How India can Manage Solar Photovoltaic Module Waste Better

Learnings from Global Best Practices

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Image: PV Diagnostics

Summary

Solar photovoltaic (PV) technology will play a critical role in India's clean energy transition. The phenomenal rise in annual deployments over the past five years has powered solar to reach a cumulative capacity of 40 GW. However, with rapid deployments arises the issue of waste management of the PV modules. The International Renewable Energy Agency (IRENA) estimates the global PV waste will touch 78 million tonnes by 2050, with India being one of the top five PV waste creators.

This policy brief captures the Indian and international policy landscape of PV module waste management. First, we delve deep into the multidimensional impacts of the PV module waste. It is followed by a review of the technology landscape of recycling processes and a listing of some commercialised programmes. Then we review the globally implemented regulatory and voluntary mechanisms to manage PV module waste. Lastly, we outline some immediate interventions for India to prepare for the systematic and responsible management of PV module waste.

A responsible management of PV module waste and efficient recovery of different components would prevent the leaching of various toxic elements into the environment and render them available for the manufacturing industry. PV module recycling is a multistep process involving dismantling, delamination, and metal recovery. Several techniques are available to recover the intrinsic components in the PV modules. Some of these, like chemical delamination, yield undamaged solar cells, which could be reused directly or with little refurbishing. Mechanical and combustion delamination, on the contrary, yields damaged solar cells that are treated electrochemically or metallurgically to recover the metals.

Globally, only a few regulations cover PV modules in any waste category. The European Union (EU) is the first to revise its Waste Electrical and Electronic Equipment (WEEE) legislation and bring PV modules under its ambit. It also provides some financing mechanisms to cover the waste management costs. The solar industry is also gradually focusing on waste management. PV Cycle and First Solar are the two renowned PV module recycling initiatives, promising more than 90 per cent of the recycling yield. PV Cycle is a not-for-profit organisation of module manufacturers providing regional compliance services to its members. First Solar, a US-based PV module manufacturer, runs an in-house thin-film recycling programme.

These international developments provide many learnings for India. Our research outlines the following priority areas for policymakers and industry to tackle the issue of PV module waste.

Policymakers should:

1. **introduce a ban on dumping of waste modules** by different entities in the landfills;
2. **formulate a dedicated PV module waste management** regulation; and
3. **introduce incentives like green certificates to provide a level-playing field** and encourage recycling and mineral recovery by the industry.

The industry needs to do the following:

1. **improve the PV module design to minimise the waste at the disposal stage.** This can include sustainable design with reduced use of toxic minerals or adopting a 'design to disassemble' approach
2. invest in the **second-life use of sub-standard modules** to delay the waste creation
3. collaborate with research institutes to **develop recycling techniques and support pilot demonstrations**
4. conceptualise new **business models to manage and finance the waste disposal**

1. Introduction

India's solar energy sector is growing exponentially and has set sights on an ambitious target of 100 GW of solar energy by 2022. The cumulative capacity of grid-connected solar photovoltaic (PV) installations is 40 GW as of March 2021 (Ministry of New and Renewable Energy 2021). Of the current capacity, about 35.6 GW is generated from ground-mounted plants and 4.4 GW from rooftop solar. Concomitantly, there are distributed and off-grid installations like floating solar, canal top solar, mini/micro grids, solar pumps, and various other innovative solar PV-powered applications. The rapid advancement of solar PV deployment has been accompanied by, and is a function of, a significant decline in solar electricity tariffs in the last few years, making it increasingly competitive to conventional energy sources. Progressive policies by the government and rising consumer awareness around clean energy sources will further drive solar deployments.

The rapid adoption of solar also brings with it an impending issue of their end-of-life waste management. Solar panels have an estimated life of 25 years after which they have to be discarded. As the Indian solar industry took off around 2010, most of the installed systems are new and early in their calendar life cycle. Given the initial phase of the solar industry, it may be argued that there are negligible waste modules, and hence waste management is not an alarming issue. However, end-of-life is only one of the possible waste streams for PV modules. There are several other stages where modules get damaged and are discarded, especially during transportation and installation activities. Additionally, modules may develop defects during the plant operations and would be discarded even before their actual 25-year life span. Some of the prevalent issues that may result in the short life span of PV modules are variable structural tilt in the adjacent

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tables, which leads to accelerated degradation due to temperature difference between shaded and unshaded modules, the salinity of the ground beneath, which at high concentration corrodes the frames and unstable structures due to weak tightening of nuts and bolts (PV Diagnostics 2020).

Furthermore, India is prone to natural calamities such as typhoons, floods, and earthquakes, which have, in the past, destroyed several installed projects. So, even though most of the current capacity is well short of decommissioning, there could be substantial quanta of waste modules arising from these alternative streams like damages during installation, operation or natural disasters. A preliminary analysis suggests that PV modules have generated a cumulative waste of 285 kilo tonnes, as of FY21, from the early-life loss of the installed 40 GW grid-connected solar capacity.[1] Hence, it would be imprudent to ignore and delay the issue of PV waste management anymore.

Global outlook

The global PV waste is projected to reach 1.7 million tonnes by 2030 and to grow to 60 million tonnes by 2050 (IRENA and IEA-PVPS 2016). Interestingly, this corresponds to a regular loss scenario, where waste is created from the stipulated end-of-life loss of PV modules. Another forecast for an early-loss scenario considers increased loss from damage during installation/transport or other streams before the end of their useful life. The cumulative global waste would increase to 8 million tonnes in 2030 and eventually to 78 million tonnes by 2050. China, the United States, and Japan are expected to be the top three waste creators, followed by India and Germany.

Conscious of this looming issue, several countries have initiated deliberations around the management of waste arising from PV panels. In 2012, the European Union revised its Waste Electrical and Electronic Equipment (WEEE) Directive to include PV panels as one of the waste categories (The European Parliament and The Council of the European Union 2012). Soon, many member countries like Italy (2014), The Netherlands (2014), Spain (2014), and Germany (2015) adapted this directive to suit their national electronic waste management regulations. The United States and Japan are actively engaged in discussing policies and investing in recycling technologies to manage PV waste.

