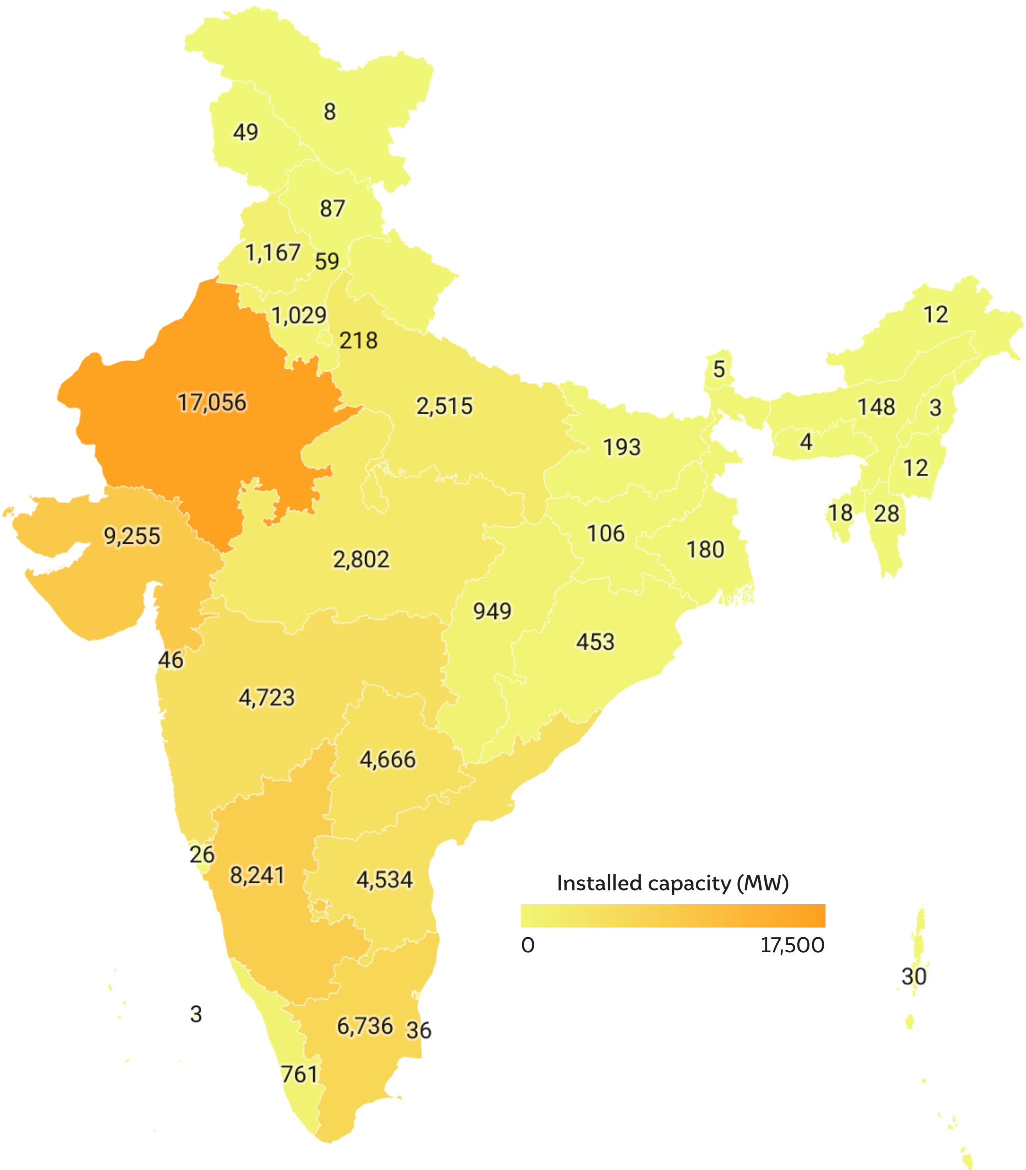
Source: Authors' analysis

1. Solar energy driving India's clean energy transition

In recent years, with the decline in solar photovoltaic (PV) module prices and increased investments, solar power has become the cheapest source of clean electricity around the world (IEA 2022). A recent analysis shows that, based on the levelised cost of energy (LCOE), utility-scale solar projects are cheaper to build than operating existing coal plants (Lazard 2021). India also has aggressive plans for solar capacity deployment as part of its commitment to fight climate change.

India's solar capacity has grown 26 times in the last decade, reaching 73.32 GW in December 2023 (PIB 2023b). Solar energy now powers end-use applications, such as pumps, lanterns, cold storage, etc., which have made inroads across geographies and consumer categories (MNRE 2023). This trend is expected to continue as India would need about 292 GW of installed solar capacity by 2030 (CEA 2023). Furthermore, India would need about 1,700 GW of solar capacity by 2050 and 5,600 GW by 2070 to achieve its 2070 net-zero target (Chaturvedi and Malyan 2021). The majority of the current capacity is deployed in the southern (37 per cent) and northern (34 per cent) states of India (Figure 1). Rajasthan, with 26 per cent (17 GW) installed solar capacity, is at the top followed by Gujarat, Karnataka, Tamil Nadu, and Maharashtra.

Figure 1 Southern and northern regions account for 71% of India's installed solar capacity



Source: Authors' analysis of MNRE's installed solar capacity database

2. Solar waste management is imperative

Given the large-scale solar capacity deployment expected in India in this decade, it is imperative to focus on the management of waste generated from existing as well as upcoming installations. While the design life of the modules is 25 years, some of them witness an early end of life (EoL) due to various factors during their lifecycle. For instance, modules may be damaged during transportation from the manufacturing facility to the installation site, module handling, and project operations. During operations, various technical failures and human errors are responsible for module loss. Cell cracks and snail tracks in crystalline silicon modules, hot spots in thin-film modules, and back contact degradation are some examples of failure types in different PV technologies (Köntges et al. 2014). Human errors such as poor installation and maintenance practices also contribute to early module loss. Lastly, some modules are also damaged due to local geography and natural calamities like cyclones and earthquakes (Tyagi and Kuldeep, 2021).

Handling this waste sustainably is essential from an environmental, economic, and social point of view. Solar waste contains different types of materials with varying levels of toxicity and economic value. Metals such as lead, cadmium, and tellurium are toxic to humans as well as the environment. Their leaching into the environment could contaminate water and soil resources. This is of huge concern given solar projects are located in remote as well as densely populated areas. The waste also contains metals like silver and silicon that have high economic value. They have applications in manufacturing industries like semiconductors, electronics, etc. Furthermore, irresponsible handling and disposal of solar waste could adversely impact the health of the workforce involved in the collection, dismantling, and recycling of this waste.

Responsible solar waste management also lays the foundation for a circular economy. Materials recovered from solar waste can be used for manufacturing new PV cells and modules. This will reduce the demand for virgin materials and will have a positive environmental impact by decreased mining and purification of virgin materials. Additionally, the entire process of waste management – collection, transportation, and recycling – can lead to the new employment opportunities.

Therefore, the management of solar waste is essential from both resource management and socio-economic perspectives.

Recently, the Ministry of Environment, Forest and Climate Change (MoEFCC) issued *E-waste Management Rules 2022* that shall govern the management of solar PV cells and modules waste in India (MoEFCC 2022). These rules, which are based on the extended producer responsibility framework, mandate the producers of solar cells and modules to manage their waste. The Indian solar industry must prepare for these new responsibilities by arranging for reverse logistics, storage, dismantling centres, and recycling facilities. They should also develop new financing mechanisms and business models for managing waste. Access to reliable data on the current waste estimates and its future trajectory will be critical to these activities.

2.1 Estimating solar waste

Various studies provide estimates for solar PV waste in different geographies. Some of these studies have projected the volume of PV waste for many countries up to 2050 for a 'regular loss' and an 'early loss' scenario, including Spain (Santos and Alonso-García 2018) and Australia (Mahmoudi, Huda, and Behnia 2019). According to International Renewable Energy Agency (IRENA), India's 200 GW–capacity, coupled with additional off-grid solar PV deployment, will generate 50 kilotonnes (kt) and 325 kt of solar waste in regular- and early-loss scenarios, respectively, in 2030 (IRENA and IEA-PVPS 2016). The input parameters used to estimate the waste are same across all countries and do not capture the impact of local geography on module performance.

