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International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability

PVPS

Status of PV Module Recycling in Selected IEA PVPS Task12 Countries

2022

Report IEA-PVPS T12-24: 2022

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The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6 000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

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What is IEA PVPS Task 12?

Task 12 aims to foster international collaboration in safety and sustainability that are crucial for ensuring that PV penetration increases enough to make a major contribution to the energy needs and emissions reductions of the member countries and to the world. The overall objectives of Task 12 are to (1) quantify the environmental profile of PV compared to other energy technologies; (2) investigate end-of-life management options for PV systems as deployment increases and older systems are decommissioned; and (3) define and address environmental health and safety and other sustainability issues that are important for market growth. The first objective is well served by life cycle assessments that describe the energy, material, and emissions flows in all stages of the life of PV. The second objective is addressed through analysis of recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest.

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COVER PICTURE

PV module recycling facility, courtesy of NPC Incorporated, Japan

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LIST OF ABBREVIATIONS

Ag	silver
a-Si	amorphous-silicon
c-Si	crystalline silicon
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
Cu	copper
EOL	end of life
EPR	extended producer responsibility
EU	European Union
EVA	ethylene vinyl acetate
EWC	European Waste Catalogue
FIR	Formulario di Identificazione Rifiuti (waste identification form)
FIT	feed-in-tariff
GSE	Gestore dei Servizi Energetici
GW	gigawatt (= 1 million kW)
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JPEA	Japan Photovoltaic Energy Association
kW	kilowatt
MITERD	Spanish Ministry for the Ecological Transition and the Demographic Challenge
MOE	Ministry of Environment (Japan)
NEDO	New Energy and Industrial Technology Development Organization
OECD	Organisation for Economic Co-operation and Development
PV	photovoltaic(s)
PVPS	Photovoltaic Power Systems Programme
R&D	Research and Development
SEIA	Solar Energy Industries Association members
TCP	Technology Collaboration Programme
US	United States
WEEE	Waste Electrical and Electronic Equipment

EXECUTIVE SUMMARY

Photovoltaic (PV) deployment has accelerated in recent years compared to projections in the early 2010s. This means that PV end of life (EOL) waste streams will also increase at a higher pace than anticipated. To meet and optimise PV EOL management, appropriate regulatory and technological approaches must be implemented in the near term, ensuring that available options are adapted to the conditions of each country or region. This report aims to review the current regulatory and industrial landscape for selected countries belonging to the International Energy Agency's PV Power Systems technology collaboration programme, to assess status of PV EOL management, allow for comparison and cross-fertilization, and establish a foundation for future tracking of progress.

In Europe, the European Union has adopted PV-specific EOL regulations. In other parts of the world, PV EOL is typically handled under each country's legislative and regulatory framework for general waste treatment and disposal. In some countries, however, policy approaches for accelerating PV EOL management, including supporting technology R&D, have been developed or are in the process of being developed. In South Korea, EPR (extended producer responsibility) regulations will be enforced in 2023, whereas in Australia, PV modules are expected to be covered by the Product Stewardship Act 2011, in addition to state-level discussions. In the United States, regulations specific to EOL PV exist in some states. In Japan, although there is no PV-specific waste regulation, several recycling activities and R&D projects for supporting PV EOL management have been carried out, with commercial PV recycling technology now available. Similarly, while in China policies and regulations on PV module recycling and EOL management are still under development, ECOPV was officially established early 2020 with the goal of achieving a "PV green supply chain". Although there are no reliable world data on the volume of EOL PV, it seems that a few thousand tons of EOL PV modules are annually processed in Germany, France, Italy, and Japan. In Spain and South Korea, the amount of EOL PV modules is still less than 1 000 tons/year.

Although regulations can promote PV EOL management, a gap can still exist compared to expected impacts in the markets. To understand the status in the market, a questionnaire with intermediate processors treating EOL PV modules was conducted. Although the total number of responses was small, the responses reflect the current situations and barriers to PV module recycling in certain countries.

Considering the treatment of EOL PV modules in the market, regardless of whether PV-specific EOL regulations have been implemented, several companies around the world are treating EOL PV modules to achieve proper EOL management and recycling. As such, companies are treating multiple types of PV modules, with different recycling technologies in use. Most use mechanical approaches (developed originally for electronic waste) and/or a combination of approaches, such as thermal and chemical processes. The estimated average rate of material recovery[1] from PV modules is more than 80% in weight, although the recycling rate[2] is marginally smaller than the recovery rate. On the other hand, the average treatment capacity by PV recycling plants included in this survey is a few thousand tons/year, with most plants below 1 000 tons/year. Comparatively, in most plants, the actual treatment amount is less than

[1] Recovery rate: ratio of the weight of materials recovered after processing, to the weight of the PV module before processing.

[2] Recycling rate: ratio of the weight of materials recycled for secondary use, to the weight of the PV module. Materials recovered but not used are not counted in the recycling rate.

100 tons/year. Because the capacity factor of these plants is currently low, high treatment costs per unit are expected, with several plants stockpiling PV modules until they have enough volume to process. After treatment at the initial recycling plant, materials recovered from PV modules are sent to other destinations for further recycling or processing, such as smelters, processing plants, and secondary markets; however, it seems that crystalline silicon PV cell materials and plastics/polymers are not currently recycled. Also, although at first glance glass seems to be recycled, the use of recovered glass is limited to less valuable products, with high transportation costs being an issue.

Although volumes of EOL PV modules are still small, EOL PV is treated and recycled in a proper manner in the countries and regions that have EOL regulations in place. However, the current low volumes, limited available recycling technologies, logistics challenges, and undeveloped markets for recovered materials result in a high-cost, low-revenue scenario for PV module recycling globally. Nevertheless, the implementation of PV EOL regulations in more countries and R&D investment in PV recycling is expected to accelerate further improvements to meet future demand and to achieve high-value, low-cost recycling.

We hope this report contributes to understanding the global status of PV recycling and to accelerating its development as a promising option for the proper EOL management of PV modules in the coming decades.

It is noted that data in this report was collected in 2021, reflective of the latest year available.

1 INTRODUCTION

Photovoltaic (PV) technology is one of the most promising technologies for improving energy security and mitigating climate change. The PV market is growing rapidly, and further market expansion is expected around the world. In addition to PV's positive impacts on energy security and climate change, it is one of the most environmentally friendly technologies among all energy generation technologies, particularly when evaluated from a life cycle viewpoint, including end of life (EOL) management.

With PV deployment increasing exponentially, the number of PV modules that reach the end of useful life will also increase, accumulating proportionately as waste after the time lag of operation. When a product cannot be repaired or reused, recycling is the next preferable option before disposing as waste. In anticipation of the large volume of EOL PV modules, and to retain PV's position as a clean energy technology, PV module recycling has become an important emerging and strategic topic, with numerous global, regional, and country-specific activities conducted and developed by governments, organizations, and companies in recent years.

Globally, newly installed PV capacity reached approximately 175 GW/year in 2021, leading to a cumulative capacity of 942 GW by 2021 [1]. In addition to the traditional leading PV markets - such as China, the United States (US), Japan, and countries in Europe—India, Australia, Korea, and Vietnam recently expanded PV installations (see Fig. 1-1 and Fig. 1-2).

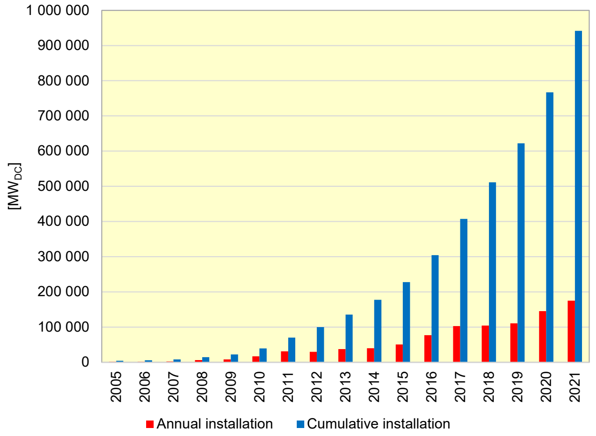


Fig. 1-1 Trends in PV installations around the world [1][2]

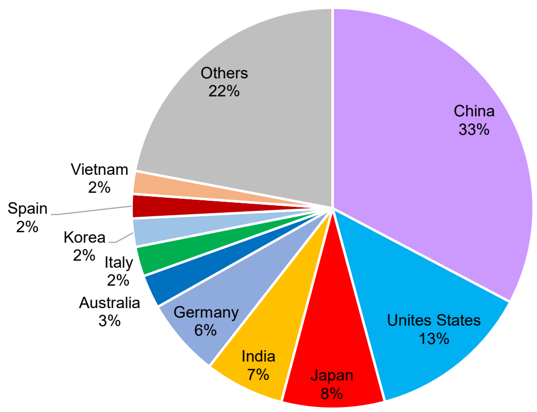


Fig. 1-2 Regional distribution of the cumulative installation of PV technology at the end of 2021 [1]

Given that PV is becoming one of the most economic and environmentally competitive electricity generation technologies globally, and therefore offers a viable solution for the necessary decarbonization of energy systems, it can be foreseen that PV deployment will continue to expand around the world. For example, in May 2021, the International Energy Agency (IEA) published a decarbonisation roadmap for the global energy sector, *Net Zero by 2050*. As shown in Fig. 1-3, PV is forecasted to provide more than 20% of the world's electricity generation by 2050 [3]. In addition to current leading PV markets, increased deployments in Africa, the Middle East, Latin America, and other non-Organisation for Economic Co-operation and Development (OECD) regions are expected.

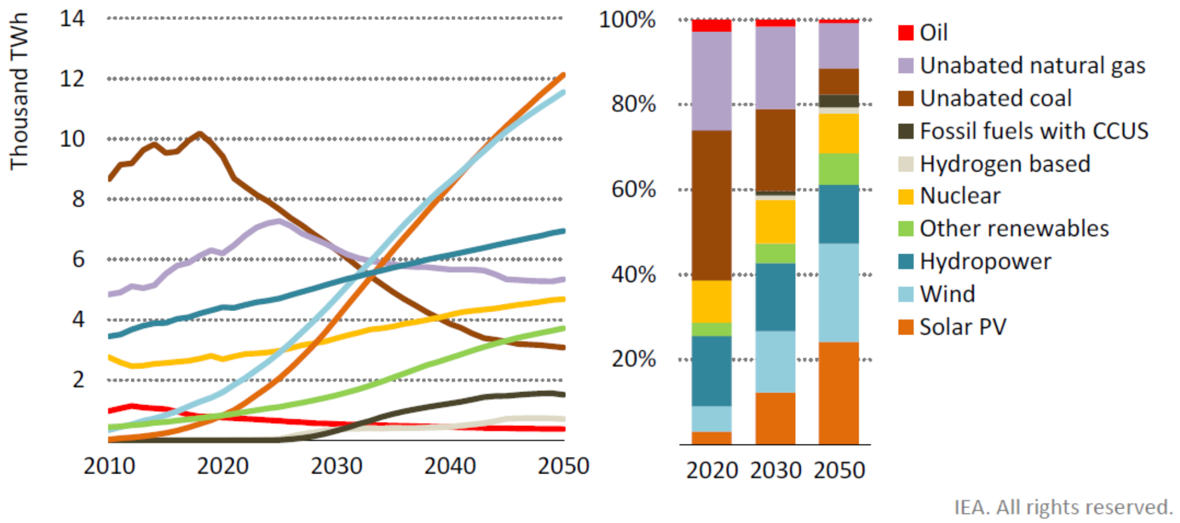


Fig. 1-3 Global electricity generation by source in the *Net Zero by 2050* Announced Pledges case [3]

(Source: OECD/IEA 2021, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, Figure 1-14, page 46)

Because PV technologies offer economic and environmentally favourable electricity generation, stakeholders of PV deployment should implement environmental processes and policies, including responsible EOL management strategies. A framework supporting the early development of EOL strategies will foster good progress toward comprehensive policies. Moreover, better projections of future waste amounts and waste composition will help establish the basis of such a framework.

A previous analysis by the IEA Photovoltaic Power Systems Programme (PVPS) Task 12 and the International Renewable Energy Agency (IRENA) in 2016 [4] estimated the future amount of PV module waste. The projection of cumulative PV waste volumes to 2050 was based on IRENA (2030) and IEA (2030-2050) PV system deployment trajectories, converted through a Weibull distribution that incorporated statistical data on early failure modes of historic PV modules. The conversion ratio between weight and power (Watts) for historic and projected future PV modules was fitted by an exponential curve based on trends from the past to today.

Fig. 1-4 shows the estimated cumulative waste volumes of EOL PV modules around the world. In the regular loss scenario, a PV module waste volume of 43 500 tons was projected by 2016, with an increase to 100 000 tons by 2020, and 1.7 million tons by 2030. An even more drastic increase to approximately 60 million tons can be expected by 2050. The early loss scenario projection estimates much higher total PV waste streams, with 250 000 tons by the end of 2016. This estimate would increase to 850 000 tons by 2020, 8 million tons by 2030, and a total of 78 million tons by 2050 because the early loss scenario assumes a higher percentage of early PV module failures than the regular loss scenario.

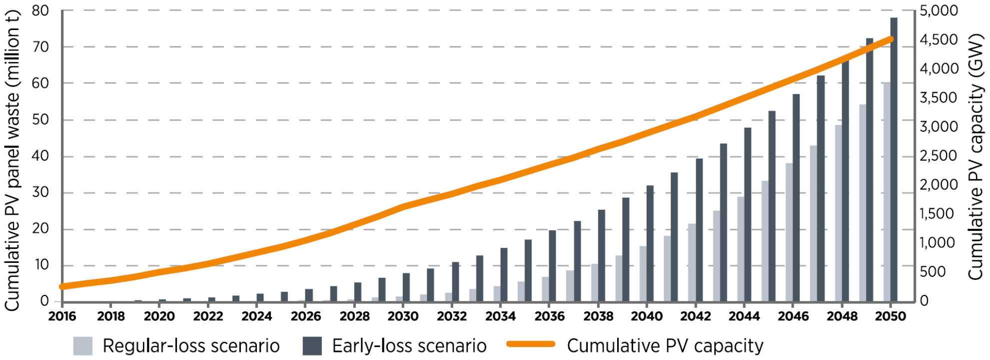


Fig. 1-4 Estimated cumulative global waste volumes of EOL PV modules by IRENA/Task 12 [4]

Fig. 1-5 shows the estimated annual waste volumes of EOL PV modules around the world. In 2040, 2.5-3.5 million tons of PV module waste (depending on scenario) is predicted in comparison to 6.5 million tons in new PV module installations. As well, in 2050, 5.5-6 million tons of PV module waste is predicted in comparison to 7 million tons in new PV module installations.

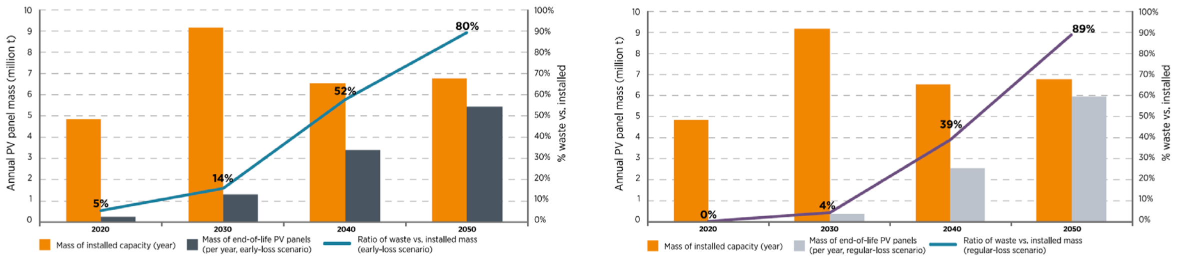


Fig. 1-5 Annually installed and end-of-life PV modules 2020-2050 (in % waste vs. t installed) by early-loss scenario (left) and regular-loss scenario (right) by IRENA/Task 12 [4]

However, looking at the world PV market, PV deployment has been accelerating at a higher rate than expected in the early 2010s, and further acceleration is anticipated to achieve net zero emissions by 2050. This means that PV waste will increase more quickly in the coming decades.[3,4]

Given this, integrated regulatory and technological approaches are needed to optimise EOL PV management plans, together with adaptations to the unique conditions of each country or region.