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Study objectives

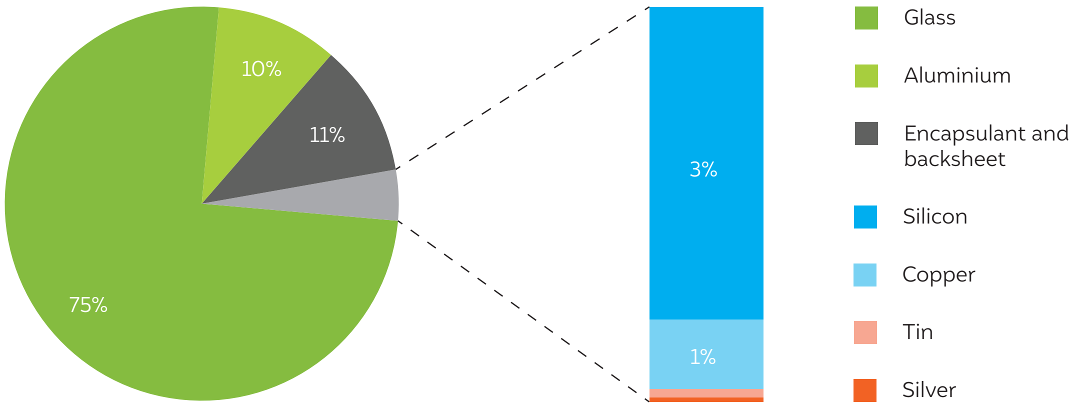
This policy brief envisions a roadmap for managing India's PV module waste. First, we discuss different aspects of waste management that are critical from an Indian standpoint. Next, we compare available recycling technologies on various parameters for their suitability to India's situation. Finally, following a brief overview of the status quo of PV module waste practices in India, we present a detailed evaluation of international waste management practices. The combined information is used to propose a potential strategy for India to ensure timely action.

2. The need for PV waste management

A dedicated PV waste management and recycling policy becomes quite important from environmental, resource management, and socio-economic perspectives. Although PV panels are sturdy, some of their constituent elements could negatively impact the local surroundings upon exposure. Hence, PV modules need to be safely disposed of to have a minimum environmental impact. Further, many of the elements present in the modules are valuable from an economic viewpoint. They are extensively used in alternate industries and hence have a significant demand outside the clean energy sector. So, it is essential to recover them from the waste modules. Lastly, the collection and recycling of waste open up new employment opportunities. Besides the additional workforce required in the recycling facilities, India's existing informal scrap collectors can benefit from the formalisation of recycling processes. Overall, the PV waste management policy could have a multifaceted impact on the Indian economy. The following sections discuss these impacts in detail.

1 This number is a sum of year-on-year waste created from the damage during the transportation, installation, and other pre-mature damages from until the 10-year life of the installed capacity (IRENA and IEA-PVPS, 2016, End-of-Life Management: Solar Photovoltaic Panels) assuming an 82 tonnes/MW conversion factor (EU-India: Technical Cooperation-Energy Project, 2021, PV Waste Management in India: Comparative Analysis of State of Play and Recommendations).

Figure 1 Composition of the crystalline silicon module

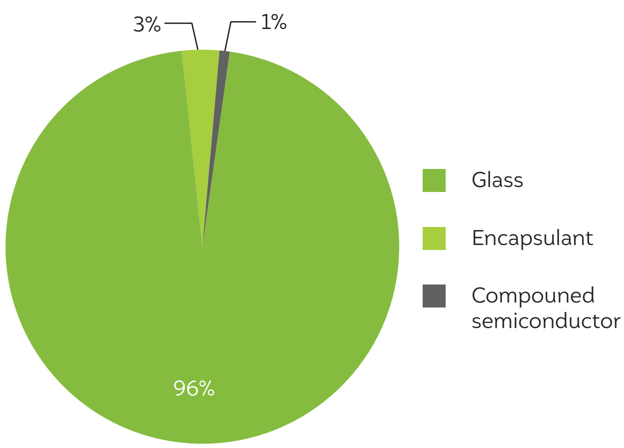


Source: European Commission DG ENV 2011.

2.1 Environmental impact

The environmental aspect reflects the ecological impact. Crystalline silicon (C-Si) and thin-film (mainly cadmium telluride, CdTe) are the two most prominent module technologies in India, with a respective market share of 93 and 7 per cent (Suresh, Singhvi and Rustagi 2019). The major components of a crystalline silicon module are glass, silicon (Si), aluminium (Al), copper (Cu), and silver (Ag), with traces of lead (Pb) (Figure 1). On the other hand, compounds of tin (Sn) and cadmium (Cd) (compounded semiconductor) are the main components of thin-film modules besides glass and polymer sheets (Figure 2). Further, some other bulk components of the modules also contain metals. For instance, glass in PV modules contains antimony to improve the module's stability under light irradiation. The frame enclosing a module is made of Al. Hence, metals are an integral part of the modules.

Figure 2 Composition of the CdTe thin film module



Source: IRENA and IEA-PVPS 2016

Each of these metals has a distinct environmental impact, which necessitates their careful handling and disposal procedures. While Al and Si are relatively less toxic, heavy metals like Pb and Cd are an ecological hazard and a human carcinogen. Studies indicate that the leaching of these metals depends on the pH of the surroundings. At the same pH levels as the module, there is no reported threat of leaching of these metals. However, on exposure to low pH (acidification), for instance, in a landfill, leaching of Pb and Cd can increase up to 90 and 40 per cent, respectively, equivalent to about 518 g/tonne of Pb from C-Si and 153 g/tonne of Cd from CdTe PV modules (European Commission DG ENV 2011). The polymer sheet used as an encapsulant in modules is also a toxic polluter. Upon damage, it is often incinerated, which produces toxic gases like sulphur dioxide, hydrogen fluoride, hydrogen cyanide, and some volatile organic compounds (Liao et al. 2020). So, due to a variety of materials used in PV modules, it is necessary to handle and dispose of PV module waste responsibly to prevent ecological damage.

2.2 Resource management benefits

The resource management perspective looks at the criticality and importance of different metals present in the modules. Most of the metals used in the solar industry are competitively used in other sectors and have limited reserves. For instance, Al, the largest metal component present in C-Si modules, is one of the second most used metals in the world. It finds applications across the power sector, infrastructure, machinery, and equipment manufacturing. India's per capita consumption of Al (2.5 kg) is far lower than the global average (11 kg) (Ministry of Mines, Government of India 2019). However, given the government's push for the *Make in India* campaign, clean energy, and smart cities, the domestic demand for Al is expected to increase further. Despite being an abundant metal, recycling of Al is believed to be an environmentally benign and

Recovery of metals from waste modules is critical for sustained production and deployment of PV technology.

economical way to produce Al, over mining and refining bauxite ore (Saraswat and Ghosh 2017). In a similar way, Si, which, besides solar, is competitively consumed in the production of aluminium alloys, silicones and silanes, and semiconductors.