Another study estimates the solar waste for low, medium, and high installation capacity scenarios until 2030 to be 11 kt, 21 kt, and 35 kt, respectively (SolarPower Europe, PV CYCLE, and NSEFI 2021). The scope of the study is limited to the transportation, installation, and operation stages of the PV module lifecycle; degradation of modules during the project operation has not been considered in these estimates.

These studies have some limitations with respect to the scope or methodology adopted and, hence, an India-centric study is needed to have an understanding of the local waste quantum and its geographical and temporal spread. Such assessment will also guide policies and market models by industry.

2.2 Objective

The study bridges the information gap for India-specific solar waste estimates by developing a comprehensive, coefficient-based model for solar waste estimation from various waste streams, excluding manufacturing. The coefficients are based on the primary data on module failure observed in Indian geographies. It is used to provide the temporal and spatial waste projections for India from the existing and new capacity additions.

The key value propositions of this work are:

- primary data on module failures and project performance across geographies for India-specific waste estimates
- granular spatial distribution of the waste at the state level
- delineation of the contribution of various waste streams (installation, transportation, operations, and EoL) to identify improvement opportunities
- reusability of the model by changing and adding various input parameters

The granular details on state-level estimates will highlight the likely waste generation centres to develop innovative waste management business models. It will also guide the strategic deployment of necessary infrastructure – collection centres, recycling facilities, etc. – which will lead to a holistic ecosystem with improved logistics and economics.

Image: iStock

3. Solar waste estimation model

This chapter describes the approach for solar PV module waste estimation and model development. The scope is limited to PV modules and excludes the balance of systems (BoS) used in solar projects. Broadly, there are two waste streams: waste during the manufacturing of solar modules and waste from the field (project lifetime) (Figure 2). These are further sub-categorised as follows:

a. Waste from module manufacturing

i. **Manufacturing scrap**: This stream refers to the scrap generated during PV cell manufacturing and module production.

ii. **Quality**: This stream refers to the waste arising from PV modules failing quality tests.

b. Waste from the field (project lifetime)

i. **Transportation and handling**: These streams refer to PV modules damaged during transportation and handling activities.

ii. **Project operation**: These streams refer to PV modules damaged from operational negligence or manufacturing defects arising during the project life.

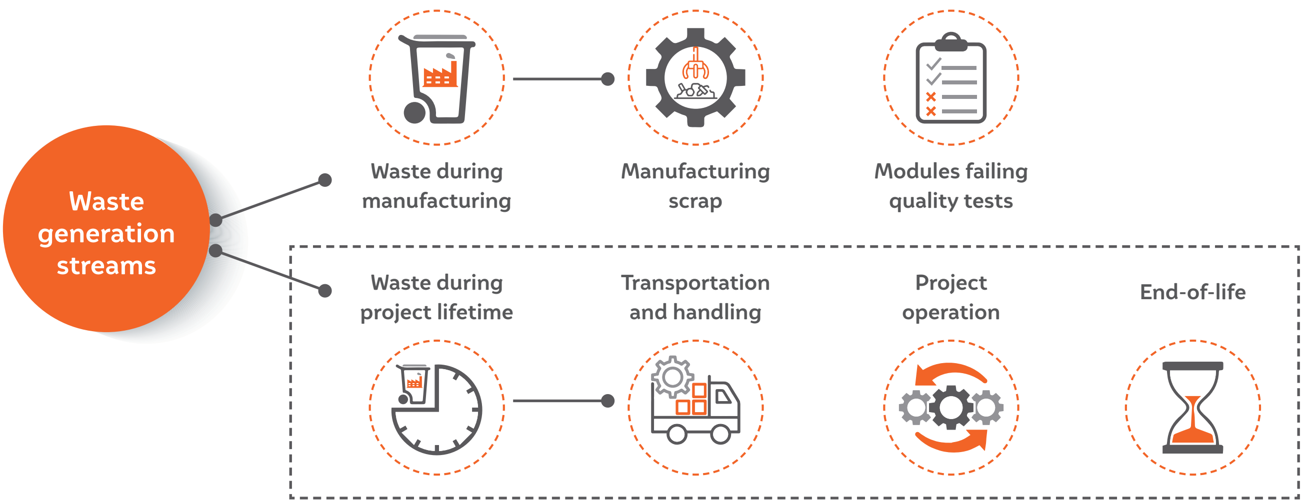
iii. **End-of-life**: This stream refers to the modules reaching EoL due to performance degradation observed in the field due to geographic and/or climatic conditions. Details of degradation rates observed across Indian states in different geographies are mentioned in Table A4 in Annexure 2.

3.1 Scope

For this study, **only the waste from the field (project lifetime) has been considered** and PV cell manufacturing and module production have been excluded. Each of these waste streams has a separate coefficient, derived from the primary data.

Other factors contributing to solar waste that have not been considered in this model are waste generated as a result of natural calamities and repowering. Solar projects are also damaged during natural events such as earthquakes, torrential rains, hailstorms, and landslides among others. Furthermore, with the increasing efficiency of PV modules due to technological advancement, repowering of existing capacity is also plausible. Repowering is the process of replacing older PV modules with new ones that have significantly improved performance and are also economically efficient. It also leads to a high power-to-mass ratio. However, based on the industry discussions, repowering is excluded from the current scope of the model. Lastly, the composition and manufacturing process of the modules has been considered for crystalline silicon–based modules and fixed for the entire analysis period (2009 to 2050). Technological changes – for instance, reduction in the silver content in silicon-based modules and deployment of heterojunction or bifacial modules – have not been considered, as their share in India's existing capacity is minimal.

Figure 2 Multiple streams contribute to solar waste



Source: Authors' analysis

Note: The streams marked in the box denote the scope of the model.

3.2 Assumptions

Some key assumptions of the model are:

- The annual capacity deployment begins in 2009 and ends in 2030. No further addition in installed capacity post-2030.
- The average lifespan for a PV module has been determined by calculating the number of years until the module efficiency remains above 80 per cent (Jordan and Kurtz 2013), and
- The average mass of 1 MW of solar modules has been taken as 65 tonnes for the entire analysis period (SolarPower Europe, PV CYCLE, and NSEFI 2021).

The following sections describe the approach, data collection, and coefficient development for all waste streams. This is referred as 'base case' in the study.

Transportation and handling

Approach: Transportation and handling (T&H) waste streams contribute to the first year, i.e., the year in which capacity is deployed. Waste generated during T&H ($W_{T\&H}$) is equal to the product of the mass of the capacity (M) and the coefficient ($C_{T\&H}$) (Equation 1):

$$W_{T\&H} = M * C_{T\&H} \qquad 1$$

Data: $C_{T\&H}$ is calculated from the primary data collected from solar power plant developers. A total of 2.3 GW capacity, spread across 24 projects, was analysed in this study. Annexure 1 (Table A1) presents the sampling strategy and representativeness of the sample set. Project age ranged from the installation year (zero year) to 11 years, with the average being 10 years (Table A2, Annexure 2). The coefficient is calculated as Equation 2. An average of coefficients for different plants gives $C_{T\&H}$:

$$C_{T\&H} = \frac{\text{Capacity damaged (MW)}}{\text{Total capacity analysed (MW)}} \qquad 2$$

Coefficient ($C_{T\&H}$): 0.2 per cent

Project operation

Approach: Project operation (PO) waste stream contributes from the installation year (zero year) to the penultimate useful life year (EoL – 1). Waste generated during project operation (W_{PO}) is equal to the product of the mass of the capacity (M) and the coefficient (C_{PO}) (Equations 3 and 4):

$$W_{PO} = M * C_{PO} \qquad 3$$

Cumulative waste is:

$$W_{PO} = \sum_{i=\text{installation year}}^{EoL-1} (W_{PO})_i \qquad 4$$

Data: C_{PO} is calculated from the primary data collected from solar power plant developers. A total of 2.3 GW capacity, spread across 24 projects, was analysed in this study. Project age ranged from the installation year (zero year) to 11 years, with the average being 10 years (Table A3 Annexure 2). For a capacity of a certain age, the coefficient is calculated as Equation 5. An average of coefficients for different plants gives C_{PO}:

$$C_{PO} = \frac{\text{Capacity damaged (MW)/ Total capacity analysed (MW)}}{\text{Plant age (years)}} \qquad 5$$

Coefficient (C_{PO}): 0.5 per cent

End-of-life

Approach: The expected EoL of the capacity is calculated depending on the annual degradation rate (DR). At the EoL, it is assumed that the remaining plant capacity (M_{Eff}) will be decommissioned over five years (EoL + 4) (Equation 6). The capacity turning into waste over these five years is 10 per cent, 15 per cent, 20 per cent, 25 per cent, and 30 per cent, respectively, of the remaining useful capacity at EoL (M_{Eff}) (Equation 7).

$$M_{Eff} = M - (W_{T\&H} + W_{PO}) \qquad 6$$

$$W_{EOL} = \sum_{i=EoL}^{EoL+4} W_i \qquad 7$$

where M is the mass of the capacity installed, W_i is $M_{Eff} * C_i$ and C_i is 10%, 15%, 20%, 25%, and 30% for the five years, respectively.