The European Union (EU) has adopted PV-specific waste regulations. In other parts of the world, little specific legislation for handling EOL PV modules yet exists, and PV waste is typically handled under each country's legislative and regulatory framework for general waste treatment and disposal; however, policy approaches for accelerating PV EOL management, including supporting technology research and development (R&D), are under development in several countries.

[3] According to the recent report by IRENA, "World Energy Transitions Outlook 2022", it is projected that PV module waste from global cumulative solar PV projects will increase to 4 Mt in 2030, almost 50 Mt in 2040 and more than 200 Mt by 2050.
[4] According to the latest report by IEA, "Special Report on Solar PV Global Supply Chains" published in July 2022, it is estimated that the global cumulative flow of decommissioned solar PV capacity will reach around 7 GW by 2030 and could increase to over 200 GW by 2040. This represents 400-600 kt of embodied materials cumulatively by 2030 and 11-15 Mt by 2040.

This report provides an overview of the status of PV module recycling in some IEA PVPS Task 12 participating countries in two main sections. First, regulatory schemes, information on PV module waste and relevant companies, and the outlook of each region and/or country are surveyed based on contributions by IEA PVPS Task 12 members. Second, practical treatments of PV module recycling in the markets are surveyed by questionnaire to PV module recyclers in some countries. The data were collected in 2021, reflective of the latest year available.

We hope this report contributes to understanding the status of PV module recycling and to accelerating PV module recycling as a promising option for the proper EOL management of PV modules in the coming decades around the world.

2 STATUS OF PHOTOVOLTAIC MODULE RECYCLING

This chapter examines the status of PV module recycling from the viewpoints of regulatory schemes, information on PV module waste from relevant companies, and overall outlook. Considering the current situation of PV markets and PV recycling activities, the following countries were selected from among the IEA PVPS Task 12 participating countries, organized by region:

- Europe: Germany, France, Italy, and Spain
- Asia and the Pacific: Japan, South Korea, China, and Australia
- North America: United States of America.

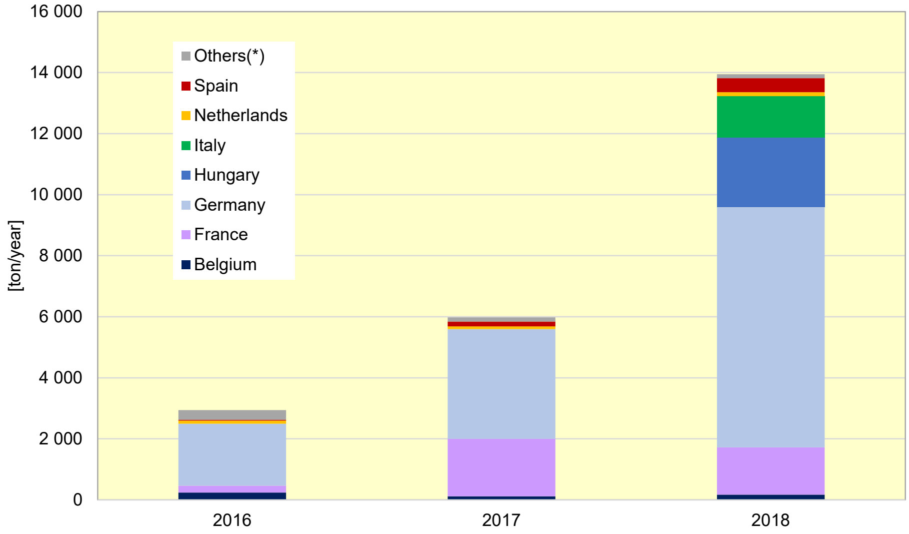
2.1 Europe: Germany, France, Italy, and Spain

In the runup to the world PV markets, in Europe, starting in 2012, PV module recycling was mandated through the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [5], which includes the collection, recovery, and recycling targets for waste from electrical and electronic equipment, including PV panels. Since 2012, all EU members have implemented the PV regulation into national law, requiring all PV panel manufacturers in the EU market to either operate their own take-back and recycling systems or join existing producer compliance schemes.

According to the EU directive [5], from 2019, the minimum collection rate to be achieved annually shall be 65% of the average weight of the electrical and electronic equipment placed on the market in the three preceding years in the member state concerned, or, alternatively, 85% of WEEE generated on the territory of that member state.

Corresponding to the WEEE directive, several European R&D initiatives are driving the improvement of recycling technologies for the different PV technology families. These initiatives aim to decrease recycling costs and increase the potential revenue streams from the secondary raw materials recovered through the recycling process. Also, the European Committee for Electrotechnical Standardization developed specific PV treatment standards for different fractions of the waste stream to support a high-value recycling approach.

Statistical data of PV module waste under the WEEE directive are available via EuroStat statistics [6]. Fig. 2.1-1 shows trends in PV module waste since 2016. Table 2.1-1 shows some details about year 2018, with 13 951 tons of PV module waste collected from 12 countries.



* Austria, Czech Republic, Denmark, Greece, and the United Kingdom

Fig. 2.1-1 PV module waste collected under WEEE in Europe from 2016 to 2018 [2]

Table 2.1-1 PV module waste collected under WEEE in Europe in 2018 [2]

[tons/year]	Germany	France	Italy	Spain	Hungary	Others*	Total
a) Waste collected	7 865	1 555	1 350	462	2 289	430	13 951
b) Waste treatment	7 865	1 555	1 598	276	2 218	296	13 799
c) Recovery	7 708	1 513	1 408	249	1 890	126	12 894
d) Recycling and preparing for reuse	6 896	1 399	1 361	240	1 890	116	11 902
e) Preparing for reuse	909	-	-	-	-	-	909
Ratio: (c/b)	98.0%	97.3%	88.6%	90.2%	85.2%	42.6%	93.4%
Ratio: (d/b)	87.7%	90.0%	85.7%	87.0%	85.2%	39.2%	86.4%

* Austria, Belgium, Czech Republic, Denmark, Greece, the Netherlands, and the United Kingdom

The status of PV module recycling in Germany, France, Italy, and Spain—the top four countries in the EU excluding Hungary—is presented in the next sections from the viewpoints of “relevant regulations and schemes,” “treatment of PV module waste,” and “outlook.”

2.1.1 Germany

(1) Relevant regulations and schemes

The EOL management of PV modules in Germany is covered by the regulation “Elektrogesetz” or “ElektroG” since 2018, which complies with WEEE. Manufacturers and retailers are required to register PV modules placed in the market. The registration is conducted by the "Stiftung Elektro-Altgeräte-Register", wherein PV modules are categorized according to their size. The required collection rate for EOL PV modules is 85%, whereas the required recycling rate of recovered scrap materials is 80%. According to the extended producer responsibility (EPR), manufacturers must ensure that collection rates and recycling quotas are achieved. All PV modules require a registration and a specific EOL treatment, but, depending on the type of application - business-to-business (used for a business or by a company) or business-to-customer (used by private customers, such as residential) - different requirements are applied. Business-to-customer PV modules are collected without charge for the customers on municipal waste collection points. Manufacturers and retailers must confirm default-free guarantees for these modules. Business-to-business PV modules require a direct take-back/collection but no default-free guaranties; hence, collection fees could apply for business customers.

(2) Treatment of PV module waste

According to the EuroStat statistics [6], in Germany, the volume of PV modules placed on the market in 2018 was 211 142 tons. The amount of collected PV modules was 7 865 tons, whereas 2 259 tons were collected from households, and 5 606 tons were collected from other sources. Of the 7 708 tons recovered, 6 896 tons were recycled, with 909 tons listed to be prepared for reuse.

The take-back, recycling, and reuse of EOL PV modules in Germany are organized by service providers, such as PV CYCLE or take-e-way GmbH, which provide full-service administration, take-back, and recycling of EOL modules.

The recycling of crystalline silicon (c-Si) PV modules is mainly done by glass recycling companies, such as Reiling Unternehmensgruppe. A specific recycling line of cadmium telluride (CdTe) PV modules is operated by First Solar in Frankfurt (Oder).

(3) Outlook

According to the IRENA/PVPS Task 12 report on EOL PV panels published in 2016 [4], a projection range of cumulative waste volume in Germany, depending on the scenario of average lifetimes of PV modules, is between 400 000 tons and 1 million tons for the year 2030, and is expected to increase to 4.3 million tons in 2050.

In May 2021, the nongovernmental organization Environmental Action Germany (Deutsche Umwelthilfe, DUH) published a white paper [7] addressing the challenges and opportunities for improving the circularity of the PV sector in Germany. This white paper is based on expert interviews and stakeholder surveys, and it summarizes and discusses the main challenges and opportunities for strengthening the circular economy of PV along its life cycle—from product design, to market placement, to collection, repair, and reuse—as well as the recycling of PV modules at their EOL.

The white paper highlights the need for improvements in the current collection of used and disposed PV modules with regard to the collection process but also in terms of transparency and economic aspects. As a result of improper treatment, the repair and reuse of used modules is not always ensured. Further, improper collection might also lead to the disposal of modules. Also, there is the need for better communication and information to relevant stakeholders and to the public regarding the collection and take-back, processes, and responsibilities in the recycling and disposal of used or disposed PV modules. In this regard, public collection systems must be improved to ease the return of PV module waste for private users (e.g., when returning large amounts of modules). An additional challenge for business-to-business modules describes the EPR of the ElektroG that requires PV module producers to provide possibilities to return and recycle used modules that were placed in the market after 24 October 2015. On the one hand, it must be ensured that all producers comply with these requirements; on the other hand, under current conditions, collection and recycling is expensive. Currently, there are no similar regulations addressing modules that have been placed in the market before 24 October 2015; hence, the costs for collection and recycling were not included in the pricing of sold modules, and owners could incur return fees. There is a need for more cost-effective solutions for disposing used modules so they are not placed in improper recycling systems.

Further, the white paper states that the amount of collected modules in the EU as reported to WEEE is still low compared to the expected volumes of used and waste modules, but it is not clear whether the lifetime of the modules is higher than expected or whether used modules have bypassed the collection system (e.g., by being resold in second-hand markets or by being illegally exported). This shows the need for increased transparency in the disposal of used and waste modules. If modules have left the German market to countries with less developed waste collection or waste management systems, there is a risk that waste modules are not being properly recycled or disposed; thus, there is a need to enhance the possibilities of the repair and reuse of used PV modules while also stopping illegal exports and improving circularity.

The white paper also states that modules are difficult to recycle; therefore, valuable materials are often downcycled for other applications or get lost. There is a high potential to develop better technical solutions for better recycling (e.g., for glass and silicon (Si) recycling); however, investments in recycling require security, which will be improved with increased volume streams of used or PV module waste. Specific recycling requirements could also provide incentives for the introduction of best practice technologies. Further, improved recyclability of modules must be implemented during product development, which could be enhanced by eco-design regulations.

2.1.2 France

(1) Relevant regulations and schemes

In France, the transposition of the directive 2012/19/EU was made into French law in 2014 by the Décret n° 2014-928 [8] of the French code of the environment. The Article R.543-172 [9] defines a specific category for PV equipment (category 7) which facilitates considerably the reporting of reliable data in France compared to other countries regarding the collected PV waste stream. Article 5 of the decree from 14 October 2014 [10] established minimum recovery and recycling ratios of 85% and 80% respectively. These ratios were initially to be increased through a national consultation in 2021, but finally were not modified.

(2) Treatment of PV module waste

The only non-profit eco- organization so called Producer Responsibility Organization (PRO) approved by ministerial decree in France for the treatment of PV waste is Soren (formerly PV CYCLE France[5]), which consequently has a monopoly on PV module waste management. Soren manages both collection and recycling by operating private tendering procedures that enable the centralization of PV waste management in France. The organization is subject to a set of specifications defined at the national level, which might require more stringent obligations

[5] The brand name PV CYCLE France was changed to Soren in July 2021.

(e.g., ratios for collection, recovery, and/ or recycling) than the regulations previously introduced [8][9].

In France, the amount of collected PV module waste has increased by more than 13 times from 366 tons in 2015 to 4 905 tons in 2019, as shown in Fig. 2.1-2. The smaller amount collected in 2020 (4 102 tons) is explained by the impacts of the COVID-19 pandemic—few collection points operated during lockdown, and health rules made collection slower because only one truck could be at one site at a time. Several dismantlement processes were also delayed.

The distribution of PV module waste in 2019 and 2020 by technology is shown in Fig. 2.1-3, including c-Si, CdTe, amorphous-silicon (a-Si), copper indium gallium selenide (CIGS), and flexible PV. Most waste comprises c-Si and CdTe, whereas a-Si represents more than 15%. In 2019, PV module waste was sent to different recycling facilities, with c-Si waste treated at the recycling facility Triade Electronique (Veolia subsidiary), CdTe in Germany, and others sent to specific treatment plants.

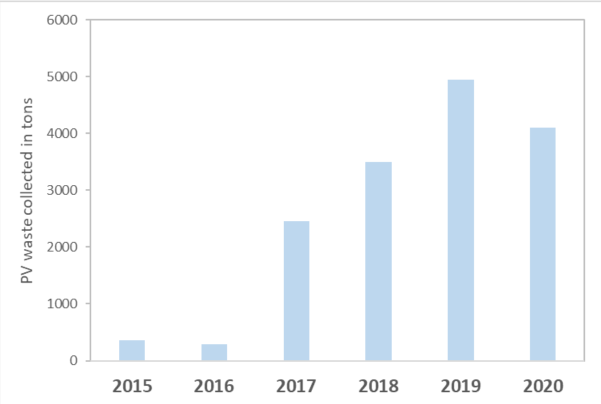


Fig. 2.1-2 PV waste collected in France (2015–2020) [11]

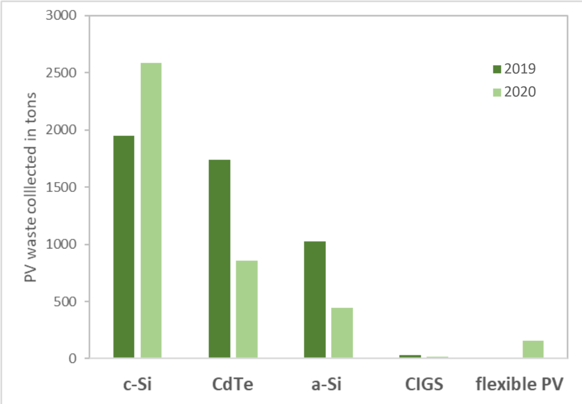


Fig. 2.1-3 PV waste collected in France by technology (2019–2020) [11]

The first facility dedicated to c-Si PV module waste recycling was implemented by Veolia in 2017, contracted by Soren in Rousset (located in the south of France). The PV modules are visually sorted and weighed, and the aluminium frame, junction boxes, and cables are semiautomatically removed. Finally, the multilayer PV laminates are cut into strips before being crushed and sorted using an eddy current separator to extract the metallic parts. The processing time is approximately 1–1.5 minutes per module, with a recovery ratio of almost 95%. The secondary raw materials are recovered in the appropriate channels depending on their purity, which is not disclosed as well as the recycling ratio. The mandate given to Veolia by Soren to operate the recycling of PV waste in France ended in December 2020 and the associated operations in April 2021.