Despite representing less than 1 per cent of the module mass, there is another set of metals that hold immense value. Cadmium (Cd), tellurium (Te), indium (In), gallium (Ga), and germanium (Ge) are some of these precious metals. They have limited natural reserves and are often recovered as a by-product from the production of other metals (Bleiwas 2010). For instance, Te is retrieved from the production of Cu, Ga during the production of alumina from bauxite, and Ge from the coal ash. It would be unlikely that the production of these base commodities (Al, Cu, and coal ash) would be increased just to meet the demand for these precious metals. Hence, going forward, their recovery from waste modules becomes critical for sustained production and deployment of thin-film PV technology.

Conscious of these facts, national agencies like the Ministry of Mines and NITI Aayog have classified aluminium, copper, lead, gallium, and indium as strategic metals[2] (Niti Aayog 2011) (Gupta, Biswas and Ganesan 2016). Furthermore, a study conducted at Council on Energy, Environment and Water identifies silicon as a critical commodity[3] for the Indian manufacturing sector (Gupta, Biswas and Ganesan 2016). Hence, the recovery of metals from waste modules is vital to minimise resource loss and ensure their sustained supply.

2.3 Socio-economic benefits

The socio-economic benefits of waste management and recycling encompass the employment and welfare aspects. India is one of the fastest-growing solar markets. Still, it doesn't have an established module manufacturing industry to meet the demand. Most Indian module providers assemble the modules by importing cells from countries such as China and the Philippines, and only a few manufacture wafers. According to the Ministry of New and Renewable Energy (MNRE), the domestic manufacturing capacity provides a mere 3 GW in solar PV cells and 10 GW in modules annually. At the same time, India does not produce silicon, ingots, and wafers (Ministry of New and Renewable Energy 2018). The production of silicon, ingots, and wafers is capital intensive and requires high technical expertise. Indian companies seem unwilling to invest in these value chains and instead rely on imports and assembling the imported parts. However, by not investing in the production of silicon, ingots, and wafers, the Indian economy is losing out on significant value creation and employment opportunities. Research indicates that indigenisation of the entire solar value chain would create more jobs than mere cell manufacturing or module assembling (FICCI 2013).

Recycling of waste PV modules to recover critical materials would further aid the Indian economy. Indian companies can access high-grade metals and support their manufacturing. The collection, treatment, and recycling of module waste would create additional jobs. For instance, compared to a voluntary PV waste management scenario, the responsible treatment of the total installed PV capacity of the EU under the WEEE directive would create about 2,500 jobs/million tons of waste treated by 2050 (European Commission DG ENV 2011).

The electronic waste collection sector in India is largely informal, engaging people of all age groups and gender. Currently, almost 95 per cent of e-waste recycling in India occurs through this informal sector. The dismantlers work in miserable conditions and handle hazardous waste without following any safety protocols. Their daily wage varies between INR 200 and 800 (International Labour Office, Sectoral Policies Department 2019). Further, women are paid less than men, who perform acid treatment and other hazardous activities post dismantling. The income of collectors and recyclers correlates with the amount of scrap handled. This informal sector can benefit significantly by institutionalisation of PV module waste collection and recycling. If institutionalisation is achieved, various socio-economic benefits and better quality of life would be bestowed on the workforce. In parallel, the recycling industry can utilise the network of this informal sector and get access to discarded modules from different sources. This can simplify the recycling

2 NITI Aayog (previously Planning Commission) defines strategic minerals as those with limited substituents, concentrated production in selected geographies, increasing global demand or extensively used in emerging technologies, and those which are produced as by-products of other minerals or are mined without following proper regulations.

3 Criticality of minerals is defined on a different basis like importance of usage, supply risks, or environmental risks associated with mineral processing. In CEEW's study, it is judged on the basis of economic importance of these minerals in the manufacturing sector and associated supply risks.

> **Collection of waste PV modules is one of the most challenging steps in the recycling process and can be supported by recognising the informal sector.**

process as waste collection is fundamental yet one of the most challenging steps in the entire process. So, both industry and people employed in it can benefit from a regulated recycling policy framework. Therefore, a mandated PV waste management policy would have profound socio-economic impacts by providing new and quality employment opportunities.

3. Module recycling techniques

Recycling of waste modules allows the recovery of valuable materials and reduces the quantum of waste released to the environment significantly. Different types of recycling techniques are employed currently, and each has different material recovery rates, the quantum of leftover waste, energy consumption, and process complexity (Komoto and Lee 2018). This section gives an overview of the available techniques and reviews them based on different techno-economic parameters.

3.1 Overview of the recycling process

Module recycling can broadly be classified into three steps: disassembly, the disintegration of the laminated structure (delamination), and recovery of metals.