Calculating the EoL of modules

The EoL of the capacity is calculated by taking module performance at the beginning as 100 per cent, module performance at the beginning of a year as ME_{start}, and module performance at the end of a year as ME_{end}:

$$ME_{end} = ME_{start} - DR \qquad 8$$

The iterative process of calculating ME_{end} is conducted until it reaches less than 80 per cent. The number of years taken to reach less than 80 per cent performance (X) from the installation year gives the EoL:

$$EoL = Installation\ year + X \qquad 9$$

Data: For most applications, PV modules are deemed useful by the time their output remains over 80 per cent (Waaree 2022). This gives a linear degradation rate of 0.82 per cent.[1] However, the situation can differ in the field. Degradation rates (DR) have also been calculated from the primary data on project performance across states. The average DR observed across geographies gives the pan-India accelerated degradation rate (5.2 per cent) (Table A4, Annexure 2). A periodic exercise by the National Centre for Photovoltaic Research and Education (NCPRE) also reports the observed degradation rates from different Indian geographies (NCPRE-IIT Bombay and NISE 2017). The study covers several sites of different plant sizes and technologies. The crystalline silicon–based modules showed an average linear degradation rate of 1.4 per cent per year. Due to a larger sample size, the model uses this degradation rate in the base case for calculating the EoL of modules.

Coefficient (degradation rate): 1.4 per cent

It should be noted that the data points for Tables A2, A3, and A4 in Annexure 2 are from two different data sets. Hence, there is no correlation between the waste generated during project operation with respect to the degradation rates observed across various climatic regions. Table 1 summarises the various coefficients used in this report for PV waste estimation. These are used as input parameters in the waste estimation model.

Table 1 Coefficients used in the analysis for different solar waste streams

Waste stream	Coefficient symbols	Coefficient values
Transportation and handling	$C_{T\&H}$	0.2%
Project operation	C_{PO}	0.5%
Degradation rate	C_{DR}	1.4%

Source: Authors' analysis

Hence, capacity degradation will be as follows:

- Transportation- and handling-related losses in the first year of installation ($W_{T\&H}$)
- Project operation–related losses from the installation to the penultimate useful life year (EoL – 1) (W_{PO})
- Complete loss at EoL + 4 years (W_i)

The cumulative waste generated will be:

$$W_c = W_{T\&H} + \sum_{i=installation\ year}^{EoL-1} (W_{PO})_i + \sum_{EoL}^{EoL+4} W_i \qquad 10$$

Total waste generated in a certain year (Y) is the sum of waste from transportation and handling, and total capacity under operation in that year (including any EoL waste). The same is represented as:

$$W_Y = (W_{T\&H})_Y + (W_{PO})_Y + \sum_{i=2009}^{Y-1} (W_c)_i \qquad 11$$

An example of the determination of waste generated from various waste streams due to the capacity degradation of an installation is provided in Box 1.

1. Twenty-five years is the useful lifetime of modules as warranted by module manufacturers. A linear degradation rate of 0.82 per cent is obtained for the modules to reach an efficiency below 80 per cent at the end of 25 years.

BOX 1 **Sample calculation to determine the waste generated because of a capacity degradation**

Consider a 100 MW solar PV capacity installation in 2011. The waste generated from this installation for a C_{DR} of 1.4 per cent (base case) by the year 2030 is determined as follows:

i. Mass: For a 100 MW capacity, the mass is M = 6,500 tonnes (1 MW = 65 tonnes)

ii. Waste generated during transportation and handling, i.e., in 2011:
$W_{T\&H} = M * C_{T\&H} = 6{,}500 * 0.2\% = 13 \text{ tonnes}$

iii. Waste generated during project operation from 2011 onwards, annually:
$W_{PO} = M * C_{PO} = 6{,}500 * 0.5\% = 32.5 \text{ tonnes}$
This waste is generated till the capacity reaches EoL.

iv. Time taken to reach less than 80 per cent performance (X years)
$X = 15 \text{ years}$
$EoL = \text{installation year} + X = 2011 + 15 = 2026$

v. Waste generated during the entire project operation phase:

$$W_{PO} = \sum_{i=\text{installation year}}^{EoL-1} (W_{PO})_i = \sum_{i=2011}^{2026-1} (W_{PO})_i = 32.5 * 15 = 487.5 \text{ tonnes}$$

vi. Waste generated at EoL:

$M_{Eff} = M - (W_{T\&H} + W_{PO}) = 6{,}500 - (13 + 487.5) = 5{,}999.5 \text{ tonnes}$

$W_{2026} = M_{Eff} * 0.10 = 599.9 \text{ tonnes}$

$W_{2027} = M_{Eff} * 0.15 = 899.9 \text{ tonnes}$

$W_{2028} = M_{Eff} * 0.20 = 1{,}199.9 \text{ tonnes}$

$W_{2029} = M_{Eff} * 0.25 = 1{,}499.9 \text{ tonnes}$

$W_{2030} = M_{Eff} * 0.30 = 1{,}799.9 \text{ tonnes}$

vii. Total waste generated by 2030 for an installation capacity of 100 MW:

$$W_c = W_{T\&H} + \sum_{i=\text{installation year}}^{EoL-1} (W_{PO})_i + \sum_{EoL}^{EoL+4} W_i = 13 + 487.5 + 5{,}999.5 = 6{,}500 \text{ tonnes}$$

Source: Authors' compilation

3.3 Scenarios

The study also uses some scenarios to compare the waste estimates in the base case. Scenario 1 uses the coefficient-based approach while Scenarios 2 and 3 use the Weibull function (Equation 12), as per the methodology developed by IRENA and International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) division to estimate India's solar waste (IRENA and IEA-PVPS 2016). The three scenarios are:

- **Scenario 1: Coefficient-based–regular loss (CB–RL)**
  This scenario follows the approach described in section 3.2, with a 0.82 per cent annual degradation rate, calculated from the warranted performance provided by module manufacturers.

- **Scenario 2: Weibull–regular loss (W–RL)**
  This scenario uses the Weibull function to model the PV module degradation (IRENA and IEA-PVPS 2016). The shape parameter is 5.37.

- **Scenario 3: Weibull–early loss (W–EL)**
  This scenario uses the Weibull function to model the PV module degradation (IRENA and IEA-PVPS 2016). The shape parameter is 2.49.

Table 2 summarises the three scenarios and key differences.

Table 2 Overview of waste estimation scenarios

Scenario	Code	Details
Base case	Base case	CEEW model (coefficient-based approach) with an observed annual degradation rate of 1.4%
Scenario 1: Coefficient-based–Regular Loss	CB–RL	CEEW model (coefficient-based approach) with a degradation rate of 0.82%
Scenario 2: Weibull–Regular Loss	W–RL	IRENA's model–regular loss, shape parameter: 5.37
Scenario 3: Weibull–Early Loss	W–EL	IRENA's model–early loss, shape parameter: 2.49

Source: Authors' analysis

Weibull function for solar waste estimation

Weibull function, as defined in Equation 12, is a continuous probability distribution used to analyse life data, model failure times, and access product reliability:

$$F(t) = 1 - e^{-(t/T)\alpha} \qquad 12$$

where F(t) is the cumulative density function; t is time in years; T is the scale factor (here, the average useful lifetime of the module taken as 25 years); α is the shape factor (5.37 for regular loss (Kuitche 2010) and 2.49 for early loss scenario (IRENA and IEA-PVPS 2016)).

In 2016, IRENA and IEA-PVPS used this function to assess global solar waste generation. Waste generated from the capacity installed in a particular year (with mass M) using this methodology (W_{WF}) during the analysis period (2009 to 2050: 42 years) is given by Equation 13:

$$W_{WF} = M * \sum_{t=1}^{42} F(t) \qquad 13$$

This approach is different from the coefficient-based approach proposed in this report. The Weibull function models the EoL of the PV modules. IRENA has also developed two scenarios (regular loss and early loss), with different values of the shape parameter to estimate the solar waste. The shape parameter of the function is derived from the literature in the case of the regular loss scenario whereas it is determined by conducting a regression analysis in the case of the early loss scenario and remains the same for all geographies (IRENA and IEA-PVPS 2016). A lower shape parameter considers early defects that result in a higher loss of modules in the useful lifetime of 25 years whereas a higher shape parameter results in the opposite.