(3) Outlook

Projections of expected PV waste in France are presented in Fig. 2.1-4. This shows more than 43 000 tons by 2030 and 118 000 tons by 2040, are expected annually. To meet this drastic increase, in February 2021, Soren launched a new tender process to implement three new facilities dedicated to PV recycling in France. Two facilities are currently running since June 2021: one operated by Galloo in Halluin (located in the north of France), and a second one operated by ENVIE 2E Midi-Pyrénées in Portet sur Garonne (located in southwestern France).

The third facility will be operational in September 2022 by ENVIE 2E Aquitaine in Saint-Loubès (located in southwestern France).

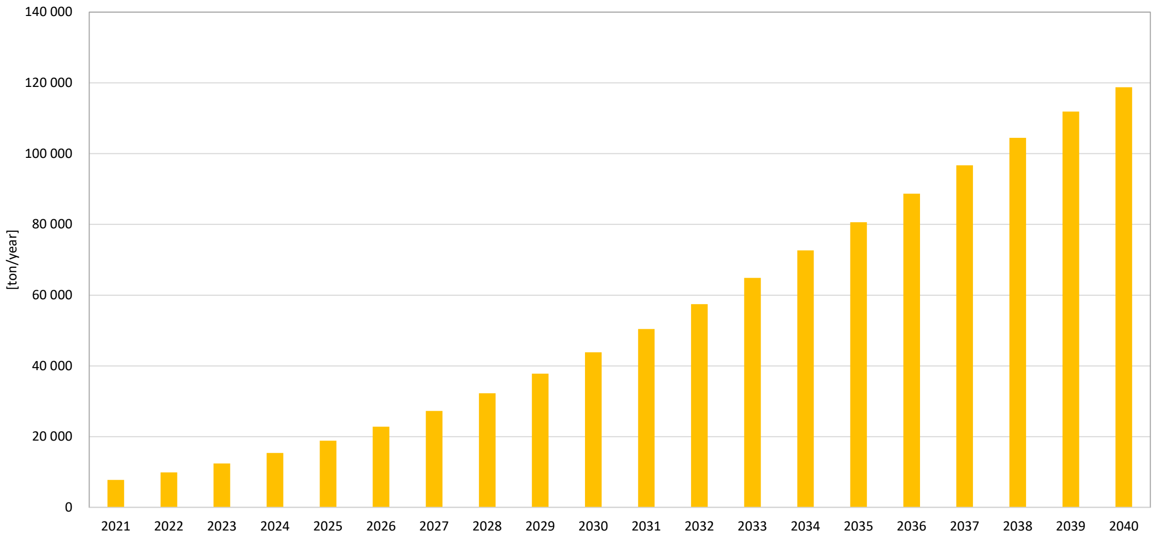


Fig. 2.1-4 Projection of PV waste collection in France (2021–2040) [11]

2.1.3 Italy

(1) Relevant regulations and schemes

The directive 2012/19/EU [5] was implemented in the Italian national regulatory system with the Legislative Decree No. 49/2014 [12]. This decree has two main objectives: (1) to prevent or reduce the negative effects resulting from the design and production of electrical and electronic appliances and from the production or management of waste derived from electrical and electronic appliances and (2) to reduce the negative impacts and improve the efficient use of resources to achieve the objectives of sustainable development in accordance with the criteria listed in the Legislative Decree No. 152/2006 – Environmental Code [13].

Legislative Decree 49/2014 applies to the categories of electrical and electronic equipment listed in Annex I of the WEEE directive until the end of the transitional period on 14 August 2018. After the end of this period, the legislative decree will apply to the categories listed in Annex III of the WEEE directive. Under this decree, PV modules are equivalent to electrical and electronic equipment and are distinguished according to the size of the plant in which they are installed:

- Modules installed in plants with a nominal power less than 10 kWp are classified as “domestic WEEE.”
- Modules installed in plants with a nominal power greater than 10 kWp are classified as “professional WEEE.”

The Italian law on electrical and electronic waste continues to place important responsibilities on EU producers. According to Article 4 of Legislative Decree 49/2014, the term “producers” also includes importers of electrical and electronic equipment, even if the manufacturer of the product is located outside of Italy. These responsibilities are in effect as provided by the WEEE directive; however, Legislative Decree 49/2014 imposes higher minimum recovery rates than the EU WEEE directive—up to 85% (PV modules) - on producers of categories of goods listed in Annex V. Legislative Decree 49/2014 also sets out the criteria that producers’ individual (Art.

9) and collective (Art. 10) recovery methods must meet. Legislative Decree 49/2014 assigns recovery costs to producers based on several factors, including whether the goods in question are for domestic (Art. 23) or professional (Art. 24) use and whether they were placed in the market before or after 13 August 2005. Legislative Decree 49/2014 also places upon producers the obligation to provide users with information regarding, among other issues, the modalities of recovery of the goods in question as well as the potential environmental impacts of any dangerous substances they may contain (Art. 26). Finally, it mandates that producers must affix a trademark to their goods so that the producer's identity can be easily recognized (Art. 28) and that before starting operations in Italy, producers must be enrolled in the National Register of Subjects Obliged to Finance the Management Systems of WEEE (Art. 29).

(2) Treatment of PV module waste

According to the EuroStat statistics [6], the amount of collected PV modules in 2018 was 1 350 tons. Collected modules from households totalled only 11 tons, whereas collected modules from other sources totalled 1 339 tons.

Italy's energy services manager, GSE (Gestore dei Servizi Energetici SpA), sets the instructions for the disposal of modules installed in Italian plants with feed-in-tariff (FIT) schemes, as contemplated by Article 1 of Legislative Decree 118/2020 [14]. The domestic PV modules that reach EOL must be either:

- Sent to a national collection center (there are more than 4 000 in Italy). The private citizen can therefore bring the used modules to the municipal ecological platform.

or

- Managed through the distributor/installer where the modules were purchased (e.g., the old modules can be returned to the installer when purchasing new ones).

In the case of the professional PV modules, once they have been decommissioned, they must be either:

- Given to an entity authorized to manage waste such as PV modules (generally belonging to the EWC (European Waste Catalogue) code 16.02.14)

or

- Transported to an authorized treatment plant

or

- Sent to a national collective system.

The plants that benefit from the FIT scheme - or, rather, the PV modules that comprise those power plants - must comply with the rules set by GSE, according to which the replacement and/or disposal of modules (identified with a serial number) must be communicated to GSE. When disposing of domestic modules, the owner is required to fill in the form Annex 8.1 and send it to GSE within 60 days of completion of the maintenance work. The document must specify who has taken charge of the management of the disposal of the panels, and a table must also be filled in reporting the brand, model, and serial number of the modules sent for treatment.

Regarding professional PV modules, the owner of the plant must send to GSE the form Annex 8.1 specifying the place of delivery of the modules (national collective system, authorized entity, or other), a copy of the FIR (waste identification form), and a certificate of treatment of the EOL PV modules issued by the destination plant. As in the domestic case, the documentation must be sent within 60 days of the completion of the maintenance work.

The GSE rules do not oblige the recycling of modules when they are decommissioned (making them eligible for reuse or resale). In order to ensure the financing of collection, transport, appropriate treatment, environmental compatible recovery and disposal of waste produced by PV modules, the GSE withholds from the incentive mechanisms in the last years of right to the incentive a share aimed at guaranteeing coverage of the management costs of the aforementioned waste. The amount withheld is returned to the holder, if it is ascertained that the obligations laid down in the Legislative Decree 49/2014 have been fulfilled; otherwise, the GSE provides directly, using the amounts retained. The share withheld (from the incentives) by the GSE is equal to:

- at a value of 12 EUR per module for domestic PV modules (at the 15th incentive year);
- at a value of 10 EUR per module for professional PV modules (fee spread over the last 10 years of incentive)

To date, in Italy, there are no recycling plants exclusively dedicated to PV modules because the volume of EOL PV modules is not sufficient to create an ad hoc market.

(3) Outlook

According to the IRENA/IEA PVPS Task 12 report on EOL PV panels published in 2016 [4], a projection range of cumulative waste volume in Italy, depending on the assumptions of average lifetimes of PV modules; is between 140 000 and 500 000 tons for the year 2030 and is expected to increase to 2.2 million tons in 2050.

2.1.4 Spain

(1) Relevant regulations and schemes

In Spain, the directive 2012/19/EU was approved into the Royal Decree 110/2015 of 20 February 2015 [15], which includes updates to Law 22/2011 of 28 July 2011 on waste and contaminated soil [16] and repeals the former royal decree on electrical and electronic waste. The current law in force about waste and contaminated soil is the law 7/2022 of April, on waste and contaminated soil for a circular economy [17].

One main concept of this legislation is the EPR. The producer (manufacturer, distributor, installer, etc.) is obliged to comply with the obligations of the product design, to adopt the necessary actions to manage the waste of its products, and to cover the cost for this management. The producers must register their products in the national register of producers of electrical and electronic equipment (RII_AEE), managed by the Ministry of Industry, Commerce, and Tourism (MINCOTUR). The registration can be done individually or through a producer responsibility organization (PRO). If the system is collective, each producer contributes a quota to the systems based on the number of product they put in the market per year. If it is individual, the producer assumes all the costs. Currently, there are 11 authorized producer responsibility organizations according to Royal Decree 110/2015: Reinicia, Ecotic, Ambilamp, Ecolec, Ecofimática, Ecolum, Ecoasimelec, ERP, Eco-Raee's, Sunreuse, and Ecoeche [18]. They are responsible for organizing and financing the management of WEEE. They collect the money from the producers and they are in charge of the management of the WEEE and of the information obligations towards the administrations and consumers.

PV modules (with a dimension larger than 50 cm) are included in the scope of the Royal Decree 110/2015. Currently, and after the modifications included in the Royal Decree 208/2022, they are included in the following categories: 7.1-Silicon non-hazardous PV panels; 7.2-Other non-hazardous PV panels; 7.3-Hazardous PV modules.

In the first quarter of each year, the MITERD (Spanish Ministry for the Ecological Transition and the Demographic Challenge) publishes the collection of WEEE targets to be achieved by collective systems for the current year. Targets for individual systems are communicated to each producer. These targets are based on the amount of WEEE placed in the market in the previous three years.

In January 2021, the Royal Decree 27/2021 [19] introduced modifications to the previous Royal Decree 106/2008 regarding batteries and accumulators and the Royal Decree 110/2015 about WEEE. The modifications addressed the EU Directive 2018/849 of the European Parliament and of the Council of 30 May 2018 [20]. In relation to the topic, the MITERD, after public consultation, issued the Royal Decree 208/2022 about financial guarantees on waste [21].

(2) Treatment of PV module waste

The treatment of waste coming from PV modules is in a very preliminary stage in Spain. The amount of PV module waste collected yearly is still small. Table 2.1-2 shows the amount of electrical and electronic equipment put on the market in Category 7, PV modules, and Table 2.1-3 shows the WEEE collected in this category.

Table 2.1-2 WEEE Category 7 (Category 4.b up to 2018): PV panels placed on the market in Spain [18]

Year	Put on the market (tons)
2017	1 532.24
2018	21 854.54
2019	83 256.34
2020	221 998.21

Table 2.1-3 WEEE Category 7: PV panels (4.b up to 2018) collected [18]

Year	Total collected (tons)	Treated (tons)	Recovery (tons)	Preparing for reuse and recycling (tons)
2017	155.13	149.00	134.10	102.21
2018	461.89	276.00	248.55	240.35
2019	226.15	120.53	117.29	104.33

The collective systems that have targets for PV waste collection in 2022 according to the last publication of the MITERD [22] are:

- ECOASIMELEC
- ECOTIC
- EUROPEAN RECLING PLATFORM ERP SAS SUCURSAL EN ESPAÑA
- FUNDACIÓN ECOLEC
- SUNREUSE ASSOCIATION

However, there are individual systems that contribute to the amount of PV waste that are not included in this list.

(3) Outlook

The amount of PV waste in Spain is currently small, but it will increase in the short to medium term caused by the EOL of the first PV plants installed and in the long term caused by the aging of plants recently installed and the new ones that will be installed in the coming years.

PV waste projections are highly dependent on the historical evolution of yearly installed PV capacity and the predictions for future installations. Fig. 2.1-5 presents the yearly installed PV capacity (a) and the cumulative PV capacity (b) from 2007 to 2020. As shown, the evolution of PV capacity in Spain does not follow a linear trend, which should be considered when predicting the future amount of waste. Another remarkable point is the increase of installed PV power in 2019 and 2020 compared with the previous years. This change is in line with the new actions to achieve climate neutrality.

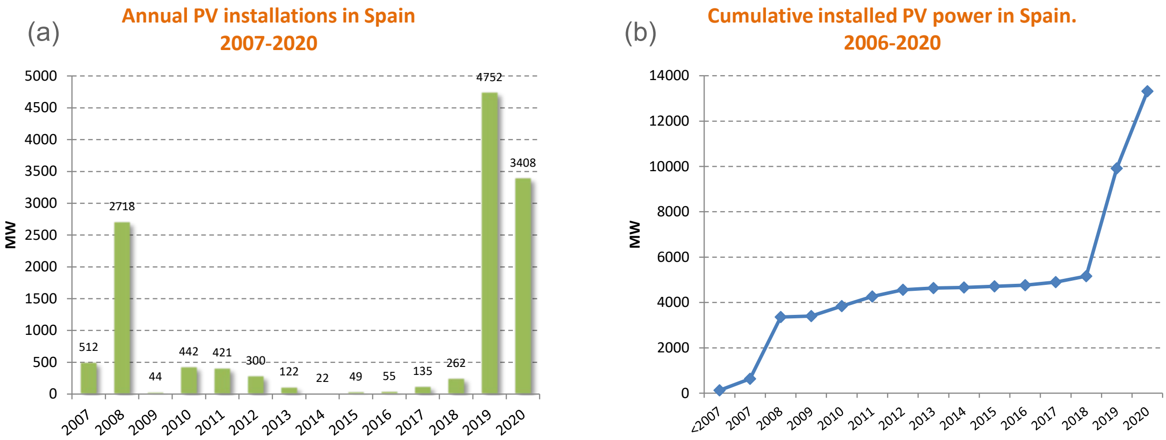


Fig 2.1-5 Yearly (a) and cumulative (b) installed PV capacity in Spain during 2007–2020 [23]

In March 2021, the final version of Spain’s integrated National Energy and Climate Plan 2021–2030 [24] was published. This plan foresees an increase in renewable energy capacity, with a target scenario of 39 GW of installed PV capacity to 2030.

Some scientific studies have forecasted PV waste in Spain based on different projections [25, 26]. The latter [26] is an update of the former, and the different scenarios used to calculate PV waste are based on two approaches— one with an estimated PV capacity of 47 GW by 2030 and the other with 26 GW by 2030—which cover the target scenario of Spain’s current integrated National Energy and Climate Plan. Based on these projections, several regular loss and early loss scenarios for PV waste are calculated to 2050.

2.2 Asia and the Pacific: Japan, South Korea, China, and Australia

In Asia and the Pacific, there are currently no nationwide schemes for PV module recycling and EOL management; however, some countries are implementing various discussions and activities for promoting the proper EOL management of PV module waste. This section presents the status of PV module recycling in Japan, South Korea, China, and Australia.

2.2.1 Japan

(1) Relevant regulations and schemes

Currently in Japan, there are no specific regulations for EOL PV modules, which must be treated under the general regulatory framework for waste management: the Waste Management and Public Cleaning Act. The act prescribes definitions of waste; responsibilities of industrial waste generators and waste management; the handling of industrial waste, including landfill disposal, and so forth.