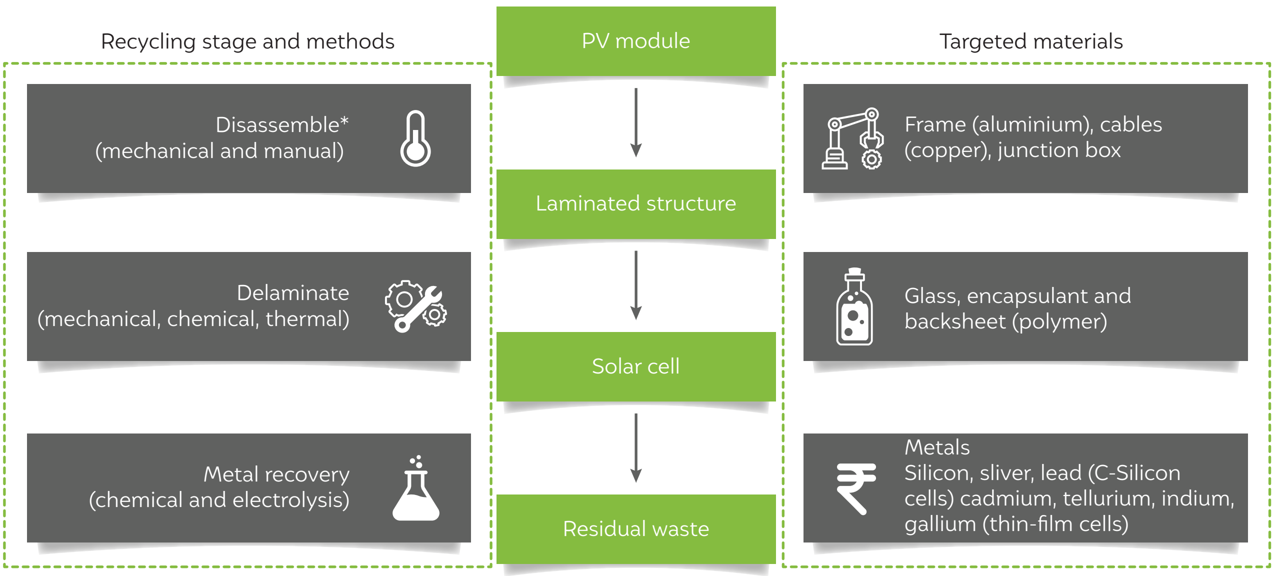
Figure 3 depicts the process flow, along with a list of materials targeted for recovery. **Disassembly** is the step in which externalities like metal frames and cables are removed from the laminated structure. This could be either done manually or automated. Following disassembly, **delamination** of the laminated structure, which involves separating the glass layer, encapsulant, and the backsheet from the solar cells, is performed. This is one of the most challenging steps in the recycling process and applies techniques such as mechanical, thermal, or chemical processing, or a combination of these. The last step is **metal recovery**, one of the most valuable parts of the recycling process. It involves a variety of chemical and electrolytic processes to recover the precious metals.

3.2 A comparison of the recycling methods

The following section lists the key features of the available module recycling techniques. It also compares them on different parameters like recovery yield, energy consumption, and quantum of residual waste.

Disassembling: Automated or manual dismantling of modules aids in the recovery of metals like Al and Cu, present in the frame and cables, respectively. The polymeric substance that forms the cover of these cables is incinerated, leading to the release of harmful gases. In some cases, the energy is recovered and reused in successive stages (Latunussa et al. 2016).

Figure 3 PV module recycling is a multistep process



*This step is not applicable for thin-film modules' recycling as these modules contain cells encapsulated between cover and substrate glass

Source: Authors' analysis

Delamination: Following the removal of externalities, the encapsulant and cover glass are removed to obtain the solar cell. This can be done by numerous techniques, as indicated in Table 1. The first step is to remove the encapsulant. Most of the available methods do not focus on recovering the polymeric substance. As a result, they lead to material loss and pollution. The encapsulant can be removed by direct heating (thermal delamination) (Park et al. 2015) (Zhang et al. 2020) (Doni and Dughiero 2011), dissolving in a solvent (chemical delamination) (Kang et al. 2012), or scrapping/ crushing/ cutting (mechanical delamination) (Azeumo et al. 2019) (Latunussa et al. 2016). In addition to these treatments, optical methods like laser treatment are also available, especially for thin-film modules (Palitzsch et al. 2018).

Thermal processes are faster and easier to implement than chemical processes, but they are more energy-intensive and polluting than the latter. Unlike these two, where the encapsulant is lost, mechanical methods yield a scrap encapsulant. But the lack of viable uses of this scrap makes it an industrial waste, the disposal of which is again a problem. The yield of glass and undamaged solar cells is maximum in the chemical processes and least in mechanical processes. In thermal processes, the yield of undamaged solar cells decreases with its thickness; hence, this method might become less viable as the solar cells become thin with the advancement in technologies.

Among these three techniques, chemical processes are suitable for small-scale on-site operations, while thermal and mechanical processes are more suitable for bulk treatment. However, most commercial plants use a combination of all these processes to improve material yield and purity. For instance, the glass and solar cell cuttings obtained after the mechanical process are chemically treated (with nitric acid or organic solvent) to remove polymeric impurities. The recovered glass is consumed in other industries while the solar cell is further treated to recover the metals in it.

Metal recovery: Chemical etching and metallurgy are the two available techniques for the recovery of metals from solar cells. The cells are first etched with acid (e.g. HNO_3) or other chemicals to obtain Si wafers or compounded semiconductors. A rigorous etching of Si cells yields high-grade wafers, which are suitable for the manufacturing of new cells (Lee et al. 2018). Metals like Ag and Cu (C-Si cells) or Cd and Te (thin-film cells), present in the spent acid, are recovered by various hydrometallurgical processes in a metal refinery. Some of the available methods for metal recovery are electrolysis, metal replacement, and precipitation

Table 1 Summary of module delamination processes

Technique	Available process	Advantages	Disadvantages	Recover yield for glass (%)[a]	Status
Thermal	Combustion	• Fast process • Easy to deploy and scale	• Emission of harmful gases • High energy consumption	95	Commercial
	Pyrolysis	• Fast process • Less polluting than combustion	• High energy consumption • Complicated instrumentation	98	Research, pilot
	Electrothermal	• Low energy consumption • Less polluting than combustion	• Slow process • Complicated instrumentation	Not mentioned	Research
Mechanical	Crushing Cutting Scrapping	• Fast process • Easy to deploy	• Yields damaged cells • Residual solid waste (scrapped encapsulant)	98	Commercial
Chemical	Acids Organic solvents	• Low energy consumption • Less polluting than thermal methods • Improved yield of undamaged cells	• Slow process • Issues with safe disposal of spent chemicals	Not mentioned	Obsolete for standalone applications

[a] Refers to the maximum yield reported

Source: Authors' analysis

(Krueger 2010) (Yi et al. 2014). The recovered metals are either used as raw materials for manufacturing new cells or redirected to other industries.