The coefficient-based approach proposed in this report allows users to estimate the contribution of different waste streams. Such an understanding can encourage process efficiencies to minimise the overall waste generation from a solar project.

3.4 Limitations

The coefficient-based approach proposed in this report has some limitations that can alter the waste estimates:

- The weight-to-power ratio of the PV modules (tonnes/MW) will decrease in the coming years with the advancement of PV technologies. This will result in a decrease in the amount of PV waste generated in the coming decades. However, the performance of these modules (degradation rates and failure modes) also needs to be observed in the field. Hence, our study uses a constant mass-to-power ratio in the entire analysis period.

- Only 2.3 GW of deployed capacity spread across 24 projects was used to determine the coefficients for transportation and handling, and project operation. Hence, the analysis may not have captured, in entirety, the variability across the country (hilly regions/plains), which affect the coefficient values in the field.

- The primary data collected from developers is largely representative of the utility-scale deployments. The rooftop solar and off-grid installations are underrepresented in this dataset. This sector can have different waste coefficients, especially for module handling and project operation stages. These deployments are also found in residential and agricultural areas where the consumers might not follow recommended maintenance practices leading to premature module damage.

- Technology- and manufacturer-specific module weight have not been considered in our model to determine the weight of the annual installed capacity.
- Repowering trends have not been covered, which would alter the annual waste projections. This is based on the industry feedback received that denied any major repowering trends in India in this decade.

Image: iStock

4. India's solar waste estimates

This chapter gives estimates for India's solar waste in various scenarios by 2050 as defined in Chapter 3. Here, we assume that installed solar capacity will reach 292 GW by 2030. The annual capacity installations between 2009 to 2023 are taken from the Ministry of New and Renewable Energy (MNRE) database, which puts the national capacity at 66.7 GW as of March 31, 2023 (FY23). The remaining capacity (225 GW) is distributed across seven years (FY24 to FY30), with a 44 per cent compounded annual growth rate (CAGR). No new solar capacity additions are assumed post 2030.

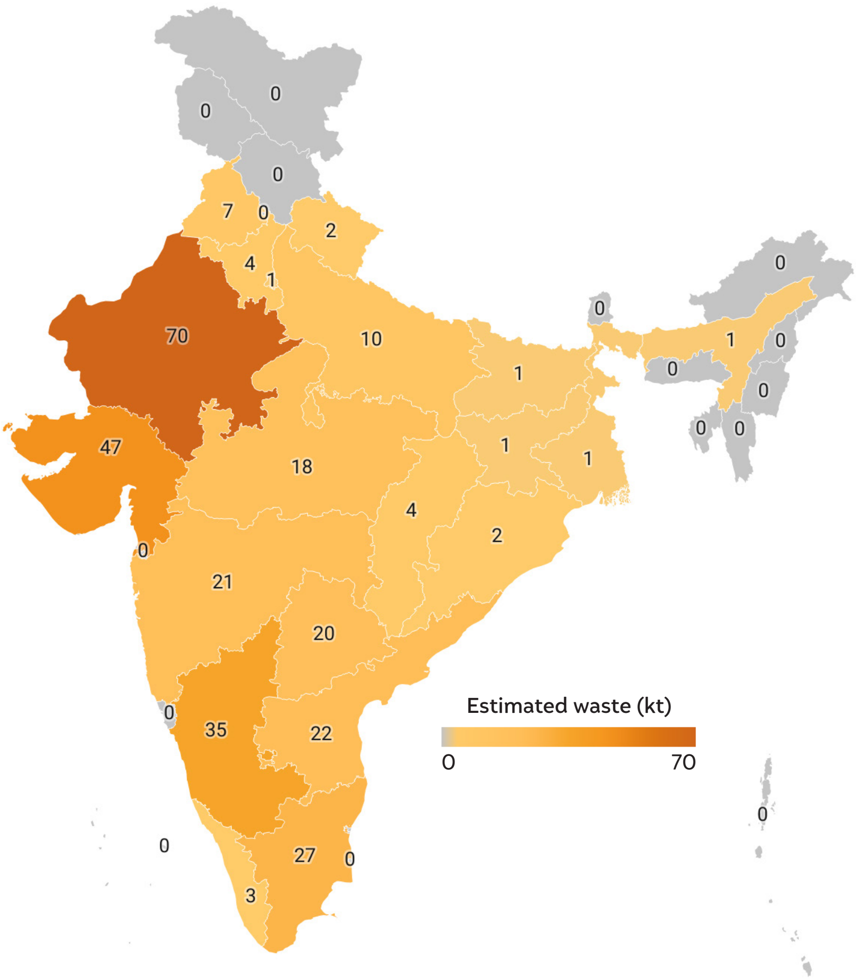
4.1 Waste estimates in the base case

This section provides the solar waste estimates in the base case, i.e., the coefficient-based approach with observed degradation rate. It further presents the waste arising from the installed and upcoming solar capacity.

Waste from installed solar capacity

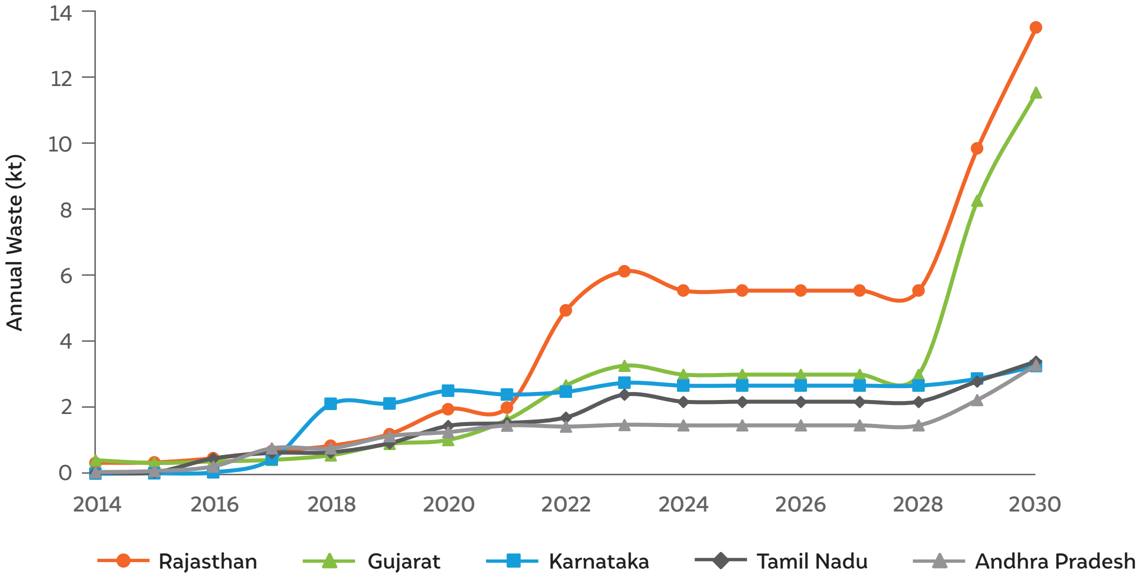
In the base case with observed degradation rate (base case), India's 66.7 GW capacity as of FY23 has already generated 99 kt (about 100 kt) of solar PV waste. This will increase more than three times, to 334 kt (about 340 kt), by 2030 (Figure 3). About 67 per cent of this waste is expected to be generated in five states, Rajasthan, Gujarat, Karnataka, Tamil Nadu and Andhra Pradesh, which are the top states for installed solar capacity (Figure 1). Rajasthan alone will account for 24 per cent of this waste, followed by Gujarat (16 per cent), and Karnataka (12 per cent). Between FY14 and FY30, Rajasthan and Gujarat will have generated about 4.1 and 2.7 kt of waste per annum, respectively (Figure 4). The remaining three states could generate 2.0 to 1.2 kt of waste per annum. Annexure 3 contains annual waste estimates for all the states and union territories by 2030. Figure A1 in Annexure 4 presents the contribution of different waste streams (transportation and handling, operation and EoL) in the cumulative waste generated by 2030.