Yet the Ministry of Economy, Trade, and Industry (METI) and the Ministry of Environment (MOE) have jointly assessed how to handle EOL PV modules. The second edition of the guideline for promoting the proper EOL treatment of PV modules, including recycling [27], was published in December 2018, as an update to the first edition, which was published in April 2016. The guideline covers basic information, such as relevant laws and regulations on decommissioning, transportation, reuse, recycling, and industrial waste disposal. Further updates to the guideline are under discussion. Also, in May 2021, MOE published a guideline for promoting the proper reuse of PV modules [28].

Also, Japan's FIT scheme will require a levy to fund the waste management of EOL PV in advance [29]. This will be in effect by July 2022, and owners of PV systems and plants, excluding residential PV systems (less than 10 kW), are obliged to comply. The amount to be reserved will vary in relation to the certificates under the FIT scheme. FIT rates for PV are calculated by considering 10,000 JPY/kW as the reserve for PV systems certified in fiscal years 2020 and 2021. This reserve will be equivalent to 0.66 JPY/kWh–1.33 JPY/kWh [30].

(2) Treatment of PV module waste

At present, there is no statistical information on PV module waste volumes in Japan. According to the guideline published in December 2018 [27], it was estimated that 4 400 tons/year of PV waste were generated; from that, approximately 3 400 tons of modules would be reused, and 1 000 tons of modules would be recycled. Also, according to the MOE [31], it was estimated that 6 300 tons/year of PV waste were generated in 2020; from that, approximately 4 200 tons of modules would be reused, and 2 100 tons of modules would be sent to recycling facilities.

Table 2.2-1 shows a list of 29 companies accepting PV modules for recycling in Japan [32]. The list was developed by the Japan Photovoltaic Energy Association, and it is updated in due time to support and promote EOL treatment.

More than half the companies listed have installed specific equipment for PV module recycling (separating the PV module's structure and components); however, because the amount of PV module waste is relatively small, the operation rate of these companies is currently low.

The other companies are treating more common types of industrial waste whose main function is to separate bulk materials.

Table 2.2-1 Examples of companies that can "properly treat" PV modules in Japan [32]

Name	Location	Name	Location
Matec, Inc.	Ishikari, Hokkaido	Econecol, Inc.	Fujinomiya, Shizuoka
Seinan Corporation	Hirosaki, Aomori	Harita Metal Co., Ltd.	Takaoka, Toyama
Mitsuba-Shigen Co., Ltd.	Towada, Aomori	Recycle Tech Japan	Nagoya, Aichi
Kankyo Hozen Service Co., Ltd.	Oshu, Iwate	Ecoadvance	Iga, Mie
Moriya	Higasine, Yamagata	Kinki Denden Yuso, Ltd.	Neyagawa, Osaka
Takaryo Corporation	Minamisoma, Fukushima	Hakuto Total Recycle System Co., Ltd.	Tottori, Tottori
Shirakawa Syouten	Koriyama, Fukushima	HIRABAYASHI METAL Co., Ltd.	Okayama, Okayama
Nisso Metallochemical Co., Ltd.	Fukushima (Taito, Tokyo)	Kangai	Kurashiki, Okayama
Mitsukaido Sangyo	Joso, Ibaraki	JFE Bars & Shapes Corporation	Kurashiki, Okayama
Kankyo Tsushin Yuso	Ushiku, Ibaraki	Sunada Co., Ltd.	Higashi-hiroshima, Hiroshima
Um-Welt-Japan Co., Ltd	Yorii, Saitama	Kaneshiro Sangyou	Matsuyama, Ehime
Re-Tem Corporation	Ibaraki (Chiyoda, Tokyo)	NPC Incorporated	Matsuyama, Ehime
Hamada Co., Ltd.	Minato, Tokyo & Takatsuki Osaka	Recycle Tech Co., Ltd.	Kitakyushu, Fukuoka
Tokyo Power Technology, Ltd.	Koto, Tokyo	Kyusyuhokusei Co., Ltd.	Kobayashi, Miyazaki
Toshiba Environmental Solutions Corporation	Yokohama Kanagawa		

Fig. 2.2-1 Map showing location of companies that can "properly treat" PV modules in Japan (based on Table 2.2-1)

(3) Outlook

It is forecasted that the amount of PV module waste will increase to 170 000–280 000 tons/year by the mid-2030s [33], as shown in Fig. 2.2-2, which will correspond to more than 10 times the current capacity of PV module recycling equipment identified.

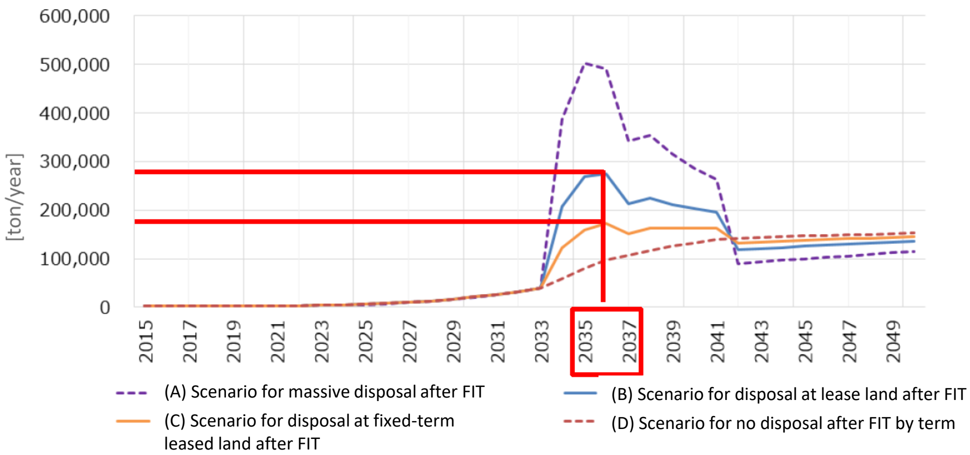


Fig. 2.2-2 Forecast of the amount of PV module waste in Japan [33]

A challenge to achieving a high-value recycling business is finding high-value products for the glass recovered from EOL PV modules. Currently, some projects to find solutions for high-value glass recycling are under development, for example, under the NEDO projects [34].

Also, the installed PV systems in Japan are dominated by residential PV systems. To achieve a low-cost recycling business, discussions have begun on how to develop efficient collection and transportation systems for EOL PV modules.

2.2.2 South Korea

(1) Relevant regulations and schemes

PV module waste has become a severe problem because of the destruction of a PV plant by a typhoon in the Cheongdo-gun area in July 2018 (see Fig. 2.2-3). On 5 October 2018, the Ministry of Environment (ME) announced that PV module waste will be included in the list of items affected by EPR regulations [35, 36]. The ME formed a consultative group with PV manufacturers to discuss a better way to design EPR regulations in the PV industry. Eventually, the government and PV module manufacturing companies agreed to introduce EPR regulations to the PV industry. On 28 August 2019, the Ministry of Trade, Industry, and Energy and the Korea Photovoltaic Industry Association, as a representative of PV manufacturers, signed an agreement to include PV panels in the EPR list. This agreement implies that EPR will be enforced in the PV industry in 2023, after the collection infrastructure for PV module waste and the development of recycling technologies is established in 2022 [37]. Legislation with an amendment of the "enforcement rule of the act on resource circulation of electrical and electronic equipment and vehicles" was completed in December 2019, although the act will be enforced only after 1 January 2023 [38]. In this rule, PV modules are classified as a separate product group that differs from existing waste groups, such as temperature exchangers, displays, communication/office equipment, and general electrical/electronic devices. In addition, intermediate processes—such as disassembling, sorting, and crushing—should be used, and the rates of recycling or reuse should meet the demand of more than 80% based on the total weight of products.

Fig. 2.2-3 PV module waste generated by a typhoon in Cheongdo-gun in 2018 [39]

(2) Treatment of PV module waste

Because the EPR regulations will go into effect at the end of 2022, the current amount of PV module waste and treated PV modules in South Korea is unknown. According to Yoonjin Tech, one of several companies in South Korea with a PV waste treatment license, most recently treated PV waste consists of defective modules generated during the manufacturing process. In almost 6 months during 2020, approximately 55 tons of PV waste generated from PV power generation plants were correctly recycled. Statistics of the Korea Environment Corporation [40] concerning PV waste declared by owners during the last 3 years indicate that approximately 540 tons of waste were disposed and recycled as of June 2020, as shown in Table 2.2-2.

Although a large amount of PV waste is currently generated from PV plants, most is landfilled after manual detachment of the metal frame because recycling is not currently compulsory.

The waste code 514104, representing waste from solar cells and pastes in electronic devices in the Wastes Control Act, was established in July 2016 as a subcategory of waste by type, but it was not used for PV module waste before 2018. After the destruction of the PV plant in Cheongdo-gun, the code was redefined to include PV module waste. Further, the use of the waste management system "Allbaro," operated by the Korea Environment Corporation, was officially applied in October 2018, when manuals for the temporary collection and storage of PV module waste were distributed. To clarify the name of the waste in the code, "waste of solar panel" has been added to the waste name in 2021. It is assumed that codes 511800, related to electronic equipment waste, or 513001, linked to glass waste, were previously used for the treatment of PV module waste because most manufacturers and users were not aware of the codes related to PV waste.

Table 2.2-2 Statistics of PV module waste declared during the last 3 years as of June 2020* [40]

Year	Waste code	Waste name	Annual PV panel waste (tons)
2018	514104	Waste of solar cells, paste in electronic devices, waste of solar panel	17.55
2019			245.605
2020			279.407

*More recent data has not been released.

Regarding companies treating EOL PV modules, Yoonjin Tech (Gyeongbuk Province) was the first company in South Korea to recycle PV waste, and therefore current statistics on treated PV waste are based on their data. The company is capable of recycling 1 000 tons/year of panel waste and has plans to expand its capacity to 3 600 tons/year. In late 2020, the company WonKwang S&T (Incheon metropolitan) launched a PV recycling operation with facilities capable of recycling 1 200 tons/year of PV waste. Further, Chungbuk Technopark (Chungbuk Province) established a PV recycling center capable of recycling 3 600 tons of PV panel waste from November 2016–September 2021. Although several other companies have plans for PV recycling, these do not include a detailed schedule for setting up the facilities.

Table 2.2-3 List of companies using intermediate processors to correctly treat PV waste in South Korea [41]–[44]

Company name	Region	Capacity (tons/year)	Method
Yoonjin Tech	Gyeongbuk	3 600	Physical
WonKwang S&T	Incheon	1 200	Physical
Chungbuk Technopark	Chungbuk	3 600	Combination of physical and thermal

Fig 2.2-4 PV module recycling facilities of Yoonjin Tech (left) [41], WonKwang S&T (center) [43], and Chungbuk Technopark (right) [44]

(3) Outlook

According to predictions of annual PV module waste by the Korea Environment Institute in 2018, representing the latest version of officially published forecasts, the amount of PV waste is expected to increase continuously over time. This forecast was estimated based on the annual amount of PV installations and specific PV module life spans. PV modules recently installed will have a longer life span than older modules, owing to improved manufacturing technology. The amount of annual module waste is predicted to reach 9 665 tons in 2023, consistently increasing to 20 935 tons in 2030, and 112 564 tons in 2040 (see Fig. 2.2-5).

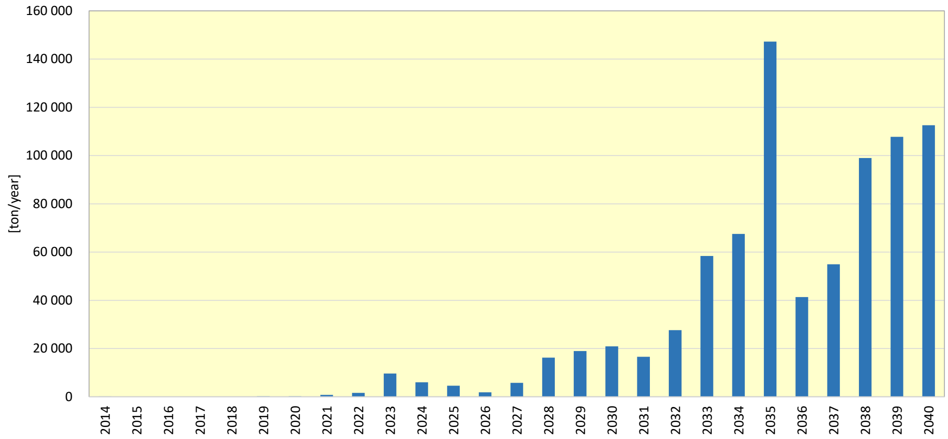


Fig. 2.2-5 Forecast of the amount of PV panel waste generated in South Korea [45]

To meet the increasing amount of PV module waste, various government-funded R&D projects to develop technologies related to PV recycling have been established in South Korea, as shown in Table 2.2-4. Some are focusing on disassembling modules through eco-friendly and low-cost processes with low energy consumption, whereas others aim to make the recovered materials applicable to other secondary markets, such as structural ceramics or construction materials.

Table 2.2-4 Recent government-funded projects related to the recycling of PV waste in South Korea [46]

Funding source	Project name (project period)	Company name
Ministry of Trade, Industry, and Energy	Establishment of PV recycling center (November 2016–June 2021)	Chungbuk Technopark

Ministry of Trade, Industry, and Energy	Remanufacturing of PV modules with material recovered from EOL PV modules (October 2018–September 2021)	Korea Institute of Energy Research
Ministry of SMEs and Startups	Development of equipment for the recovery of valuable metals by recycling EOL PV systems and application as construction materials (October 2019–September 2021)	Hanjung Energy Networks
Ministry of SMEs and Startups	Localization of equipment to separate solar cells, protective sheets, and tempered glass from PV modules (November 2019–November 2021)	Reset Company
Ministry of Ecology and Environment	Development of technology for collecting, shattering, and recycling recovery of valuable materials from EOL PV modules (May 2020–December 2022)	WonKwang S&T
Ministry of Ecology and Environment	Development of 99.99% silicon carbide powder and mechanical seal/semiconductor tube parts using recovered Si from solar module waste (May 2020–December 2022)	PLUS Manager
Ministry of Ecology and Environment	Development of 4N Si material technology by wet processing of solar cells recovered from solar panel waste (May 2020–December 2022)	Dream Mining
Ministry of SMEs and Startups	Development of an eco-friendly, low-cost, high-value recycling process for EOL PV modules using physical separation (October 2020–October 2022)	Woowontech
Ministry of SMEs and Startups	Recycling the silicon waste from the PV industry to composites for secondary batteries' anode materials (November 2021-October 2023)	J-Solution

2.2.3 China

(1) Relevant regulations and schemes

At present, China's policies and regulations on PV module recycling and EOL management are under development. There are a variety of methods and feasible technical routes in the recycling technology of PV modules in China and abroad. At the same time, the number of EOL PV modules in China is gradually growing, and the corresponding industrial chains are being developed. Therefore, in terms of policies and regulations, China is making efforts to study and introduce relevant policies to guide the PV module recycling industry:

- In February 2009, the State Council promulgated the "Regulations on the administration of waste electrical and electronic products recycling" (implemented since 1 January 2011), which stipulates that waste from electrical and electronic products can be collected in different ways and should be recycled in a centralized system. Producers of electrical and electronic products are encouraged to recycle waste electrical and electronic products on their own or by entrusting sellers, maintenance agencies, aftersales service agencies, and recycling operators of waste electrical and electronic products. Although PV modules are not included in the list of waste electrical and electronic products for disposal stipulated in the regulations, these documents can be used as a model and reference for formulating policies and regulations related to the recycling and disposal of PV modules, and they are expected to effectively promote this process in China.

- In terms of high-tech R&D projects, the state has provided support for topics related to PV module recycling. During the 12th Five Year Plan period, the National 863 project subtask "Research on PV equipment recycling and harmless treatment technology" carried out research on PV module EOL recycling and harmless treatment technology using two recycling routes (mechanical and thermal-chemical methods) and carried out relevant empirical research.