3.3 Commercialised programs

Table 2 lists some of the operational PV module recycling programmes and the maximum yield of the targeted materials. First Solar, a leading PV module manufacturer in the United States, runs an in-house thin-film module recycling programme. Using a combination of mechanical and chemical methods, this programme claims to recycle nearly 95 per cent of the semiconductor materials (metal refining outsourced to third party) and close to 90 per cent of glass (Krueger 2010). PV Cycle, a not-for-profit organisation of module manufacturers and importers, provides customised waste module collection and recycling services across different countries. It claims to achieve recycling rates of up to 96 per cent for Si-based modules and 97 per cent for thin-film modules (PV Cycle 2016). Loser Chemie GmbH, a chemical plant in Germany, has developed a collection and recycling scheme for different modules (Loser Chemie GmbH 2020). It uses an in-house recycling process in which the polymeric layer is removed by dissolution in aluminium chloride solution to extract glass, aluminium, and solar cell. The cumulative recycling rate of all materials, except Si, is about 85 per cent (PES Solar 2018). The NPC Incorporated, Japan, uses an in-house heated blade technology to remove the glass and polymeric backsheet from solar cells (NPC Incorporated 2018). Toshiba Environmental Solutions, Japan, has also developed a recycling technology to separate glass from solar panels. It uses a mechanical process to yield powdered cells, which are further processed by a third party to recover precious metals like Ag (Tomioka 2016).

Table 2 Several efficient PV module recycling programmes are operational across the world

Organisation	Origin country	Maximum reported recycling rate
First Solar	United States	Glass: 90% Semiconductor: 95%
PV Cycle	Belgium	C-Si modules: 96% Thin-film modules: 97%
Loser Chemie GmbH	Germany	Glass, Cu, Al: 85%[a]
NPC Incorporated	Japan	Not specified

[a]Cumulative recovery rate for the mentioned materials.

Source: Authors' analysis

3.4 Recycling costs

The large scale adoption of PV waste management and recycling is closely linked to the overall economics. The main cost components in this process are waste collection, transportation to recycling facility, treatment and residual waste disposal fee. A direct benefit is from the sale of the recycled materials. Other benefit could come from monetising the reduction in greenhouse gas emissions resulting from amount of virgin minerals replaced by recovered minerals. A recent study for PV waste recycling in China estimates the recovery cost of PV modules as 25.11 USD/kW against a benefit of 25.68 USD/kW (Liu, Zhang and Wang 2020). The total benefits-cost ratio for recycling was 1.023. It underlines the importance of the sale of recycled materials to improve the overall economics of the process.

4. PV waste management in India

In India, electronic waste (or e-waste) is electrical or electronic equipment discarded by a consumer and rejected from manufacturing, refurbishment, and repair processes. Such waste is treated as per the E-Waste (Management) Rules, which holds the producer responsible for these activities under the Extended Producer Responsibility (EPR) (Ministry of Environment, Forest and Climate Change 2018). Surprisingly, PV modules, whose sole purpose is to generate electricity, are not listed as e-waste. Hence, none of the prevalent Indian waste management regulations covers the waste PV modules.

The treatment and recycling of module waste is a developing concept for the Indian solar industry as well. A recent study captured the awareness and outlook of PV module manufacturers and sellers (Indian and international) operating in India (Nain and Kumar 2020). About 97 per cent of the respondents acknowledged the need for end-of-life management of PV modules, with about 87 per cent interested in recycling. However, a mere 24 per cent of PV module manufacturers are involved in the second life use and recycling of PV modules. The remaining 76 per cent of them do not recycle any component of the damaged modules and prefer to pass on the waste to the informal sector (Nain and Kumar 2020). Some leading PV module manufacturers like REC, First Solar, and Vikram Solar have institutional initiatives to recycle their products at the end of their useful life (Vikram Solar 2015, Sinha et al. 2017). While First

The MNRE has drafted a proposal for the safe handling and disposal of module glass to prevent antimony leaching into the environment.

Solar has developed its module recycling process, REC and Vikram Solar are members of PV Cycle, an industry association that provides waste collection and recycling services.

Solar Waste Action Plan (SWAP) is an initiative by Sofies, a sustainability consulting and project management firm, aimed at promoting and building local capacity for solar waste management in India (Sofies India 2018). In parallel, to address the issue of scale and finance, E[co]work Association is developing shared workspaces for e-waste micro-entrepreneurs (E[co]work 2019). By providing rental recycling facilities, they aim to promote safe and efficient e-waste recycling practices in India by offering micro-entrepreneurs a safe working space, efficient machinery and tools, and production equipment like transportation services, training, and health care. Financing is offered to them via plan pay-per-use schemes for working, storage, and services. Their first pilot in Delhi is at the development stage, likely to be ready by 2021 (E[co]work 2020).

Lately, there is a growing consensus on the urgency and need for effective waste management. To curb the environmental impact of waste PV modules, the MNRE has drafted a proposal for the safe handling and disposal of module glass to prevent antimony leaching into the environment (Ministry of New and Renewable Energy 2019). Due to the harmful effects of antimony on humans, the draft proposes handling it under the provisions of Hazardous and Other Wastes Management Rules, 2016, with authorisation from the concerned State Pollution Control Boards. It further notifies that the glass containing antimony should not be mixed with the glass procured from other sources to prevent antimony contamination of the entire waste. It assigns generators or manufacturers as the responsible authority to recycle and reuse module glass.

The Department of Science and Technology has launched a programme to support research activities for waste management in the power industry (PV Magazine India 2020). The programme focuses on developing small- and medium-scale solutions for solar panel and battery storage waste management and recycling.

5. International practices

Many countries have already started taking note of the solar PV module waste becoming a problem in the future and have taken steps to manage the waste in effective and environment-friendly ways. This section discusses some global examples of PV waste management strategies and compares them on different aspects like responsible actors, financing models, and efficacy.

5.1 WEEE directive in the European Union

The European Union (EU) is the first to come up with regulatory guidelines to handle the PV module waste. Many countries in the EU such as Germany, the UK, and Italy have a mature solar industry, which nudged the EU to devise the first waste management regulation. Since 2003, the EU's Waste Electrical and Electronic Equipment (WEEE) directive provides guidelines for all electrical and electronic waste management in the EU member states. Following the rapid growth of the PV sector in the EU member countries, the directive was modified in 2012 to include PV panels as one of the 10 categories in electronics (The European Parliament and The Council of the European Union 2012). The member countries can adapt parts of the directive to suit their national laws of waste management (Table 3). The UK (Department for Business Innovation & Skills 2014), Germany (hesselmann service GmbH 2015), and France are some of the early adopters of this directive and have included the suitable parts of the directive into their national laws.