Figure 3 ~67% of solar waste in 2030 will occur in five states



Source: Authors' ana

Figure 4 Rajasthan and Gujarat will lead the solar waste generation in 2030



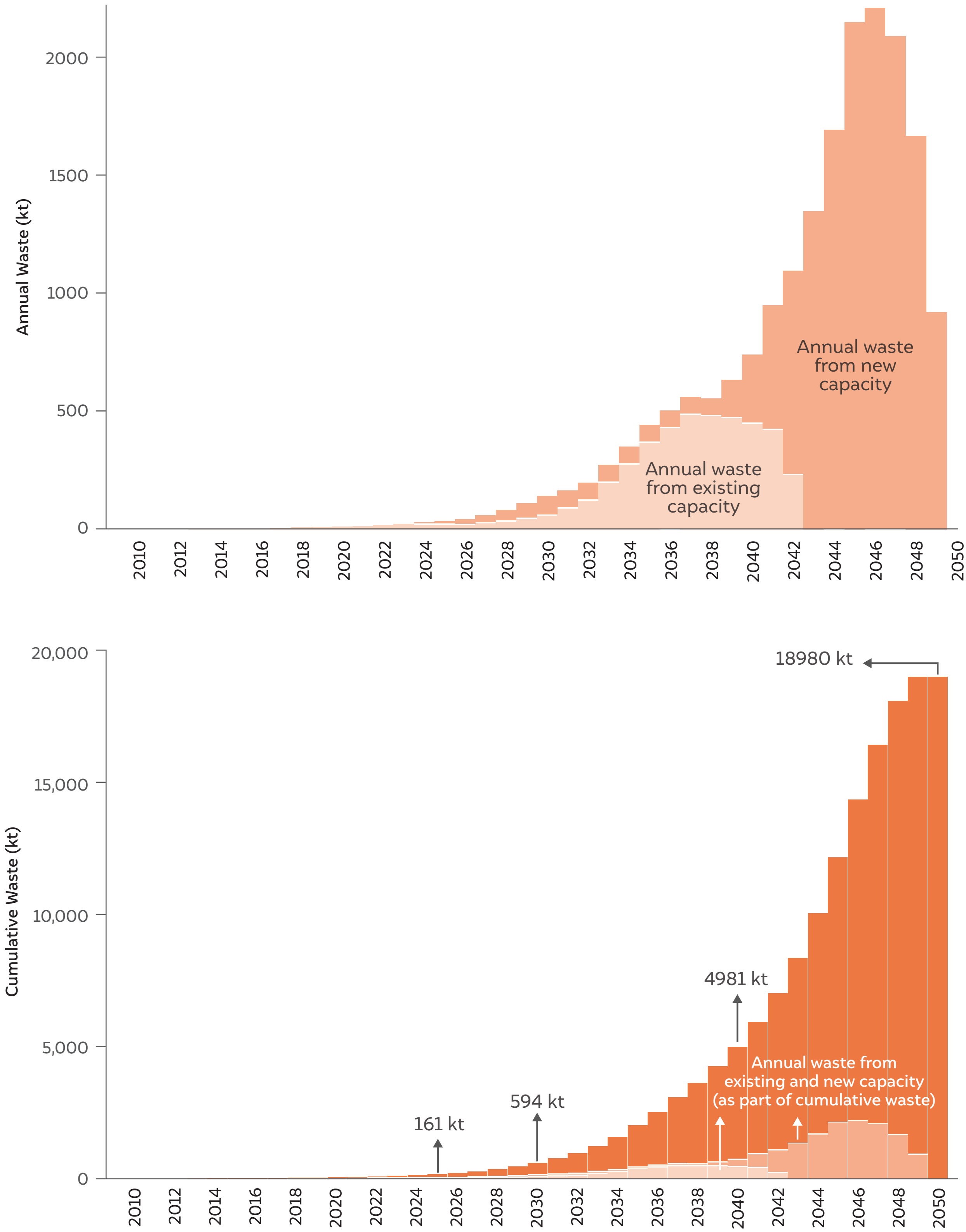
Source: Authors' analysis

Waste from future capacity

The study assumes that India will deploy about 225 GW of new solar capacity between FY24 and FY30 to reach 292 GW capacity. This capacity will generate 594 kt (about 600 kt) of waste by 2030 in the base case (Figure 5). About 56 per cent (334 kt) of this cumulative waste will come from existing projects (installed no later than FY23). The new installations deployed between FY24 and FY30 will represent the remaining 44 per cent (260 kt) of cumulative waste in 2030. By 2040, the cumulative waste could increase more than eight times, to reach 4981 kt (Figure 5). Around 74 per cent (3689 kt) of this will come from the existing capacity (until FY23), while the remaining 26 per cent (1292 kt) from the new installations (post-FY23). This increase is because existing installations will have reached EoL. As for 2050, all the capacity deployed until 2030 will have reached EoL, generating a cumulative waste of 18,980 kt (about 19000 kt) (Figure 5). The annual waste quantum between 2047 and 2050 decreases as the majority of the installed capacity has already reached EoL and no new capacity additions are assumed post 2030.

Image: iStock

Figure 5 **India's cumulative solar waste would increase about 32 times between 2030 and 2050**



Source: Authors' analysis

4.2 Waste estimates across scenarios

Figure 6 compares the waste generation in the base case with other scenarios as discussed in the following sections.

Coefficient-based–regular loss

This scenario employs a lower degradation rate of 0.82 per cent, based on the 80 per cent performance warranted by module manufacturers up to 25 years. This degradation rate extends the useful life of the module by 10 years. Hence, by 2030, Scenario 1 produces 14 per cent less waste (511 kt) than the base case (594 kt). This translates to about 1.3 GW (83 kt) of solar capacity, withstanding premature damage. Results also suggest that by 2030, the non-EoL waste streams – transportation, handling, and project operations – will dominate.

It is important to note that the impact of a reduced module life due to a change in degradation rates (1.4 per cent in the base case versus 0.82 per cent in Scenario 1) is visible post-2030 when the majority of the installed capacity will start reaching EoL. This results in a difference of about 3,400 kt between the base case and Scenario 1 in 2040 and about 13,000 kt in 2050 (Figure 6). These results show that imposing tighter quality standards to rein in early degradation as well as better transportation and module handling practices in the solar industry can bring down the decadal waste production.

BOX 2 Material composition of the solar waste

Currently, the majority of the installed solar capacity (93 per cent) uses crystalline silicon–based module technology while the remaining uses cadmium telluride–based module technology (Suresh, Singhvi, and Rustahi 2019). The 334 kt of waste generated from the existing capacity by 2030 translates to about 5.1 GW in solar capacity (using the 65 tonnes/MW conversion factor). Furthermore, it will likely contain a total of 252 kt of glass, 32 kt of aluminium, 10.4 kt of silicon, and 12–18 tonnes of silver. It will also contain 16 tonnes of cadmium and tellurium each, and 190 tonnes of lead (See Annexure 5).

Source: Authors' compilation

Image: Goldi Solar

Weibull– regular loss and early loss

Waste estimates using the Weibull function for Scenarios 2 and 3 are 106 kt and 722 kt by 2030, respectively, are different from the base case (594 kt). However, the trend of greater waste generation with shape parameters is the same as the coefficient-based method proposed here. By 2040, for Scenarios 2 and 3, the waste estimates stand at 2,101 kt and 4,820 kt, respectively, which are also lower than the base case estimates.