To promote training and capacity building, public awareness, and an international cooperation platform in green manufacturing, the China Green Supply Chain Alliance was established by the International Economic and Technological Cooperation Center of the Ministry of Industry and Information Technology of China. This was done in cooperation with key industry organizations, universities, scientific research institutes, financial institutions, and industry associations.

In January 2020, ECOPV was officially established as the PV committee of the China Green Supply Chain Alliance, with the goal of achieving a "PV green supply chain" and a "better ECO battery PV." The establishment of ECOPV is conducive to achieving China's national goal of renewable energy and emissions reductions obligations, filling the gap of third-party professional services committed to the PV and green supply chains in China, promoting the innovative research and application of environmental protection and new PV products and materials, and solving the environmental and ecological risks in the whole life cycle of PV. ECOPV provides a good communication platform for the research of PV module recycling technologies, which can better promote the development of the recycling industry.

To open up the last key link of the photovoltaic green supply chain, harmless treatment, recycling and reuse after photovoltaic EOL, with the support of China Green Supply Chain Alliance and ECOPV, together with relevant enterprises and colleges, a national, comprehensive, service-oriented, non-profit cooperative organization "PV Recycle Industry Development Center" (hereinafter referred to as "PV Recycle Center") was established. In the next few years, the PV Recycle Center will complete the preparation and release of the "Annual China Photovoltaic Recycle and Circularity White Book", and will hold the annual China Photovoltaic Green Supply Chain Conference (PV Recycle International Forum) and the construction of the "China Photovoltaic Recycle Exhibition Hall". In addition, the PV Recycle Center will also prepare to launch the "Photovoltaic module recycling market forecast and the creation of digital system and platform", "Qualification accreditation management system research project of photovoltaic recycling factory" and "Full life cycle carbon footprint and LCA analysis of photovoltaic modules". The three projects are the focus work of PV Recycle Center around the common, basic and urgent problems of the industry.

(2) Treatment of PV module waste

China has started pilot treatment demonstration in scientific research projects, production enterprises, state owned and environmental protection enterprises.

Since 2017, the SDIC Yellow River Hydropower Development Co., Ltd., the largest PV enterprise in Qinghai Province (also taking part in and being the Chair Unit of the PV Recycle

Center), has taken the lead in independently carrying out research on key technologies and equipment for environmental protection treatment and recycling of photovoltaic modules. As of December 2021, the R&D project of "Research on recycling industrialization and equipment localization of crystalline silicon photovoltaic modules" carried out by the company has successfully passed the acceptance. This means that the company has officially built the first PV module recycling pilot line in China with a comprehensive recovery rate of more than 90% and an annual processing capacity of 110 000 modules (roughly equal to 2 750 tonnes). The company has formed a vertical integrated, closed loop PV whole-of-industry chain of polysilicon, silicon wafer, cell, module and photovoltaic power station planning, design and construction, operation and maintenance, detection and evaluation, and module recycling. Technical reserves have been made to reduce the impact of photovoltaic industry on the ecological environment.

But because of the high cost of PV module recycling—such as the extra cost of equipment purchase and maintenance as well as the transportation cost in the centralized collection process of waste modules and waste materials—the economic benefits of PV module recycling are low. This makes many enterprises or research institutions that want to enter the PV module recycling industry hesitate, and the domestic market has little power to recover PV modules; therefore, there is still a long way to go to achieve the goal of the large-scale recycling of PV module waste in China.

Table 2.2-5 Major enterprises/institutions engaging in research on PV component recycling in China [47]

No.	Enterprise/ organization	Research content	Research results	Application
1	Zhuhai Xingye New Energy Technology Co., Ltd.	Research relevant standards of PV module recycling.	A national standard (General technical requirements for recycling of PV modules, GB/T 39753-2021) has been released and will be implemented in 2022. And international standard (Glass in building -- General technical requirements of building integrated photovoltaic modules recycling, ISO 21480) was established in the ISO/TC160/SC 1 working group and entered the committee draft (CD) stage of the international standard.	The standard concerns by many research institutions and enterprises in the industry
2	Jingke Energy Co., Ltd.	Carry out the experimental research on the low-consumption green disassembly of PV modules and the recycling of PV cell materials.	Completed the environmental protection stripping experiment of the back plane, the low-loss pyrolysis experimental process of the module, the recovery technology of bare Si without metal, and the recovery technology of Ag and aluminum on the surface of the PV cell	R&D status, preliminary recovery data have been obtained

3	Yingli Energy (China) Co., Ltd.	Carry out R&D of the intelligent PV module frame disassembly process and the mechanical separation process among different components of glass, EVA, and related equipment.	Form a preliminary solution of intelligent frame disassembly and thermal separation process of glass and EVA based on the physical method.	R&D status, preliminary recovery data have been obtained
4	Beijing Jikedian Renewable Energy Technology Development Center Co., Ltd.	Undertake the research on the "harmless treatment and recycling of PV equipment" of the 863 project of the Ministry of Science and Technology of China in the 12th Five Year Plan.	Complete the domestic PV recycling market forecast and value analysis, the international PV recycling experience summary, and laboratory technology research.	R&D status
5	Chinese Research Academy of Environmental Sciences	Carry out the EVA pyrolysis method and related equipment research.	Put forward the technology route of PV module waste with pyrolysis technology as the core, and carry out the research on the pyrolysis mechanism of EVA, and other plastics in c-Si PV modules.	R&D status
6	China Electronics Standardization Institute	Standard for the recovery and reuse of PV modules	General technical requirements for recycling of c-SI PV modules, T/CPIA 0002-2017	Referred by the domestic manufacturers that plan to carry out the work in the recycling of PV modules
7	SDIC Yellow River Hydropower Development Co., Ltd.	Research on recycling industrialization and equipment localization of crystalline silicon photovoltaic modules	First pilot module recycling line in China with a comprehensive recovery rate of more than 90% and an annual processing capacity of 110 000 modules	R&D status, preliminary recovery data have been obtained

(3) Outlook

The official statistics of the China Photovoltaic Industry Association show that the forecasted amount of PV module waste to be recycled will exceed 4 million tons by 2035 [48]. On the other hand, a recent study [49] estimated that a range of annual PV module waste in 2040 would be 1.3-4.0 million tons and that of accumulative PV module waste by 2040 would be 6.8-36.1 million tons.

In April 2019, the project on "Complete sets of technologies and equipment for recovery and treatment of crystalline silicon PV modules," a key national R&D plan for renewable energy and hydrogen energy, was officially approved and implemented. Its completion is expected by March 2022. This project is the first national R&D project for PV module recycling technology and key equipment in China. It will reveal the evolution of the structure and surface bonding characteristics of organic adhesive film in c-Si PV modules with an external treatment process and a de-bonding mechanism; develop a complete set of technology and key equipment for the environmental protection treatment of modules based on mechanical and thermal-chemical methods; build demonstration lines; develop new technologies for the environmental protection treatment of new materials and new structure modules; establish an evaluation system for the recycling and treatment of c-Si PV modules; and provide standards and policy suggestions. In 2020, the key equipment of the two technical routes of the mechanical and thermal chemical methods were developed. The first 10-MW demonstration lines in China are built in Baoding, Hebei Province, and Shangrao, Jiangxi Province, in 2021, respectively, and the technical and economic analysis has been carried out.

The mechanical method uses hot knife technology, with grinding and separating technology for successfully recovering the aluminium frame, the complete glass, the PV cell powder, the brazing strips powder, and the plastic powder. This technology has low waste liquid and exhaust emissions and is suitable for the on-site recovery of c-Si PV modules. The recovery rate is more than 98%, and the element recovery will reach >96% for Si and >97% for copper (Cu).

The thermal-chemical approach contains two processing stages. The first stage enables the separation of all major module parts though mechanical treatment and thermal reactions. This stage includes several inline semi-mass-production processes, frame removal, junction box removal, back sheet removal, and encapsulation material delamination. In the second stage, PV cells are treated in a batch chemical tool. The recovery is more than 97%, and the element recovery will reach >93% for silver (Ag) and >99% for Cu.

The standard system is divided into basic and management standards, module EOL assessment standards, recycling technology standards, reuse standards, and recycling standards. One of the most important standards is the “Standard for assessing the EOL of crystalline silicon PV modules”— that is, under what circumstances are the modules not allowed to continue to serve? This is related to the degradation of performance and safety caused by the aging attenuation of modules. In 2021, through reliability testing and demonstration, the key parameters and technical indicators were improved and finally determined, and the standard for assessing the EOL of crystalline Si PV modules was formulated. In addition, the technical specifications for the green design of PV modules, which is the main green evaluation standard promoted by the Ministry of Industry and Information Technology in China, was released by 2020. It is clearly proposed that the recycling link should be added to guide the industry's attention and research on the recycling of c-Si PV modules from the perspective of standard formulation. At present, this group of standards will be all released shown in Table 2.2-7.

Since 2014, the State Council and the Ministry of Industry and Information Technology have paid increasing attention to green manufacturing and green supply chains. By 2020, the green manufacturing system of national key industries, including PV, was established. In the past two years, LONGi, Chint, Tongwei, and many other enterprises have won the title of “Green Factory” and “Green Supply Chain” of the Ministry of Industry and Information Technology. Among them, LONGi put forward an initiative at the supplier conference to promote whole chain suppliers to jointly build a green manufacturing system. Non fluorine backsheet is one of the options of LONGi, Suntech, Chint, Haitai and Yingli (ect.) for eco-design, DSM and Zhejiang Sinopoly Materials provided recyclable non fluorine backsheet for module green manufacturing.

Table 2.2-6 Major policies on relevant to photovoltaic recycling

No.	Time/ released	Released department	Policy name	Policy content
1	2017.12.27	MIIT*/ MST**	National catalogue of major environmental protection technology and equipment encouraged (2017 Edition)	The "complete set of equipment for resource recovery of waste crystalline silicon solar panels" was included in the catalogue
2	2021.3.18	NDRC***	Guiding opinions on comprehensive utilization of bulk solid wastes in the "14th-five-year-plan"[6]	Explore ways of standardized recycling and recyclable and high-value recycling of solid wastes from emerging industries
3	2021.7.1	NDRC***	Circular economy development plan in the "14th-five-year-plan"	Classified recycling and centralized treatment of waste materials including retired photovoltaic modules and wind turbine blades
4	2021.10.24	State Council	Action plan for carbon peak by 2030	Promote the recycling of waste from emerging industries such as decommissioned power cells, photovoltaic modules and wind turbine blades
5	2021.12.23	MOF****	Catalogue of enterprise income tax preference for comprehensive utilization of resources (2021 Edition)	Included recycling and comprehensive utilization of waste solar photovoltaic panels
6	2022.1.4	MIIT*	Action plan for innovation and development of intelligent photovoltaic industry (2021-2025)[7]	Promote the R & D and industrial application of recycling technology of waste photovoltaic modules, and accelerate the comprehensive utilization of resources
7	2022.2.9	NDRC***	Guiding opinions on accelerating the construction of urban environmental infrastructure	Promote the construction of solid waste disposal facilities and carry out 100 demonstration projects for the comprehensive utilization of bulk solid waste
8	2022.2.10	MIIT*	Implementation plan for accelerating the comprehensive utilization of industrial resources[8]	For the first time, waste photovoltaic modules are defined as emerging solid waste, and it is proposed to strengthen the R&D and promotion of complete sets of technology and equipment for comprehensive utilization, while exploring technical routes of emerging comprehensive utilization of solid waste.

*MIIT : Ministry of Industry and Information Technology
**MST : Ministry of Science and Technology
***NDRC: National Development and Reform Commission
****MOF : Ministry of Finance

[6] https://www.ndrc.gov.cn/xxgk/zcfb/tz/202103/t20210324_1270286_ext.html
[7] http://www.gov.cn/zhengce/zhengceku/2022-01/05/5666484/files/daf24576801549ecbde531fd9346b1e5.pdf
[8] http://www.gov.cn/zhengce/zhengceku/2022-02/11/5673067/files/6b1bb86497954e97a6753310c06dc333.pdf

Table 2.2-7 Major standards on Photovoltaic recycling

No.	Time/released	Released department	Standard name	Standard content
1	2017.9.18	CPIA*	General technical requirements for recycling and reuse of crystalline silicon photovoltaic modules （T/CPIA** 0002-2017）[9]	It specifies the terms and definitions, basic principles, collection, transportation and storage, disassembly, treatment (including basic principles, frame treatment, lead out end treatment and laminate treatment), recycling (involving semiconductor materials, metal materials, glass and polymers) of recycling and reuse of crystalline silicon photovoltaic modules. This standard is a general and guiding technical document
2	2020.11.1	CPIA*	Technical specification for green-design product assessment—Photovoltaic module（T/CPIA** 0024-2020）[10]	It specifies the evaluation requirements and methods of green design products of photovoltaic modules, as well as the preparation method of product life cycle evaluation report. The standard is applicable to crystalline silicon photovoltaic modules and thin film photovoltaic modules
3	To be released	CPIA*	Plan Name: Guidelines for scrapping crystalline silicon photovoltaic modules	The standard will be standardized from the classification of scrapped components, technical requirements for scrapping evaluation, experimental methods for scrapping evaluation, inspection cycle and other contents
4	2020.6.2	Glass in Buiding-TC255	General technical requirements for recycling and reuse of thin film solar cell modules for buildings (GB/T*** 38785-2020)	It specifies the terms and definitions, basic principles, collection, transportation and storage, disassembly, treatment, recycling of recycling and reuse of thin-film photovoltaic modules for building.
5	2021.3.9	Glass in Buiding-TC255	General technology requirements for photovoltaic (PV) module recycling and recovery (GB/T*** 39753-2021)	It specifies the basic principles, collection, transportation, storage, disassembly, disposal, recycling and management of photovoltaic module recycling

*CPIA : China PV Industry Association
**T/CPIA: China PV Industry Association Standards
***GB/T : Recommended national standards

[9] http://www.ttbz.org.cn/StandardManage/Detail/22224/
[10] http://www.ttbz.org.cn/StandardManage/Detail/48036/

2.2.4 Australia

(1) Relevant regulations and schemes

In Australia, the State of Victoria passed legislation banning all electronic waste, including PV modules, inverters and PV batteries, from landfills as of 1 December 2019; however, currently, no other Australian state or territory has mandatory regulation on PV module disposal. PV modules are not explicitly classified as hazardous waste under the National Environment Protection Measure, and there is no requirement on reporting the transportation and handling of discarded PV modules [50]. Further, the Australian Standard AS/NZS 5377—which covers electronic waste collection, storage, transportation, and treatment—does not include PV modules and has not been updated since 2013, but it is now under review [51].

The EPR principle is enacted in Australia through the Product Stewardship Act 2011 [50]. Currently, there are no recycling or product stewardship requirements for PV modules, inverters, and batteries in any state or territory in Australia; however, PV systems are a "listed class of products" to consider under the Product Stewardship Act since 2016 [52, 53]. An activity to evaluate the inclusion of PV systems in the national stewardship program was led by Sustainability Victoria, a statutory authority with a board appointed by the Minister for Energy, Environment and Climate Change. The findings published in 2019 [54] show that either voluntary or co-regulatory approaches for PV modules might be feasible in Australia and are likely to achieve the environmental, health, and safety objectives of the Product Stewardship Act, improving the management of EOL PV modules and opportunities to reuse valuable materials. Further, the National Waste Action Plan of 2019 established that a preferred PV stewardship scheme is identified by 2021 and in place by 2023. In December 2020, the Department of Agriculture, Water, and Environment released a partnership call to develop an industry-led product stewardship scheme for PV systems (PV modules and inverter equipment) over 3 years, with the objective of implementing the national scheme by 2023, but the department decided not to progress with the partnership agreement at this stage [55]; hence, progress in designing the PV stewardship program has been slow to date. This is expected to change with the recently created Product Stewardship Centre of Excellence, which is leading the codesign of the national product stewardship for PV systems, with the aim of reaching an industry-agreed, nationwide scheme by June 2022, starting operations by June 2023, and including an approach to deal with legacy PV panels.