EU's WEEE directive is based on extended producer responsibility (EPR). A producer is defined as any person involved in manufacturing, designing, or marketing equipment in a member state territory. A reseller would also be deemed a producer unless the equipment bears the identity of the original brand. A producer is responsible for taking back, recycling, and disposing of the modules they sell in the EU member countries. The consumers return their waste modules

EU's Waste Electrical and Electronic Equipment (WEEE) directive was modified in 2012 to include PV as one of the electronic waste commodity.

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via collection schemes, free of charge, to a responsible entity, such as a municipality or distributor, who passes it on to a producer. Other responsibilities of the producer include the following:

- **Financing waste collection** from the entire chain of its products
- **Ensuring availability of finances for future recycling** and disposal processes
- **Sensitising users** about their role in the collection and safe handling of waste modules
- **Informing consumers** about the economics, treatment, and disposal of modules at the time of sale
- **Maintaining a record of the weight of waste PV modules (entering and exiting) at different stages** such as collection, treatment, reuse, and recovery or recycling
- **Sharing updates** on the recycling targets achieved

The directive sets minimum annual targets for the collection and recycling of PV modules for each member state. The collection rate for the period 2016–2019 is 45 per cent of the total weight of WEEE created in the given year.[4] From 2019 onwards, the target was increased to 85 per cent of the weight of WEEE created in a given year.[5] The member states would ensure the achievement of these targets by collating information from the collection and treatment facilities, distributors, producers, or third parties. The directive provides relaxations in minimum collection targets to a few member countries like Bulgaria, Latvia, Hungary, and Poland because of the lack of required infrastructure and less electrical and electronic equipment (EEE) consumption.[6] Post collection, the member states must ensure that the producers, or third parties acting on their behalf, properly treat their waste modules. For PV panels, the treatment includes removal of all external electric cables, and preparation for reuse, recovery, or recycling. From 2018 onwards, the recovery target is 85 per cent of the total weight entering the recovery facility post-treatment. Further, for reuse and recycling, the target is 80 per cent of the complete waste entering this facility.

As mentioned before, the directive assigns producers for financing the collection, recycling, and disposal of their waste. For private households (business to consumer, B2C), irrespective of the member countries, the producer must bear the entire cost of waste collection, treatment, recycling, and disposal. The producer can either finance these operations individually (pre-funding) or set up a collective scheme. For non-private households (business to business, B2B), the member countries can choose to provide cost-sharing arrangements between the producer and the consumer via a contractual agreement.

> **In the pay-as-you-go (PAYG) model, the producer arranges for waste management costs when the waste occurs. The pay-as-you-put (PAYP) approach involves charging an additional payment, corresponding to the estimated value of collection and recycling, when a product is placed on the market.**

Depending on the business, B2C or B2B, the producers can choose from the available financing models, such as pay-as-you-go (PAYG) and pay-as-you-put (PAYP). In the PAYG model, the producer arranges for waste management costs when the waste occurs. As PV modules have a long life, it takes a considerable time for them to reach the waste stream. During this period, the producer may go out of business and therefore cannot undertake the disposal activities. So, the producers opting for the PAYG model often combine it with last-man-standing insurance covering the cost of collection and recycling if they run out of business. The PAYP approach involves charging an additional payment, corresponding to the estimated value of collection and recycling, when a product is placed on the market. Often, the producers can jointly manage the waste created from a specific product. In such cases, they set up a joint-and-several liability scheme. Different developers join in setting a funding guarantee for paying the collection and recycling costs depending on the share of products they put on the market.

4 The WEEE weight is expressed as the average weight of electrical and electronic equipment (EEE) put on the market during the preceding three years.
5 The WEEE weight is expressed as the 65 per cent of the average weight of EEE placed on the market in the preceding three years.
6 The minimum collection rate is decreased to 40 per cent and the achievement period has been extended to 2021.

Table 3 **Adoption of WEEE directive by different European countries**

Germany

National law: ElektroG
Implementing agency: Stiftung Elektro-Altgeräte Register (Stiftung EAR)[7]

Country-specific guidelines:

1. Compliance

   The producer

   - should register themselves and PV panels with the Clearing House (Stiftung EAR) before marketing their product;
   - include various waste management costs into the product price to ensure no financial burden on the consumer;
   - mark all the products with brand label and crossed-out wheel-bin;
   - report to the Clearing House regularly; and
   - pay a penalty of up to €100,000 or stop sales on violations of rules in case of compliance violations.

2. Financing: *Guarantee fee*

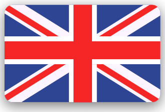
   The producer would finance the B2C transactions. Further, they should submit a guarantee fee and trusteeship for the possible event of bankruptcy.

   - The guarantee fee depends on three factors: the number of panels registered (annually) with EAR, presumed percentage of panels reaching the collection centres (return rate), and the presumed disposal cost (EUR/t).
   - The validity of the guarantee further depends on presumed medium life expectancy and average maximum life expectancy.
   - To help producers calculate their guarantee fee for PV panels collected from private households, EAR has finalised the following numbers for the presumed return rate, disposal cost, and medium and average life expectancy.

Type of panel	Return rate (%)	Disposal cost (€/tonnes)	Medium life expectancy (years)	Average maximum life expectancy (years)
Small (dimension < 50 cm)	20	180,00	10	21
Large (dimension > 50 cm)	20	180,00	10	21

Source: Stiftung Elektro-Altgeräte Register (EAR) 2018.

7 Stiftung EAR is a public-sector foundation that undertakes public-law activities under WEEE on behalf of Federal Environmental Agency.