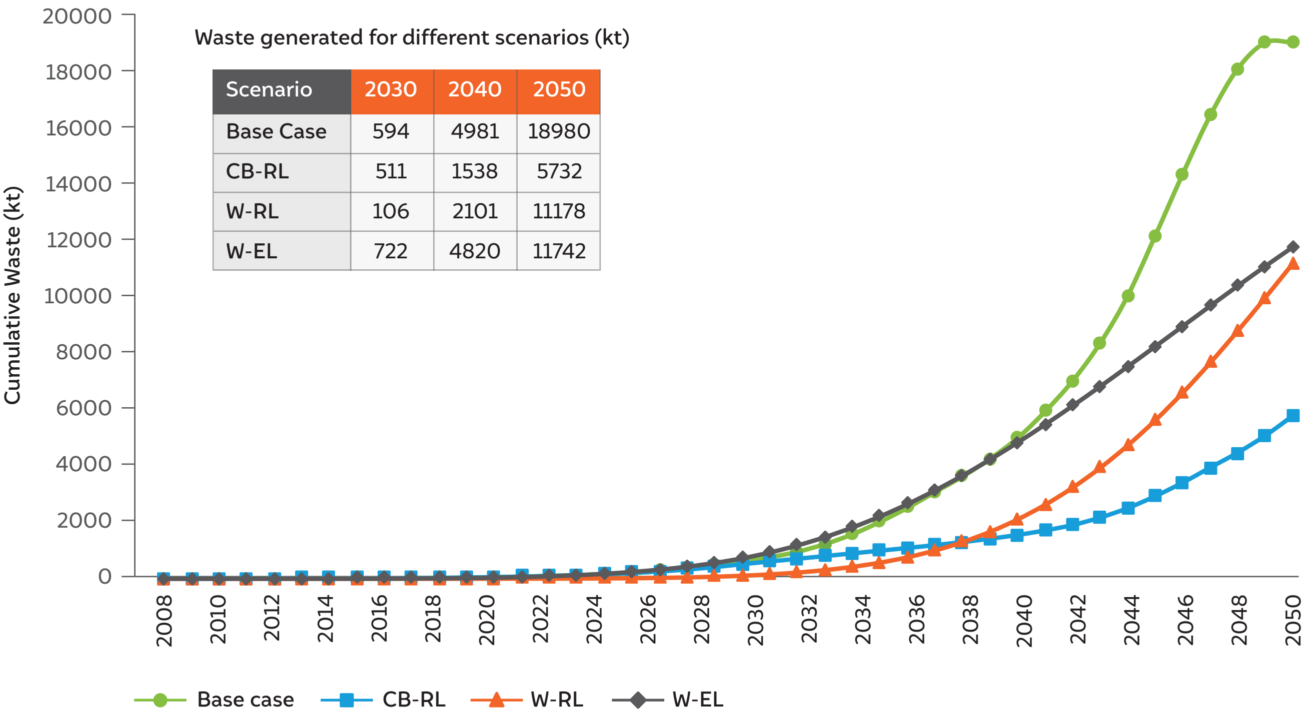
Between 2009 and 2030, the average annual waste generation is lowest for Scenario 2 and highest for Scenario 3 (Table 3). On the other hand, the annual waste generation between 2031 and 2050 is the lowest for Scenario 1 and highest for the base case.

Table 3 Variations in the average annual and cumulative solar PV waste across scenarios

Case	Code	Average annual waste (kt)		Cumulative waste (kt)
		2009–30	2031–50	
Base case	Base Case	27	919	18,980
Scenario 1: Coefficient-based–Regular Loss	CB–RL	23	261	5,732
Scenario 2: Weibull–Regular Loss	W–RL	5	553	11,178
Scenario 3: Weibull–Early Loss	W–EL	33	551	11,742

Source: Authors' analysis

Figure 6 India's cumulative waste will start increasing after 2040, as more of the capacity will reach EoL



Scenario	2030	2040	2050
Base Case	594	4981	18980
CB-RL	511	1538	5732
W-RL	106	2101	11178
W-EL	722	4820	11742

Source: Authors' analysis

5. Conclusion and recommendations

This is a crucial decade for the Indian solar industry. The solar capacity and waste quantum will grow manifold towards the end of this decade. Hence, it is important to prepare for the responsible handling of solar waste and leverage the multiple environmental, economic, and social benefits that accompany it. This will require a clear policy for waste management, recycling technologies, business models, and markets for recovered materials.

This study presents a comprehensive solar waste estimation model that uses India-specific coefficients for the estimation of module waste from different streams. Besides national-level estimates, the model also allows for waste estimation at the state level. This study indicates that India's solar waste estimates could lie between 100 to 700 kt by 2030, depending on the scenario. By 2050, these estimates could go up to 19,000 kt in the base case scenario. Several Indian states are already witnessing significant quantities of waste (in the range of 99 kt); however, the majority of the waste will likely be generated from the capacities deployed between 2024 and 2030.

Recommendations

Estimating PV waste is the first step towards a circular economy for the solar industry. Efforts from all stakeholders are required to create a comprehensive circular economy ecosystem. We have four priority recommendations to prepare for this impending waste crisis:

- **MNRE should maintain a comprehensive database of the installed solar capacity**: Accurate and granular mapping of the solar capacity (technology, producer, etc.) across various deployment modes (grid-connected, distributed, and decentralised) would aid in the mapping of waste generation locations and planning of infrastructure development for handling the waste generated. Hence, MNRE should create and update a comprehensive database of installed solar capacity.

- **MoEFCC should issue implementation guidelines for the E-waste Management Rules**: Although the rules provide the initial guidance on the responsibility of various actors, details are awaited on essaying these responsibilities. Detailed implementation guidelines for the collection and storage of solar waste will nudge the producers to build capacity and infrastructure for compliance. Furthermore, MoEFCC should also consider promoting safe recycling of and recovery from solar waste. These are new responsibilities for the solar industry, which might necessitate some time to adapt.

- **Solar module manufacturers should start building waste management infrastructure**: As per the E-waste Management Rules, producers must build collection centres and storage facilities for the waste generated until 2035. As the solar modules are huge, the storage requirements could be large. With MNRE supporting solar PV recycling, manufacturers should also build recycling facilities of their own or outsource recycling operations to third-party vendors with expertise in solar PV recycling according to their chosen business models (PIB 2023a). Furthermore, a majority of utility scale solar projects are located in remote locations, which may be far from the manufacturing centres, leading to high transportation costs for waste modules. The waste estimation model proposed here can be used for the identification of the locations for the development of these facilities to optimise the logistics and overall waste management costs.

- **Academia and industry should accelerate module recycling technology innovation**: Solar module recycling is still at a nascent stage with no commercially operational facility in India (See Annexure 6 for more details on recycling technologies). A majority of the processing routes available today allow recovery of aluminium and glass, that represent more than 80 per cent of the module mass (Table A6, Annexure 5). Limited proven solutions exist for recovery of metallic components such as silicon, silver and copper, which represent more than half of the economic value of solar modules. It is important that the recycling industry and academia expedite their efforts on developing efficient recycling technologies and processes that allow recovery of bulk as well as high value components from solar waste. Identifying a commercially viable solution would require extensive research and development, and pilot demonstrations. Solar module manufacturers and project developers should actively support recycling technology providers in this entire process.

Annexures

Annexure 1: Representativeness of primary data

Table A1 shows the coverage (per cent) of the commissioned solar capacity mapped in the sample.

Table A1 Representativeness of the primary capacity data on module failure

Zones	Total commissioned capacity mapped (GW)[2]	Capacity (GW) covered in the sample	Capacity covered (%)
Southern	16.43	1.2	7.3
North Eastern	0.10	0	0
Eastern	0.93	0.03	3.2
Central	4.57	0.31	6.8
Western	3.82	0.3	7.8
Northern	3.19	0.51	15.9
Total	**29.05**	**2.3**	**7.9**

Source: Authors' analysis

Note: Statistical calculations for capacity covered were mean: 6.9%; standard deviation: 5.4%; sampling error at 95% confidence interval for total capacity covered: 9.17%.

Annexure 2: Primary data for various coefficients

Table A2 Data points for waste generated during transportation and handling

S.No.	A: Total capacity analysed (MW)	B: Capacity turned waste (MW)	C = B/A	D = average (C) $C_{T\&H}$
1	300	0.44	0.1%	0.2%
2	150	0.25	0.1%	
3	25	0.15	0.6%	
4	20	0.02	0.1%	
5	30	0.17	0.5%	

Source: Authors' analysis

2. Out of the installed 66.7 GW solar capacity, the commissioning date in the MNRE database is mentioned for 29 GW capacity only.