(2) Treatment of PV module waste

Most discarded modules are currently landfilled or stockpiled in most states and territories, with a low recycling rate. Victoria is an exception because of the landfill ban and local enterprises are making significant effort to implement a circular economy for PV modules. In Australia, only registered PV installers can install and remove PV modules. Installers then have three options: shipping the EOL panels to local councils that accepted solar panel disposal, sending EOL panels to a landfill facility where permitted; or sending them to a recycling facility for processing with a gate fee charged to installers [56]. Recycling cost barriers include transporting PV modules to a recycling facility [57] and high processing costs [58]. As a result, only a small amount of EOL PV modules are being recycled or refurbished (locally or domestically), whereas the average recycling process can reclaim up to 17% (by weight) of a PV module by recovering aluminium frames, junction boxes, and cables because they are most commonly or easily recycled [59]. Reusing PV modules could be an alternative solution, but most disposed modules do not meet current standards, and there are safety concerns with consumer law [60]. Inverter equipment is being disposed in similar ways to the PV modules, i.e., recycled in Victoria but recycling is not required in other states. A small amount of PV system inverter equipment is being refurbished and redeployed [58]. Collection, handling, and storage present significant barriers, and solutions are not yet apparent [57].

Although the current EOL management in Australia is in its infancy, as described, there are exciting developments in the area, with several companies and startups devoted to PV module recycling, including PV Industries, Scipher Technologies, Solar Professionals, Reclaim PV Recycling, Solar Recovery Corporation, Lotus Energy Recycling, and Elecsome.

- PV Industries, based in Sydney (New South Wales), has been offering system decommissioning, collecting, and recycling services to household owners, commercial tenants, solar installers, and utility-scale service managers across Australia since 2018 [60, 61]. PV Industries are the first and only company to have an automated deframing machine in Australia. Once modules are transported to the PV Industries facility, the aluminium frames, cables, and junction boxes are immediately recovered. The remainder of the PV module is stored until the next stage of the recycling plant is operational, or they are used for R&D by universities and other research partners. PV Industries is developing its own mechanical processing technology to recover the remaining materials from the solar panels. Removing the aluminium frame reduces up seven times less space of the module for storage [60].
- Scipher Technologies, based in Melbourne (Victoria), is the largest licensed e-waste recycler in Victoria and owns the only e-waste plastic recycling facility in Australia. Scipher Technologies has been working in partnership with the University of New South Wales and research and development advisors on a commercially proven and environmentally sound solution for solar panel recycling. They have an agreement with an oversea technology supplier that can recover 80% of raw materials included in PV modules [62].
- Solar Professionals (KGM Services Pty Ltd), based in Wagga Wagga (New South Wales), has been awarded 946 000 AUD in funding from NSW EPA to design, engineer, construct, and commission the automated recycling of solar panels facility. In partnership with Deakin University, Andersons Services, and Apex Greenhouses, they claim that solar panel components will be deconstructed without the cross-contamination, and the delaminated components can be used to make new cells or will be re-engineered for other industries like the manufacture of greenhouses [63].
- Reclaim PV Recycling, based in Adelaide (South Australia), offers commercial decommissioning, collecting, and recycling services. For the past few years, Reclaim PV has collected and stockpiled approximately 10 000 modules/year. Reclaim PV is inviting industry operators, suppliers, installers, and maintenance operations around Australia to become a drop-off point for discarded PV modules and collection network partners [64]. Reclaim PV developed a recycling process using pyrolysis, applying heat in a furnace to melt the adhesives and separate components, which are then sorted and sent to different companies for reuse [65]. Reclaim PV is developing the first large-scale dedicated PV module recycling site in Lonsdale, South Australia [65]. The company is securing environmental licenses to conduct full-scale recycling in Lonsdale. The facility should process 70 000 modules/year, which is coincidentally the number of partly processed PV modules that are currently being warehoused [66].
- Solar Recovery Corporation, based in Melbourne (Victoria), offers recycling services for PV modules. They have collection points across Australia thanks to a partnership with SRC recycling hubs. They are committed to a circular economy, with the main goal of extracting high-quality materials from PV modules and reinjecting them into the PV

manufacturing supply chain. Their website mentions that they have access to a "state-of-the-art exclusive automated recycling machine" with "an exclusive partnership for Australia and New Zealand with the manufacturer," which allows them to "recover at least 95% of the raw materials from each PV module" [67]. No further details on the technology are provided.

- Lotus Energy Recycling, based in Melbourne (Victoria), purchased recycling machinery for solar panels in September 2020 comprising a two-roller crusher, which is now in operation. The plant claims close to 100% recovery using no chemicals. Recycled panel materials are used to manufacture tiles, tabletops and other environmental-friendly architecture materials locally in Victoria [68].
- Ojas Group (Elecsome), based in Kilmany (Victoria), was awarded a 3 million AUD federal government grant to establish a new recycling plant in Victoria to upcycle EOL PV modules into feedstock for cement-based construction materials through an innovative process. The technology claims to be able to up-cycle 97% of each PV module at a commercial scale, with the glass used as concrete fill, replacing sand and to be used as other construction materials, including road base materials. The project will last 3 years, from 2020–2023 [66].

Recently, Sustainability Victoria published a study investigating shredding and heating treatments as an effective approach to achieving higher PV recycling yields and identifying end users for these recovered materials in Australia [58]. This study found that the mixed glass cullet (a mixture of the tempered glass and PV cell layers) and the separate cullet (the separated glass cullet after heating treatment) can be sold to domestic glass manufacturers to produce new glass products, such as glass bottles or containers, for 30 AUD/ton and 70 AUD/ton, respectively. The quality of the recycled glass met the company requirements, and recycled glass fines can be used in asphalt aggregate as a replacement for coarse sand in road base, tiles, concrete, or cement, with a return of 0 AUD/ton–49 AUD/ton. Aluminium frames and interconnecting ribbons can be sold to scrap metal suppliers—such as Cobral Metals, Norstar, and Sims Metals—for reuse in manufacturing new metal products. The remaining back sheet, plastic, ash fines (mixture of fine glass and Si) are currently not recyclable in Australia.

There are national-level funding initiatives in 2020 in Australia to address PV module and battery EOL issues. These projects will develop innovative solutions to enable the sustainable and cost-effective management of EOL PV modules:

- The University of New South Wales received a 1.36 million AUD R&D grant from the Australian Renewable Energy Agency on behalf of the Australian government to develop and demonstrate highly efficient, low-cost, and sustainable recycling technology for EOL PV modules, with inspiration from metallurgy engineering. The project will last 2 years, from 2020–2022 [69].
- In addition, the New South Wales Environmental Protection Authority has committed to a 10 million AUD recycling fund to reduce the landfilling of PV modules and battery systems. This investment is intended to future-proof the management of this growing waste stream and help New South Wales transition to renewable energy sources within a circular economy. The two-stage funding will last 3 years, from 2021–2024 [70, 71].

Transporting EOL PV modules remains expensive in Australia, given the large, sparsely populated land area, high freight costs, and long distances of transportation. In the current circumstances, the collection and stockpiling, with some limited dismantling, appears to be the best approach until economies of scale (or scope) can be achieved [56].

(3) Outlook

It is expected that the volume of EOL PV modules will reach 10 000 tons/year by mid-2020s and will surge after 2030 as a result of the solar boom started in 2010 by FITs and government subsidies [56, 57, 72]. Early on, distributed PV systems will be the main source of the PV waste volume (~88%), but by 2035, discarded modules from utility-scale PV systems will create a big share [73]. Si PV modules comprise more than 90% of the waste stream [72]. From IRENA's prediction, the cumulative volume is projected to reach 30–145 thousand tons in 2030, 300–450 thousand tons in 2040, and 900–950 thousand tons in 2050 [4]. At present, the early loss trajectories seem to be a more accurate reflection of the situation in Australia [56] because of several factors, including low-quality PV modules entering the market (which could be up to 80%), financial incentives to decommission rooftop systems before the expected service lifetime, building upgrades, lack of maintenance by owners, inappropriate installation, and not meeting current Australian standards [57, 74]. Residential systems experience higher early decommission prior to reaching technical end of life because of economic and social factors such as receiving new rebates when replacing a small-scale PV system. On average, the practical lifetime for PV modules in Australia is only 15-20 years rather than 25-30 years because residential market dominates Australian PV market (more than 70% market share by 2020) [75]. Over the next decade, PV modules from residential market will enter the EOL market and the actual volume will be higher than previously predicted – which is good news for local PV recycling industry

The problem of EOL PV is arising in Australia, and managing this waste needs shared responsibility among government, industry, and consumers. Collaboration and open communication will be essential for the implementation of circular business models [50].

The current complication of EOL panel collection might be improved with a unique "reverse logistic" model in Australia, where installers transport the used modules back to the collection point to eliminate the need for an additional transportation company. Researchers from the University of New South Wales believe the approach would help cut the logistics cost, making recycling a more attractive proposition [76]. In a low-recovery pathway, there is a risk of crushed glass not meeting market specifications, leading to a large amount of glass stockpiling and eventually being sent to landfills. On the other hand, in a high-recovery pathway, the main barrier is the value of the commodities recovered versus the processing costs. In this sense, the most fundamental challenge for viable PV recycling and achieving economies of scale is insufficient waste volume [54]. In Australia, volumes are likely to become large enough by the end of the decade, so stockpiling with essential pretreatment (removing cables, junction boxes, and aluminium frames) can be a temporary solution.

From the stakeholder surveys, it was identified that the most common problem faced by installers and system owners is the lack of knowledge on how or where to dispose PV modules [56, 74]. Awareness training and education of the industry and consumers are necessary to increase the participation rate of recycling and diverting materials from landfills. Regulations and requirements on recycling can improve this situation.

A product stewardship regulation is necessary to support the sustainable collection and processing activities and to increase the participation rates of recycling over landfilling [54]. A mandatory scheme, such as banning landfilling, would also be a potential choice [50], whereas standardized labelling and material passports (i.e., module type, which materials are used) would make it easier to sort modules at EOL for more effective recovery processes [50].

The recycling rate for PV is currently low in Australia and far from reaching the goal under the National Waste Policy Action Plan: increasing Australia's resource recovery rate to 80% by

2030. Establishing collection systems is a priority for any recovery pathway. Further R&D is required to develop advanced processes for high-value recovery and for managing contaminated hazardous residual material. There is uncertainty about the quality of the recovered glass and the size of the available end markets. Further research into potential end markets and economics for glass recovered from PV panels will help inform future policies and investments [57].

Regarding a potential reuse market for PV modules once they have reached their technical EOL, the main barrier is lack of regulation. For example, these modules might not meet current Australian standards, guarantee terms are nonexistent, they are not eligible for government incentives, and it is difficult to find modules with similar performance and I-V characteristics to connect them in an array.

2.3 North America: United States of America

(1) Relevant regulations and schemes

The potential economic and environmental opportunities for recovering and reusing materials from EOL PV systems has increased regulatory and commercial interests and the focus on sustainable PV recycling practices in the US.

To incentivize the expansion of industrial capacity to manage the expected increase in PV waste, there has been growth in regulations specific to PV waste across various states in the US. Washington is the first state to introduce a regulation for take-back requirements for PV manufacturers at no additional cost for the owners of the PV system [77]. Beginning in 2021, California implemented regulations to classify EOL PV modules as universal waste [78] to decrease the costs of regulatory compliance and processing waste and thereby incentivize a domestic PV recycling industry. Policy mechanisms for PV waste management are being actively considered in Illinois, Hawaii, Arizona, North Carolina, and New Jersey [79, 80]. Similar to California, the North Carolina Department of Environmental Quality has recommended rulemaking efforts to define EOL PV modules as universal waste [81]. In addition, both Minnesota and Illinois have facilitated stakeholder working groups to assess solar panel recycling policies [82].

Despite the regulatory developments at the state level, there is no US federal regulations specifically designed to regulate PV waste management. PV waste is regulated by the Resource Conservation and Recovery Act, which does not contain any specific regulatory requirement for PV waste.

(2) Treatment of PV module waste

Crystalline Si and thin-film PV recyclers in the US operate at various capacities and with different degrees of experience. First Solar, which is the world's largest PV recycler [83, 84], has a recycling capacity of 150 metric tons/day in the US for its thin-film CdTe PV modules [85]. Using a high-value recycling process, First Solar recovers 90% of both bulk (e.g., glass) and specialty materials (e.g., CdTe semiconductor layer) from EOL CdTe PV modules [86]. The US has also witnessed an increase in the number of firms dedicated to recycling c-Si PV systems [87]-[89]. The potential economic and environmental gains from sustainably managing PV waste has motivated the allocation of R&D funds toward accelerating the scaling of startups focusing on recycling Si PV waste [90].

Table 2.3-1 Example vendors for PV module recycling in the US (as of October 2021) [89]

Vendor	Location
Echo Environmental Holdings	Dallas, TX
Dynamic Lifecycle Innovations	Onalaska, WI
Recycle PV Solar, LLC	Sparks, NV
First Solar	Perrysburg, OH
We Recycle Solar, Inc.	Yuma, AZ; Mount Vernon, NY
FabTech Enterprises, Inc.	Gilbert, AZ; Savannah, GA

Cascade Eco Minerals, LLC	Phoenix, AZ; Waxahachie, TX; Natrona Heights, PA; Upper Sandusky, OH; Okumulgee, OK; Hardeeville, SC; Lawrenceburg, KY; Portland, OR
ZEEP Technology, LLC	South Hadley, MA; Somerset, KY; Temple, TX; Corona, CA; Batavia, IL

The Solar Energy Industries Association operates a program to aggregate recycling services from registered vendors and make the recycling services available at lower costs for PV manufacturers that are Solar Energy Industries Association members [91]. The potential economic opportunities in PV recycling have motivated industrial firms with experience in recycling non-PV products (e.g., electronic waste, glass) to expand operations into PV waste management [92]–[95].

(3) Outlook

A cumulative PV module waste in the US is projected to reach 5.5 to 10 million metric tons by 2050 [4, 96, 97]. Beyond the literature estimates, there are no high-quality, open-source databases on the projected PV waste based on past and expected installations across the different states in the US. Data that account for the geographic dispersion of PV installation across the US can help recyclers plan to scale up operations and optimally locate recycling facilities to decrease transportation costs.

Despite the regulatory and commercial progress, a recent study has highlighted that the limitation in existing Si PV recycling technologies, the cost of Si PV recycling, and the limited Si PV recycling capacity are key barriers in managing PV waste in a sustainable manner in the US [95]. Unlike CdTe PV recycling, there is no Si PV recycler in the US operating an integrated, high-value recycling process that recovers bulk and specialty materials from EOL c-Si PV modules. By not recovering specialty materials, PV recyclers forgo an opportunity to maximize revenues from recovering and reselling precious materials (e.g., Ag) and prevent the potential downstream environmental hazards from materials such as lead. Further, the low volume of PV waste in the next 5 years can temporarily delay small-scale Si PV recyclers from increasing their scale of operations. Additional regulatory clarity is required to standardize the protocols used to classify the PV modules as hazardous or nonhazardous based on toxicity tests. The results from the existing tests, such as the toxicity characteristic leaching protocol, which are commonly used to characterize the toxicity of PV modules, vary based on the cutting method used to obtain the samples from the EOL PV module [98, 99]. The results from the toxicity tests determine if the EOL PV module is classified as hazardous waste or not, which can significantly impact the downstream processing costs of c-Si PV recycling. For example, the downstream transportation costs and landfilling tipping fees are higher for hazardous waste than for nonhazardous waste.