UK

National law: Waste Electrical and Electronic Regulations 2013
Implementing agency: Environment Agency

Country-specific guidelines:

1. Compliance:
   - All PV panels, sold to household and non-household consumers, are classified as B2C.
   - Producers selling more than 5 tonnes of PV panels must join a UK-approved producer compliance scheme (PCS) by 15 November each year or within 28 days of placing the PV panels in the UK (if entering the UK market after 15 November). The PCS works on behalf of the producer to manage the entire chain of PV waste management.
   - There is a dedicated category of small producers.[8] Unlike others, they are exempted from joining a PCS but should register on the National Packaging Waste Database (NPWD).
   - The directive also assigns distributors as responsible entities for waste collection from households. A distributor is a UK-based installer or retailer of PV panels to households.
   - The directive approves a distributor take-back scheme for arranging waste collection facilities for households on behalf of the distributors.
   - Violation of the directive can result in a fine of £5,000 at magistrates' court or an unlimited fine from a Crown Court.
2. Financing:
   - Producers pay a membership fee to avail of the services of a PCS.
   - The amount of PV waste to be collected by a producer in *a particular compliance year* is calculated as follows:

     $$\frac{X}{Y} * Z$$

     where *X* is total amount of PV modules sold in a *preceding year* (tonnes)

     Y the total amount of PV modules sold by all producers (tonnes) in the *preceding year*

     Z the total amount of PV waste to be financed by all responsible entities (producer/ scheme) in the preceding year (tonnes)
   - If the scheme does not finance the different costs, the operator can pay a **compliance fee** corresponding to the uncovered PV waste. The compliance fee, calculated by this methodology, is decided for each year.

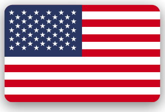
Source: Authors' analysis

5.1.1 Industry initiative

Much before revising the WEEE directive to include PV modules in the electronic waste category, PV Cycle, a not-for-profit industry organisation, had initiated general module recycling. This was a voluntary effort by producers operating in the EU. PV Cycle provides take-back and recycling services to its member companies and is operational in different countries within and outside the EU. Following the formalisation of PV module recycling, the association provides tailor-made services for collection, treatment, recovery, and waste disposal to its members following their respective WEEE regulations. For instance, in the UK, PV Cycle operates as an approved PCS.

8 A producer who places less than 5 tonnes of PV panels onto the market in a specified compliance period.

5.2 United States



The United States has an advanced PV market with cumulative installations that make it among the top five countries in the world. Yet, there are no regulations in place to handle PV waste. At present, the waste is disposed of as per the general waste management framework under the Resource Conservation and Recovery Act (RCRA) (United States Environmental Protection Agency n.d.). The PV waste is treated as per the usual hazardous waste method to assess if the sample contains contaminants beyond the regulatory levels. Recently, some US states like California and New York are proposing new bills and regulations to manage the PV module waste.

California's Department of Toxic and Substance Control (DTSC) has proposed a regulation to include PV modules in its Universal Waste Management regulations (Department of Toxic Substances Control 2019). The rule, under revision, applies to hazardous PV modules that contain heavy metals like lead and cadmium. Generators are responsible for the determination of hazardous waste and treat those as universal waste. Non-hazardous and non-toxic modules are not covered under these regulations. The regulation also proposes guidelines for universal waste handlers/recyclers to manage and dispose of the waste. The guidelines include

- notifying the DTSC a month in advance of accepting module waste;
- labelling the waste containers and track their shipment;
- keeping the total transported module waste under 100 kg, unless prepared to contain the release of toxic substances;
- dismantling the modules to treat the scrap metals and hazardous materials responsibly; and
- reporting the annual numbers in terms of waste collected and treated.

Earlier, the New York Senate approved the Solar Panel Collection Act, which assigns the manufacturers to develop programs for collecting, transporting, recycling, and disposal of damaged PV modules, besides financing the program (The New York State Senate 2018). The state's Department of Environmental Conservation (DEC) would assist the manufacturers in developing this programme. Some of the responsibilities of manufacturers under this act are (The New York Senate 2019):

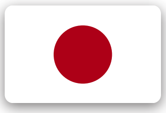
- compiling a list of solar panel wholesalers within the state (applicable from 1 July 2021);
- establishing a system to collect, transport, and recycle out-of-service PV panels from all collection sites;
- financing all the activities individually (or collectively with other manufacturers) and not pass any charges to the consumers; and
- creating awareness among the wholesalers and consumers about the PV waste management and information about different collection sites through print and electronic media.

First Solar, a US-based PV module manufacturer, runs a commercial-scale take-back and recycling program for its products.

5.2.1 Industry initiative

The Solar Energy Industries Association (SEIA) in the United States has proposed a National PV Recycling Programme. Its member companies are taking the lead on recycling waste PV modules. SEIA partners with recyclers who provide services to installers and interested manufacturers. The association also maintains a corporate social responsibility committee to review the research in recycling technologies. Some module manufacturers are voluntarily collecting and recycling their products at the end of life. One prominent example is First Solar running a commercial-scale take-back and recycling program for its products. It uses a pay-as-you-put approach for financing the recycling and disposal operations. The sale of each module sets aside a lump sum to meet the estimated future collection and recycling cost of its modules.

5.3 Japan



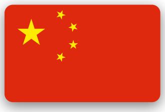
Japan is an electronically advanced country with a developed PV market. However, it doesn't have any formal regulations to manage PV waste. At present, PV waste is treated under the general regulations for industrial and construction waste—The Waste Management and Public Cleansing Act and the Construction Waste Recycling Law. In 2015, the Ministry of Economy, Trading and Industry (METI) and Ministry of Environment (MOE) released a roadmap to manage PV module waste by

- providing guidelines to decommission, collect, transport, reuse, recycle, and dispose of waste modules;
- supporting research in recycling technologies;
- investigating the market for reused modules; and
- promoting environmentally benign module designing.

5.3.1 Industry initiative

The New Energy and Industrial Technology Development Organization (NEDO) has been supporting research activities by different companies for developing low-cost PV recycling technologies. Many of these technologies were piloted between 2015 to 2018 to examine their efficiency and viability, as mentioned earlier. However, none is adopted at scale by the PV industry and remains restricted to companies' individual pilots (NPC Incorporated 2018, Tomioka 2016). In 2016, PV Cycle collaborated with JPV Collection, a Japanese network base for small PV modules (PV Cycle 2017). Together they provide waste collection and recycling services to Japanese PV companies for B2B sales.

5.4 China

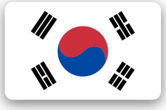


Despite being the world's largest solar market, in terms of capacity deployed and modules produced, China does not have a dedicated PV module waste recycling policy in place. Moreover, they are not covered under the general waste electrical and electronic product regulations. The Waste Electrical and Electronic Product Recycling Management Regulation of 2009 authorises manufacturers to manage and recycle their produced electrical waste. However, these regulations do not apply to the PV module waste.

Furthermore, unlike other countries, China's solar industry is also not responsive to the management of module waste, which is likely to pose challenges in the future. No special research activities have been initiated for the development of recycling technologies as of now.