Table A3 Data points for waste generated during project operation

S.No.	A: Capacity age (years)	B: Total capacity analysed (MW)	C: Capacity turned waste (MW)	D: C/B	E: D/A	C_{PO} = Average (E)
1	1	150	3.0	2.0%	2.01%	0.5%
2	5	1,000	2.8	0.3%	0.06%	
3	6	139	0.4	0.3%	0.05%	
4	7	200	0.4	0.2%	0.03%	
5	8	130	4.1	3.1%	0.39%	
6	9	470	9.9	2.1%	0.23%	
7	11	45	4.8	10.8%	0.98%	

Source: Authors' analysis

Table A4 Observed degradation rates across regions

Region	A: AC capacity analysed (MW)	B: Degradation rate (%)	Average (B) C_{DR}
Hot Arid	1,311	2.8	5.2%
Semi-Arid	4,568	2.7	
Subtropical Humid	450	4.9	
Tropical Wet	2,510	10.5	

Source: Authors' analysis

Annexure 3

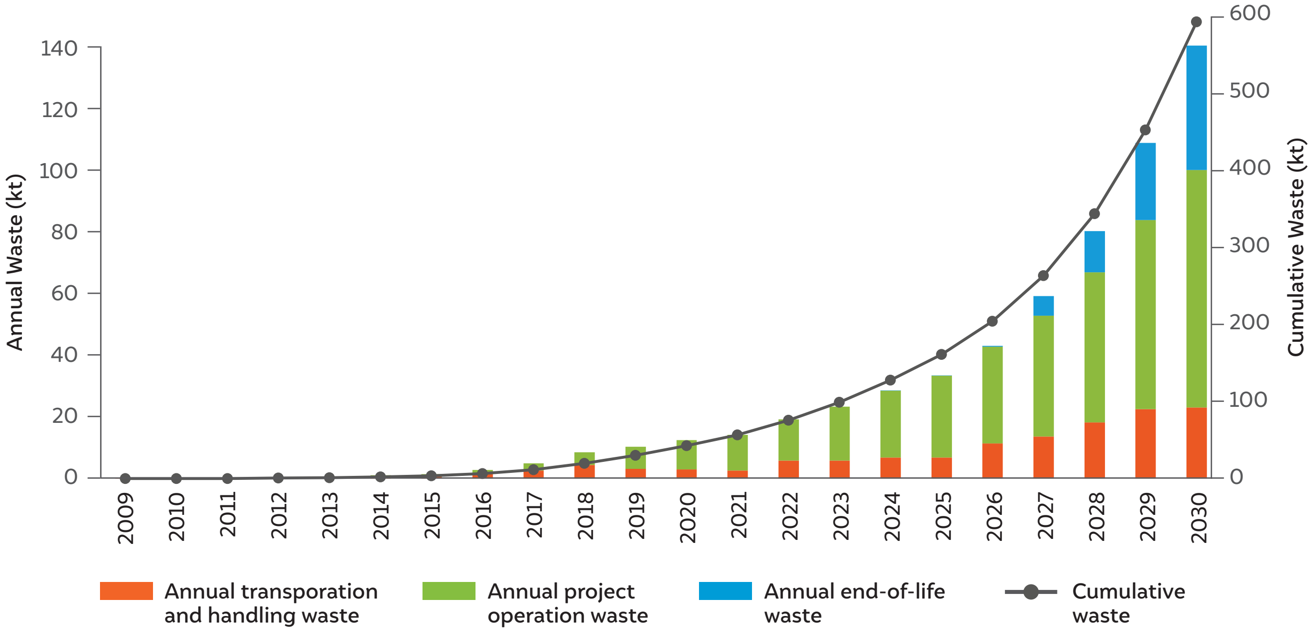
Table A5 Annual waste estimates in tonnes for different states and union territories by 2030

State/ UT \ Financial Year	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
Andhra Pradesh	1,473	1,439	1,494	1,475	1,475	1,475	1,475	1,475	2,247	3,292
Arunachal Pradesh	4	4	4	4	4	4	4	4	12	18
Assam	17	47	53	49	49	49	49	49	58	65
Bihar	61	65	64	64	64	64	64	64	72	77
Chhattisgarh	147	177	364	308	308	308	308	308	438	529
Goa	2	8	9	8	8	8	8	8	9	9
Gujarat	1,646	2,686	3,278	3,008	3,008	3,008	3,008	3,008	8,267	11,528
Haryana	180	352	349	334	334	334	334	334	430	497
Himachal Pradesh	17	27	28	27	27	27	27	27	44	58
Jammu & Kashmir	14	15	16	16	16	16	16	16	60	90
Jharkhand	26	33	38	36	36	36	36	36	132	184
Karnataka	2,409	2,493	2,762	2,677	2,677	2,677	2,677	2,677	2,886	3,265
Kerala	104	128	298	246	246	246	246	246	270	289
Ladakh	0	4	3	3	3	3	3	3	3	3
Madhya Pradesh	859	908	923	912	912	912	912	912	2,897	5,150
Maharashtra	820	897	1,809	1,537	1,537	1,537	1,537	1,537	2,962	4,353
Manipur	4	3	3	3	3	3	3	3	8	13
Meghalaya	1	1	1	1	1	1	1	1	6	11
Mizoram	0	0	9	7	7	7	7	7	12	19
Nagaland	0	0	0	0	0	0	0	0	7	11
Odisha	139	151	148	148	148	148	148	148	326	429
Punjab	322	374	389	380	380	380	380	380	503	1,527
Rajasthan	2,010	4,946	6,126	5,543	5,543	5,543	5,543	5,543	9,834	13,487
Sikkim	1	2	2	2	2	2	2	2	11	16
Tamil Nadu	1,543	1,716	2,405	2,188	2,188	2,188	2,188	2,188	2,804	3,404
Telangana	1,330	1,541	1,535	1,516	1,516	1,516	1,516	1,516	1,516	1,873
Tripura	4	5	5	5	5	5	5	5	22	58
Uttar Pradesh	678	782	852	817	817	817	817	817	1,076	1,534
Uttarakhand	130	211	187	187	187	187	187	187	253	290
West Bengal	58	56	61	60	60	60	60	60	160	215
Andaman & Nicobar	12	10	10	10	10	10	10	10	40	56
Chandigarh	16	19	20	19	19	19	19	19	35	57
Dadar & Nagar Haveli	2	2	2	2	2	2	2	2	2	2
Daman & Diu	15	13	13	13	13	13	13	13	13	13
Delhi	67	71	71	70	70	70	70	70	102	123
Lakshadweep	1	1	1	1	1	1	1	1	11	16
Pondicherry	4	5	14	11	11	11	11	11	12	12

Source: Authors' analysis

Annexure 4

Figure A1 Contribution of various waste streams to annual waste by 2030



Source: Authors' analysis

Annexure 5

Table A6 Composition of a crystalline silicon PV module and cadmium telluride thin film module

Module technology	Material	Share (%) (kg/kWp)	Quantity (kt) in waste by 2030 (base case) from existing capacity
Crystalline Silicon	Glass	74.16	230
	Aluminium	10.3	32
	Silicon	3.35	10.4
	Copper	0.57	1.8
	Tin	0.12	0.4
	Silver	0.004–0.006	0.012–0.018
	Zinc	0.12	0.4
	Lead	0.06	0.19
	Tedlar (Backsheet)	3.6	11.2
	EVA (Encapsulant)	6.55	20.3
Cadmium Telluride (CdTe)	Glass	95	22
	Cadmium	0.07	0.016
	Tellurium	0.07	0.016
	Copper	1	0.23
	Tin	0.043	0.01
	Zinc	0.01	0.0023
	Silicon	0.0064	0.0015
	Aluminium	0.35	0.08
	EVA	3.5	0.8