To obtain reproducible and representative toxicity characteristic leaching protocol results for EOL PV modules, the ASTM E44 committee has developed a sample preparation protocol for PV modules [100]. In addition, the ASTM E44 committee is working on a new protocol which specifies a waterjet-based cutting method to obtain PV module samples and test if they pass the U.S. Environmental Protection Agency (EPA) method 311 for toxicity characterisation [101]. Additional R&D efforts are required to determine the technology strategies to reduce the costs of Si PV recycling. Current estimates show that the net cost of Si PV recycling (after accounting for the economic value of recovered materials) is 25 to 30 USD per module [96, 98], which is significantly higher than the cost of landfilling the module in the US [98]. Landfilling the EOL PV module forgoes an opportunity to recover and reuse precious (e.g., Ag) and energy-intensive materials (e.g., solar-grade Si) in PV manufacturing. The U.S. Department of Energy has established a PV end-of-life action plan with recycling cost target of 150 USD/ton (3 USD/module) by 2030 [102].

Further, there is a lack of publicly available data on the storage duration of PV modules prior to recycling [79, 80], the design and material composition of the PV modules, and the key drivers of PV modules to reach EOL (e.g., early EOL as a result of damage during transportation and installation or manufacturing defects [103]). Each of these items will impact the planning for the expansion of recycling capacities and the choice of recycling technology that is best suited to manage PV waste in the future. For example, if the defect in the module can be addressed through repair (e.g., replacement of the damaged junction box), it will avoid module recycling, though recertification standards are needed to safely and reliably deploy repaired modules.

The choice of recycling technology will need to account for the presence of hazardous and precious materials, such as fluorine and Ag, in the PV module. The presence of fluorinated back sheets might require additional equipment, such as scrubbers, to manage the fluorine emissions when high-temperature PV recycling processes are used [104]. The decline of Ag content in PV modules [105] will decrease the potential revenue for Si PV recyclers from recovering and reselling Ag. A low Ag content will favour cost-effective recycling processes that depend less on the revenue from Ag. Further, recent progress in the design of PV modules may enable more efficient recycling, though trade-offs with long-term durability need to be assessed. For example, laminate-free design [106], wherein the ethylene vinyl acetate encapsulant is replaced with edge sealants, could facilitate recycling without economically and environmentally burdensome thermal, chemical, or mechanical processes required to eliminate the encapsulant. Publicly available data on the material and design composition of PV modules will help PV recyclers better adapt and customize recycling technologies to more effectively recycle the expected volume of PV waste.

3 SURVEY ON PHOTOVOLTAIC MODULE RECYCLING IN THE MARKETS

As described in Chapter 2, PV module recycling is mandatory in Europe, whereas in other countries, actions promoting PV module recycling are under development; hence, information on current PV EOL treatment methods available in the market will be useful to understand the current situation and to encourage projects for PV module recycling.

To understand the status of PV module recycling across several IEA PVPS Task12 participating countries, a survey on PV module recycling was conducted during 2020–2021. Although the total number of responses is small, the responses reflect the current situations and barriers for PV module recycling in certain markets.

Note that because this survey covers limited countries and companies, the results should not be considered general world trends.

3.1 Methodology of survey

The PV module recycling survey was conducted across PVPS Task 12 from 2020Q4 to 2021Q2. Expected respondents were companies and organizations treating PV module waste for recycling. A weblink address was sent by PVPS Task 12 members to relevant companies and organisations in their countries, except in Japan, where a survey sheet was delivered and collected. Items for the questionnaire are shown in Table 3.1-1.

Table 3.1-1 Items for questionnaire on PV module recycling in the markets

- Location of company or organisation
- Legislation on PV EOL management
- Existing PV EOL collection and take-back management
- Waste treated in the waste management plant
- PV cell technology treated in the plant
- PV module structure treated in the plant
- Treatment technology for PV modules used in the plant
- Materials recovered from PV modules
- Estimation of the average material recovery rate from PV modules [%]
- Estimation of the average material recycling rate from PV modules [%]
- Current available treatment capacity for PV modules [tons/year]
- Current amount of PV modules treated [tons/year]
- Cost for treatment (excluding transport) [USD/ton]
- Destination for each recovered or recycled material: glass, ferrous metals, nonferrous metals, Si, Ag, Cu, plastics, and polymers
- Potential issues or barriers for recovering or recycling materials: glass, ferrous metals, nonferrous metals, Si, Ag, Cu, plastics, and polymers.

3.2 Survey results

During the survey period, from 2020Q4 to 2021Q2, 29 answers were obtained in total, as shown in Fig. 3.2-1, with 6 respondents from Europe (Germany, Spain, and the Netherlands), and 23 respondents from Asia and the Pacific (Japan, South Korea, and Australia). The largest number of respondents was 21, from Japan.

Results for each question are shown in this section. Note, however, that because countries and companies/organizations covered by this survey are limited, these results should not be considered general world trends.

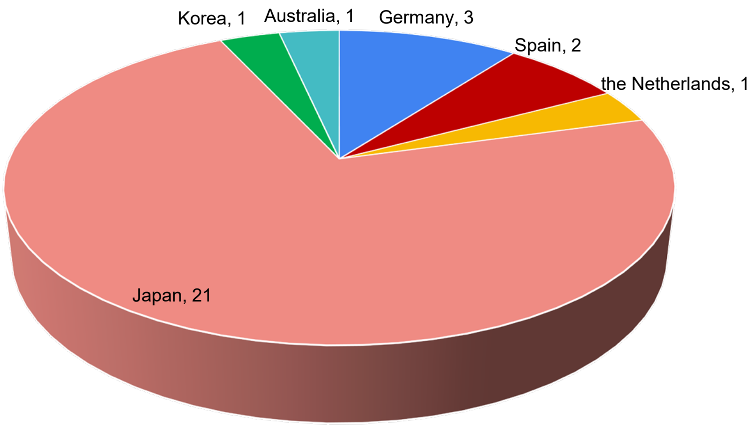


Fig. 3.2-1 Number and country distribution of respondents to the questionnaire

3.2.1 Relevant legislation and take-back management

(1) Relevant legislation

In Europe, PV module recycling has been mandated through the WEEE Directive 2012/19/EU. EU member states have approved the directive into national law, requiring all producers that put PV modules in the market within the EU to either operate their own take-back and recycling systems or join what are known as producer compliance schemes.

In other countries—such as Japan, South Korea, and Australia—there are no nationwide specific legislations for PV module waste; therefore, PV module waste is treated under the general national and local legislation for waste management. As described in Chapter 2.2, however, in South Korea, the EPR will be enforced in the PV industry in 2023, after the establishment of the collection infrastructure for PV module waste and the development of recycling technologies in 2022. In Australia, an EPR scheme is expected to be designed and agreed upon in June 2022, with the expectation of being implemented by June 2023.

(2) Take-back management

In European countries, direct collection from the site to the recycling plant, central collection and sorting, and PV CYCLE collection schemes (collection services through PV CYCLE) are used. On the other hand, in Japan, South Korea, and Australia, direct collection is commonly used.

In Japan, a demonstrative take-back and collection scheme, such as PV CYCLE, was trialled under the MOE project. Further, to identify barriers and propose an effective take-back management process, a survey study of the proper EOL management of PV modules was implemented under a NEDO project.

3.2.2 Waste treated in the waste management plant

Most survey respondents are treating different waste streams, with EOL PV modules being one of them. As shown in Fig. 3.2-2, only three respondents treat only PV module waste, with the other respondents normally processing metals, glass, electronic waste, etc. In Japan, more than 10 respondents are using specific equipment for PV modules, even though most are treating other waste streams. Currently, it seems difficult to operate a recycling business focusing on PV modules because of the low waste volume and the associated revenue from the materials recovered.

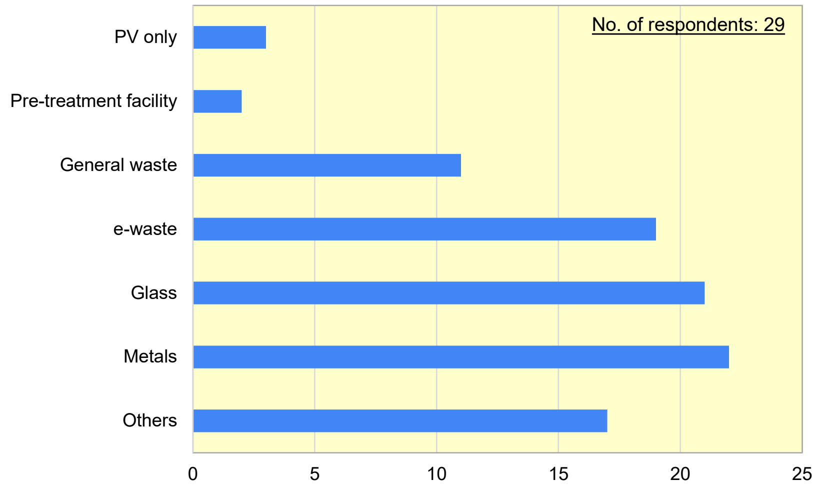


Fig. 3.2-2 Waste treated in the respondents' plants

3.2.3 PV cells and modules treated in the plant

(1) PV cell technologies

Fig. 3.2-3 shows survey data regarding the PV cell technologies that are treated. Most respondents treat c-Si PV modules, with 12 companies treating CIGS and only 4 companies treating CdTe modules. In addition to the difference in market size between c-Si PV modules and other solar cell technologies, in thin-film PV modules, solar cells are deposited on the substrate, which makes the separation of these two materials more challenging compared to c-Si PV modules. Further, hazardous materials, such as cadmium and selenium, can pose a further challenge on the recycling of thin-film PV modules.

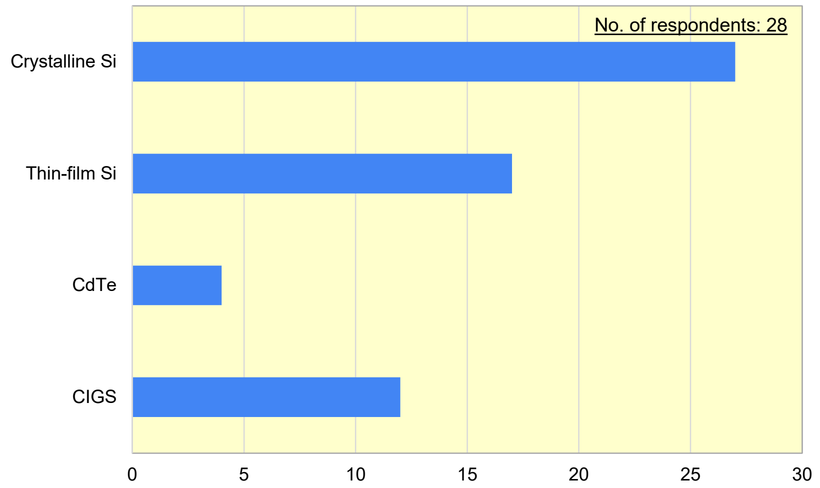


Fig. 3.2-3 PV cell technologies treated in the respondents' plants

(2) PV module structure

For the PV module structure, most installed c-Si PV modules have a glass/back sheet structure, whereas the glass/glass structure is becoming more common as the market share of bifacial PV modules increases. Thin-film PV modules use various structures, such as glass/glass without a frame (e.g., CdTe by First Solar), glass/(glass/)back sheet with a frame (e.g., CIGS by Solar Frontier), and flexible architectures.

As shown in Fig. 3.2-4, most respondents treat PV modules with a glass/back sheet structure with and without a frame, and more than half the respondents treat PV modules with a glass/glass structure. Also, flexible modules are treated by nine respondents in their plants.

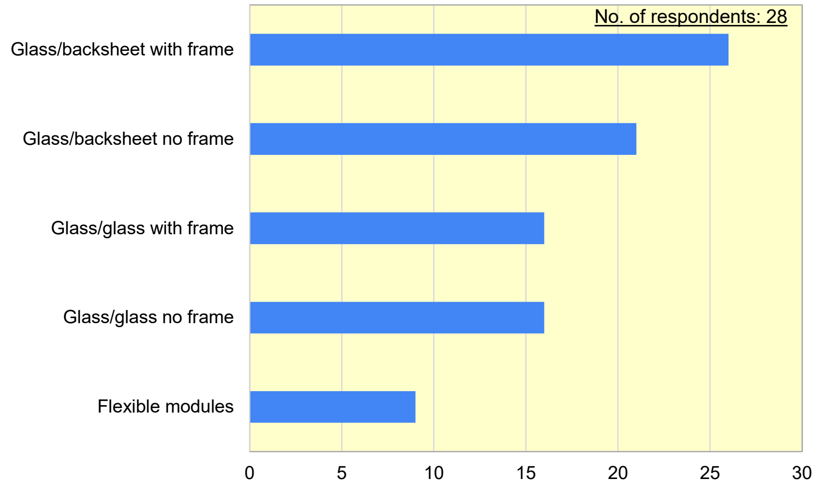


Fig. 3.2-4 PV module structures treated in the respondents' plants

3.2.4 Treatment technologies for PV modules

Generally, as a first step, the junction box and frame are removed mechanically or by hand. Then, the laminated structure is separated and recycled using different treatments available. Regarding the treatment technology for the laminated structure, 17 respondents answered that they use only a mechanical treatment—for example, shredding, separation by hot knife or wire, or scraping the glass or a plastic layer, as shown in Fig. 3.2-5. After treatment, recovered materials are sorted and sent to other companies for recycling as secondary materials or products. Another 12 respondents are using a combination of multiple technologies. All of them combine a mechanical treatment with a thermal and/or a chemical treatment. On the other hand, no respondents use only thermal treatments or only chemical treatments.

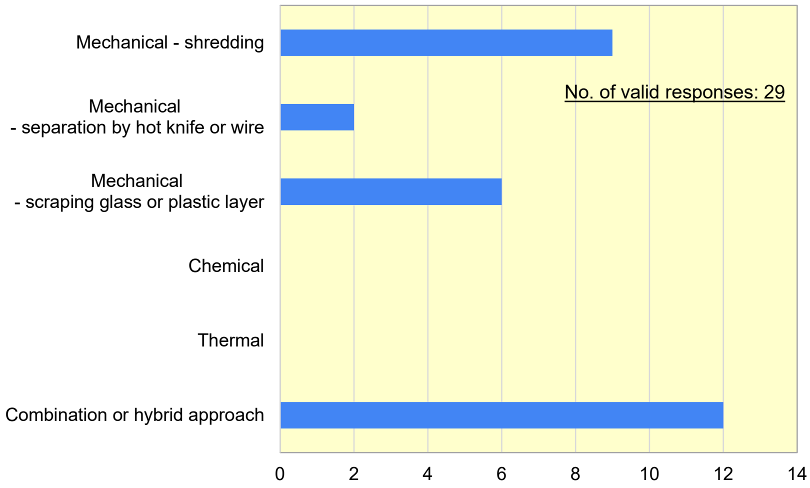


Fig. 3.2-5 Treatment technologies for PV modules

3.2.5 Materials recovered from PV modules

Fig. 3.2-6 shows the number of answers regarding materials recovered from PV modules. Nonferrous metals, including aluminium frames and glass, are recovered at most plants. PV cell materials and polymers/plastics are recovered by 20 and 13 plants, respectively; however, for c-Si PV modules, it seems that Si PV cells are recovered together with plastics as a mix material in many plants.

In the case of thin-film PV modules, after separating the glass having the thin-film layer (semiconductor metals), the PV cell materials are recovered from the glass at the next treatment process.