> South Korea's proposed regulation requires PV manufacturers pay a recycling fee approved by the Ministry of Environment in exchange of its waste recycling services.

5.5 South Korea



South Korea is one of the fastest-growing PV markets. Under its Renewable Energy 3020 Plan to increase the renewable energy (RE) capacity to 20 per cent by 2030, Korea plans to expand the solar capacity to 30 GW (Ministry of Trade Industry and Energy 2018). Currently, there is no regulation in place to manage PV waste. However, the situation is likely to improve with the government planning to introduce a new EPR scheme in 2023 (PV Magazine 2020). The proposed method identifies manufacturers as the responsible entity for module recycling. Unlike other countries, the manufacturers need not recycle waste and collect and transfer it to a recycling facility although they have to pay a recycling fee, as approved by the Ministry of Environment, to exchange the services. These payments would be used to support the recycling facilities. The government is planning to build sufficient recycling capacity in the country before formalising this regulation. Table 4 summarises the global developments around PV waste management.

Table 4 A summary of global PV module waste recycling practices

- Except for the EU, most countries do not have a regulation to manage waste PV modules and their components.
- Globally, the PV industry is spearheading the collection and recycling of PV waste. Most of these initiatives are facilitated by a third party that collects and recycles the waste PV modules using the funds collected by the member companies.
- Pay-as-you-go and pay-as-you-put are two types of financing models that are prevalent to carry out the recycling activities.

Source: Authors' analysis

6. Way forward for India

Despite a flourishing solar industry, India is yet to have a dedicated PV module waste management policy. As a result, the discarded modules lay unattended on the project sites and, in some cases, are dumped in landfills. We outline the following areas that would be crucial for PV waste management in India.

1. **Second-life use of sub-standard modules**: One of the first steps to manage the PV module waste is to reduce its generation at the source. This can be achieved by promoting the second-life use of damaged or sub-performance modules. **Developers** should

take steps to refurbish such modules found in their projects and ensure that they perform above a minimal capacity performance factor (CUF).[9] Such modules can be used in alternate streams in which electricity is not generated for earning revenue. This can considerably minimise the quanta of waste modules.

2. **Improved module design**: The **manufacturers** should focus on reducing their waste by simplifying the module design. A design-to-disassembly approach can minimise the number of steps and energy invested in recycling. Manufacturers should also avoid the use of toxic materials to allow safe handling and disposal of the damaged modules.
3. **Mandatory regulation and ban on landfills:** The need for a PV module waste management policy cannot be emphasised further. A mandatory approach outlining the responsible actors and annual targets for collection, recycling, and recovery would drive the solar industry to include safe disposal of the products in their businesses. India, like the EU, can expand its existing electronic waste management regulations to cover PV modules, which would mandate the producers to manage the safe disposal of their products. As a considerable number of installed modules are imported, the onus of waste management could be placed on the first seller in India. Further, as India is a developing solar market, it should plan a mid-and long-term strategy for PV waste management. This could include phased targets, financing schemes, and capacity building. In parallel, the **government** should impose a ban on damaged modules being dumped in landfills to prevent their adverse impact on the environment.
4. **New business models**: Refurbishing, recycling, and waste management are cost-intensive activities. The **producers** should conceptualise business models to include future waste disposal costs in the prices of their products. Besides disposal, these prices should also cover administration, collection, logistics, and treatment costs. They can choose from some of the prevalent models like pay-as-you-put, pay-as-you-go, or joint-and-several liability scheme to secure access to finance from the consumers. They should also consider the geographical distribution of installed PV capacity in estimating the expenses. The southern and western states have the maximum installed capacity. Waste from different regions can be collected and transported to these regions to avoid constructing distributed recycling facilities and to achieve economies of scale.

> **A design-to-disassembly approach can minimise the number of steps and energy invested in recycling.**

> **Policymakers could introduce different incentives based on the recycling targets achieved by the producers/sellers.**

5. **Investment in recycling technologies**: Advanced recycling technologies are essential for the industry to improve material recovery (process efficiency) and thereby the overall economics of the process. The **solar industry** should promote research around developing these technologies by collaborating with institutes and companies and conducting pilot demonstrations.
6. **Introduction of incentives**: Level-playing field is crucial for the uptake of waste management and recycling practices. For this, the **policymakers** should introduce different incentives based on the recycling targets achieved by the producers/sellers. For instance, green certifications would add value to the company's portfolio, preference in government tenders, and promotion of products manufactured from the recycled materials, and so on.

7. Conclusion

"As distributed renewable energy sources such as solar PV and energy storage penetrate deep into the Indian electricity sector it is necessary to prepare for managing the waste generated from these technologies. In addition to being environmentally benign, the 'reduce, reuse, and recover' approach offers multiple socio-economic co-benefits" (A. Tyagi 2020). The recovery of the precious minerals present in the modules can support the domestic manufacturing industry and improve its self-sufficiency. The informal sector, if institutionalised and roped into PV module waste management, could be effectively deployed for waste collection and recycling activities and derive various social benefits so that the informal workers can lead a better quality life. Inclusion and recognition of the informal sector would improve the efficiency of the entire waste management process.

9 The minimum CUF can be decided after due consultations with the MNRE, SECI, and National Solar Energy Federation of India (NSEFI) and should be communicated to the next user.

Several recycling techniques are available with varying material efficiencies, energy consumption, and environmental impact. Solar companies can customise their recycling processes by choosing a combination as per their strengths and capabilities. They can also learn from the globally prevalent financing models to arrange to fund the waste management activities. The solar industry is capable of minimising or delaying their waste by focusing on the second-life use of the sub-standard modules. For instance, they can target non-monetary applications for refurbished modules such as solar lamps and solar pumps.

The government must introduce a holistic policy framework for handling the waste from clean energy technologies. The policy should highlight the responsibility of different stakeholders across the supply chain, set annual targets for each stage of waste management (collection, recycling, and recovery), introduce innovative business models and incentive mechanisms, and provide guidelines for the handling and safe disposal of different waste categories. India is now in the midst of a clean energy transition and should not lose out on PV module waste management.

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Shakti Sustainable Energy Foundation seeks to facilitate India's transition to a sustainable energy future by aiding the design and implementation of policies in the following areas: clean power, energy efficiency, sustainable urban transport, climate change mitigation and clean energy finance.

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