Source: Paiano 2015

Annexure 6: Overview of solar module recycling technologies

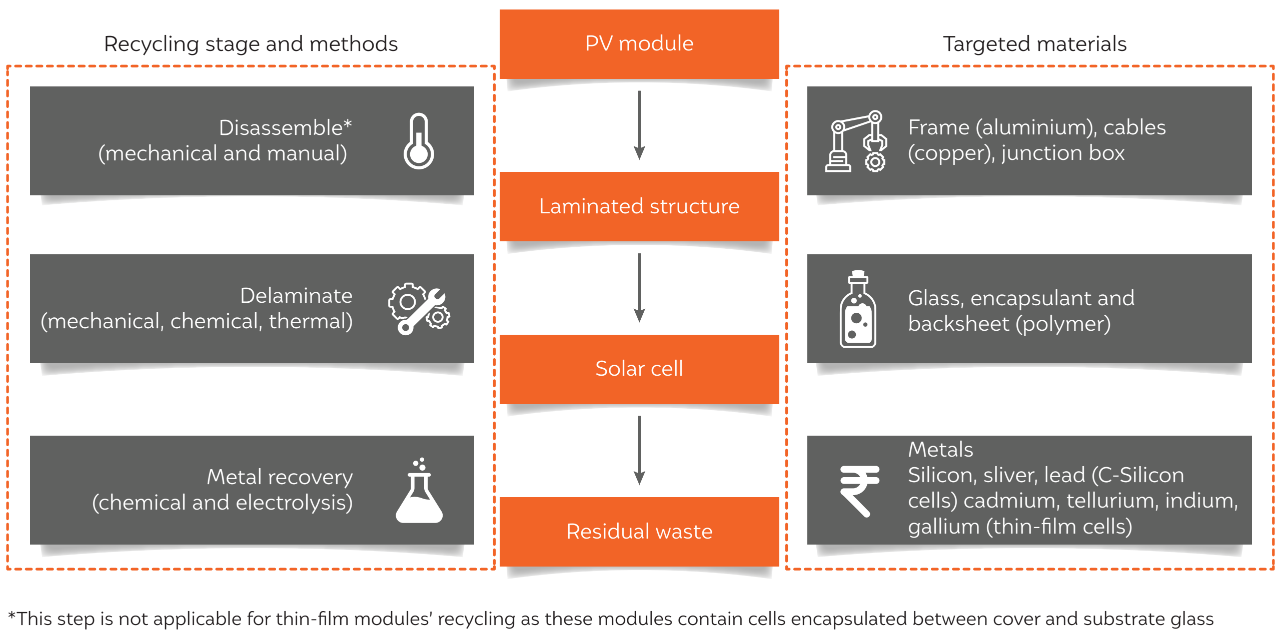
Recycling of solar panels consists of three main steps: module disassembly, delamination, and metal recovery (Figure A2). The objective of the disassembly stage is to separate the aluminium frame, cables, and junction box from the solar panel. The objective of the delamination stage is to separate the glass and encapsulation layers (EVA and back sheet) from the solar cell; while the objective of the metal recovery stage is to recover the metals and other materials present in the solar cell. Disassembly is a simple process as the components are located on the outer periphery of the solar panel and can be separated by simple mechanical or manual processes. Delamination is considered a complex process than disassemble and metal recovery because of the presence of very tightly packed glass, EVA, back sheet, and solar cell layers.

Solar panel recycling can be divided into two broad types:

1. **Conventional recycling or bulk material recycling**: Conventional recycling makes use of mechanical processes like crushing, sieving, and shearing. This method can recover 70-80 per cent of crystalline-Silicon (c-Si) solar panel raw materials by weight. Majority of the recycled materials consist of glass, aluminium, and copper (IEA PVPS TCP, 2022). The more valuable materials, like silver and silicon, are not recovered in this process. A recent mechanical process, commercialised by NPC Incorporated in Japan, is hot diamond blade cutting which uses a diamond or hot blade to cut through the photovoltaic cells, thus separating the solar panel's front glass from back sheet polymer (Lunardi, Alvarez-Gaitan, Bilbao, & Corkish, 2018; Spaes, 2021). This process also utilizes thermal energy and can separate the cells of a module from the glass in about 40 seconds. Electrostatic separation is another commercial mechanical separation process which separates various components of a mechanically milled solar panel based on their electrical conductivities (Dias, Schmidt, & Gomes, 2018; Solarcycle, 2022).

2. **High value recycling**: High value recycling makes use of a combination of mechanical, chemical, and thermal processes. With a 90-98 per cent efficiency in recovery of solar panel materials, advanced high value recycling can enable in recovering glass, aluminium, copper, silicon, and silver (IEA PVPS TCP, 2022). Chemical processes can further be classified into solvent dissolution (organic or in-organic), solvent dissolution followed by ultrasonic radiation, etching, and electrowinning. Silicon, silver and copper have different affinity to the solvents/chemical used and form stable compounds to leach out of the mixture.

Figure A2 Overview of solar module recycling technologies



Source: Tyagi and Kuldeep 2021

Table A7 Comparison of various processes for module recycling

Recycling technique	Recovered materials	Throughput	Energy/ chemical consumption
Mechanical	Glass cullet, mixture of Si and metal (and/ or plastic) powder	High	Low
Thermal	Intact/ broken glass back sheet, solar cells, ribbons	Low	High
Chemical	Intact/ broken glass sheet, solar cells, ribbons	Very Low	Very High

Source: Tyagi and Kuldeep 2021

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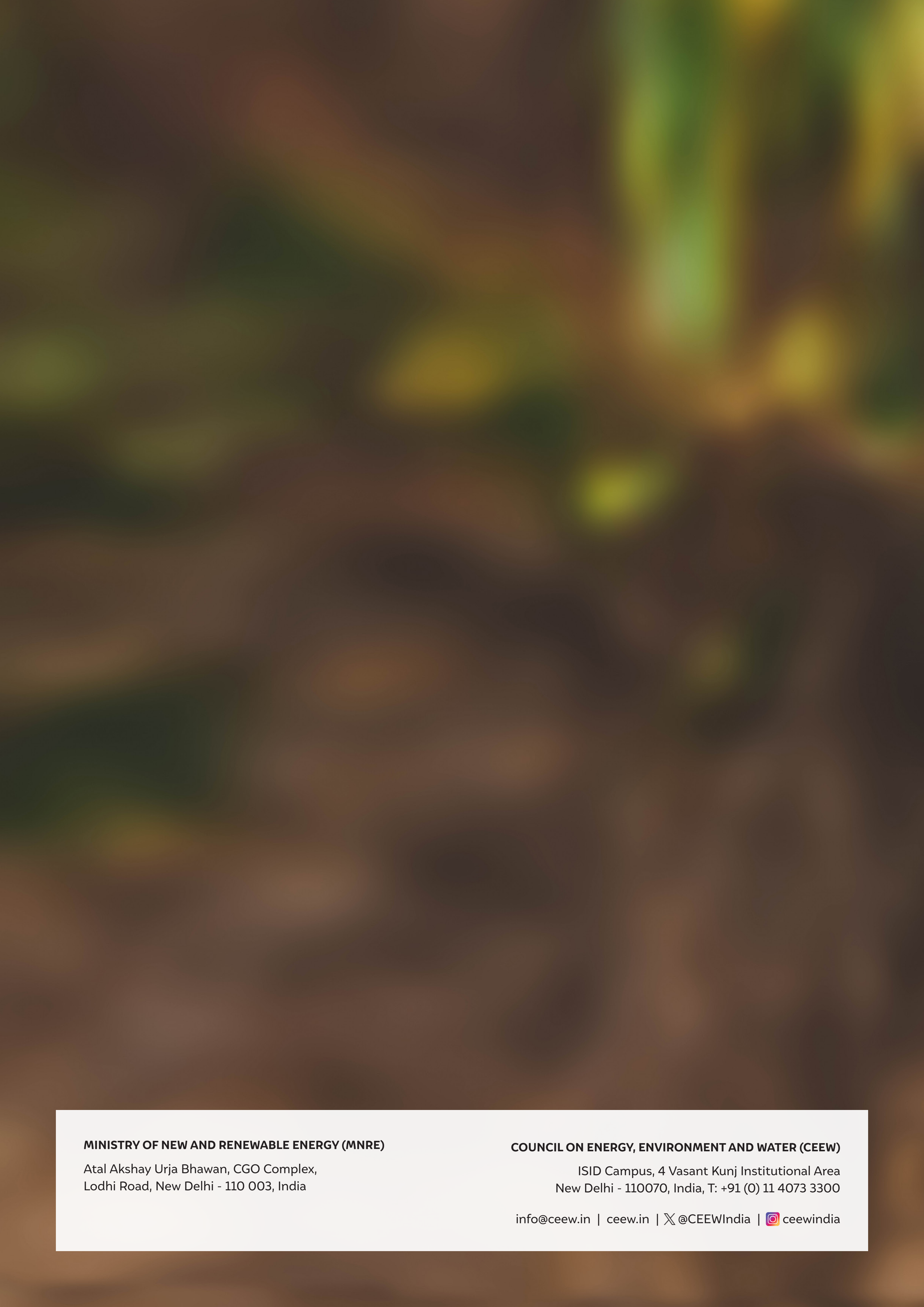
Acronyms

CAGR	compounded annual growth rate
CB-RL	coefficient-based regular loss
DR	degradation rate
EoL	end of life
E-Waste	electronic waste
FY	financial year
GW	gigawatt
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
IRENA	International Renewable Energy Agency
kt	kilotonnes
LCOE	levelised cost of energy
MNRE	Ministry of New and Renewable Energy
MoEFCC	Ministry of Environment Forest and Climate Change
MW	megawatt
NCPRE	National Centre for Photovoltaic Research and Education
PO	project operation
PV	photovoltaic
T&H	transport and handling
W-EL	Weibull early loss
W-RL	Weibull regular loss



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