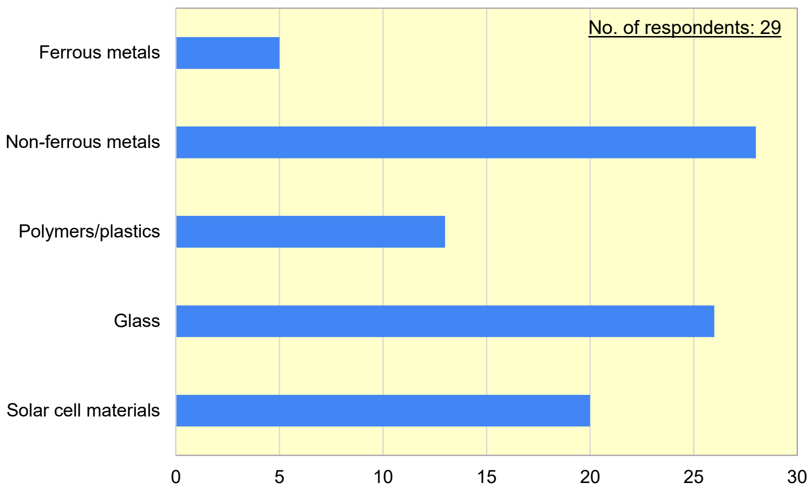


Fig. 3.2-6 Materials recovered from PV modules at the plants

3.2.6 Estimated average rate of material recovery and recycling

Answers on the estimated average rate of material recovery and recycling are discussed in this section. Recovery rate is defined as a ratio of the weight of materials recovered after processing to the weight of the PV module before processing. The recycling rate is defined as a ratio of the weight of materials recycled for secondary use to the weight of the PV module before processing. Materials recovered but not used are not counted as the recycling rate. Note that the results are based on the respondents' answers (e.g., self-enumeration).

(1) Average rate of material recovery

Fig. 3.2-7 shows the estimated material recovery rate from PV modules. Twenty-five respondents, among 28 valid responses, achieve a recovery rate of materials exceeding 80%. (Note that "80%" is easily achievable when glass and frames are recovered.)

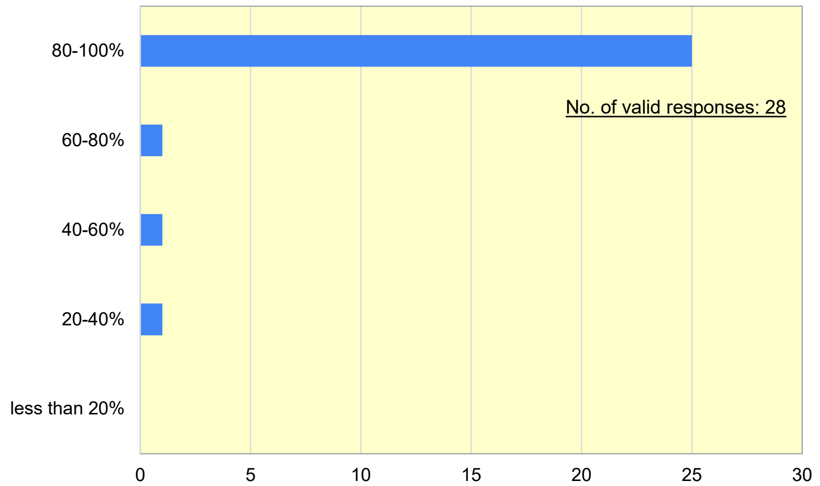


Fig. 3.2-7 Material recovery rate from PV modules at the plants

(2) Average rate of material recycling

Fig. 3.2-8 shows the estimated recycling rate from PV modules. Twenty plants have realized more than 80% of the recycling rate. Note, however, that when Si cells and polymers/plastics are recovered as mixed materials, these may be sent to smelters and treated thermally. Then, polymers/plastics are treated as energy recovery, which is not counted as "recycling," at least in Europe. Also, it seems that some polymers/plastics separated from the laminated structure are landfilled because there are no available recycling destinations.

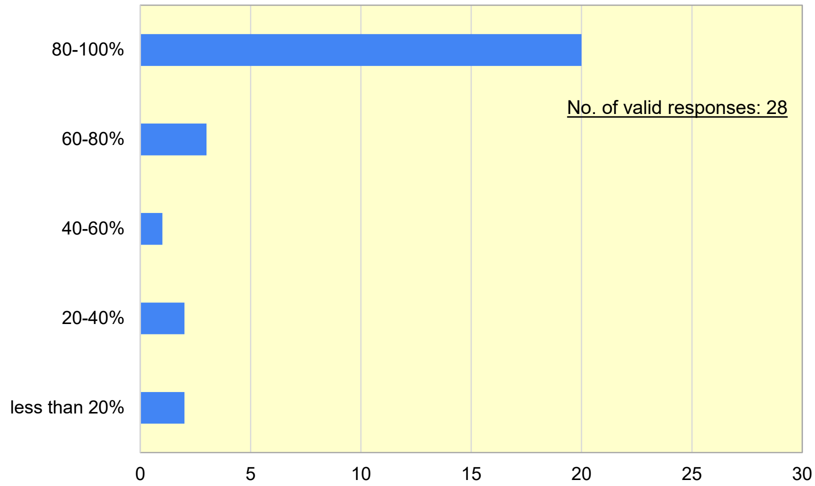


Fig. 3.2-8 Material recycling rate from PV modules at the plants

3.2.7 Treatment capacity, amount treated, and cost

Fig. 3.2-9 shows the current available treatment capacity for PV modules. Among 16 valid answers, the treatment capacity of 10 plants is less than 1 000 tons/year, whereas the largest capacity is 10 000 tons/year.

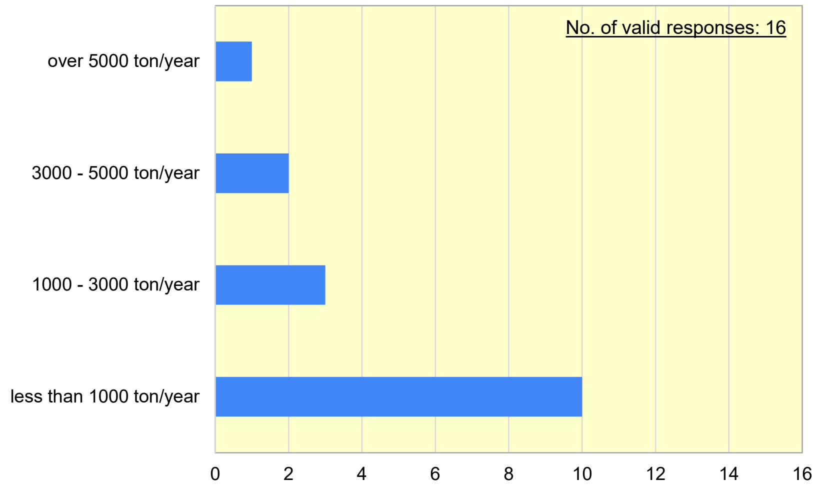


Fig. 3.2-9 Available treatment capacity for PV modules

Fig. 3.2-10 presents the amount of PV modules treated in 1 year from 24 respondents. Compared with the available treatment capacity, the current amount treated in the plants is very small. In 23 plants, the amount of PV modules treated was less than 1 000 tons/year; among those, in 14 plants, it was less than 100 tons/year. This means that the capacity factor of these plants is currently very low. At the largest plant, with a capacity of 10 000 tons/year, the amount treated was 6 000 tons/year.

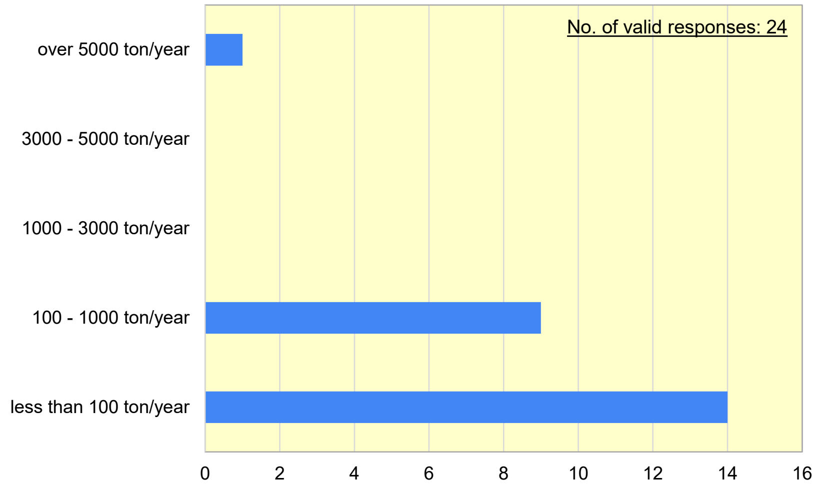


Fig. 3.2-10 Current amount of PV modules treated

Regarding the cost for treatment excluding transport, 21 respondents, all in Japan, answered that it would exceed 400 USD/ton, whereas it was less than 400 USD/ton according to 5 respondents in Europe, as shown in Fig. 3.2-11. Here, the answers obtained from respondents correspond to the "price" for receiving PV module waste rather than the "cost" for treatment.

Because the capacity factor of recycling plants using equipment specific to PV modules is less than that of recycling plants treating various types of waste, this will result in potentially higher treatment costs (price) at the plant.

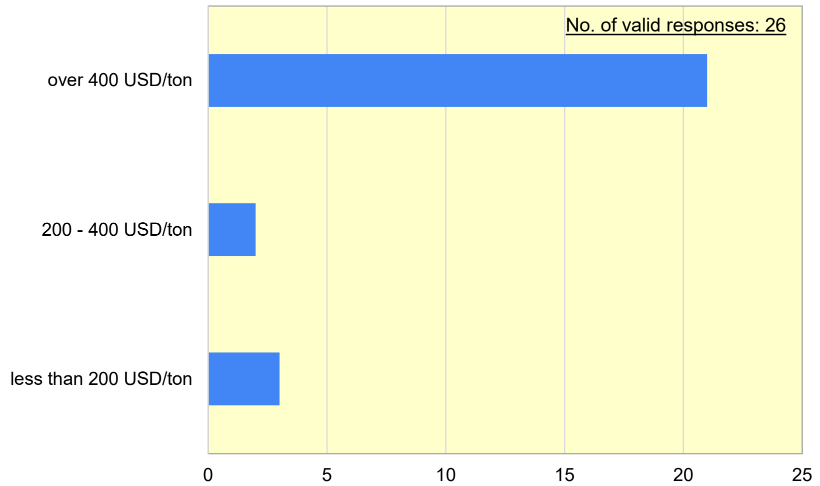


Fig. 3.2-11 Treatment cost (price) for PV module waste at the plant (excluding transport)

3.2.8 Destination of the recovered or recycled materials

After treatment at the plant, various materials recovered from the PV modules are sent to the next destination for recycling or disposal. Potential destinations include smelters, additional processing plants, secondary markets (directly), incineration plants, landfills, etc. Fig. 3.2-12 shows the destination for each material. Glass is mainly sent to the next processing plant for recycling. It seems the glass will be recycled as glass products, such as insulator materials and container glass, and sometimes used as materials for civil work. Ferrous and nonferrous metals are sent to smelters, the next processing plant, or directly to secondary markets. At the smelter or other processing plant, metals are recycled as secondary materials. Metals used for c-Si cells—such as Si, Ag, and Cu—are also sent to smelters, the next processing plant, or directly to secondary markets. In many cases, however, these metals are not separated and are sent to the next treatment as Si cells. After that, these metals are separately recovered and recycled as secondary materials, but considering the treatment cost and the value of the recovered metals, landfilling is chosen on many occasions. For plastics/polymers, the answers obtained show various destinations. This means there is currently no regular treatment for recycling plastics/polymers. Also, there will be cases when plastics/polymers are treated together with c-Si PV cells without separation.

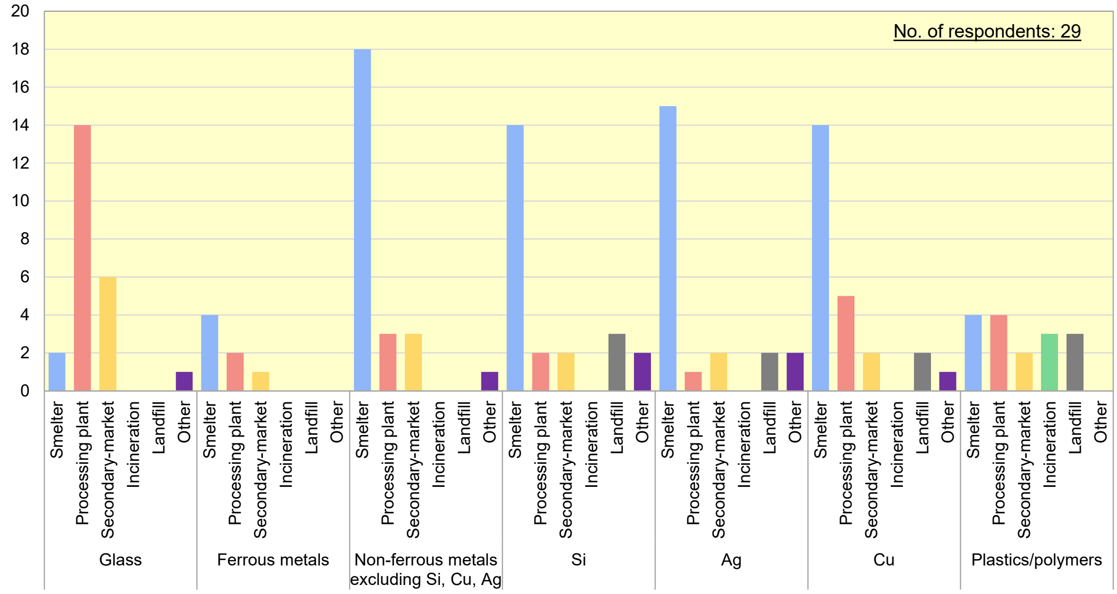


Fig. 3.2-12 Destination of the recovered or recycled materials

3.2.9 Potential issues or barriers for recovering or recycling materials

As shown in the previous section, 3.2.8, most materials recovered from PV modules are recycled in some way; however, the survey responses show that c-Si PV cell materials and plastics/polymers are not recycled frequently enough. Also, although glass is recycled, its use might be limited to lower-value products (i.e., downcycling). In order to scale up the recycling of PV waste and achieve a circular economy, further improvement might be needed, for example, from viewpoints of quality (purity of materials recovered, contamination); amount, especially for PV cell materials including electrodes metals; value (market price of materials for recycling, weight density of valuable metals in the compounds recovered); transportation (distance to the next destination, weight density and effectiveness of transportation); and destination (technical availability, economical availability including transportation).

Fig 3.2-13 shows potential issues or barriers for recovering or recycling materials from PV modules. For glass, the largest issue is "low value." Because recovered glass is used for lower-value products compared to PV glass, the net revenue is low or nonexistent. When a high-value end use is found or developed, the revenue from recovered glass will increase. The other issues for glass recovery are "high transportation cost" and "no proper destination." Because of the high weight density, the transportation cost of glass is high. Shortening the transportation distance for the downstream treatment or end use is one way to reduce costs. On the other hand, "no proper destination" could be a result of no proper facility or end use application, which could also arise because of high transportation costs.

Nonferrous metals correspond mainly to aluminium frames in terms of weight or waste volume. The answer "other" includes issues such as the difficulty of removal and the treatment of materials having significant physical damage. For other nonferrous metals (e.g., Ag and Cu), the main issue is "low recovered amount," followed by "low value." Generally, the smelters request being provided with a certain amount of metal constantly, whereas the value depends on the purity and weight density. When such metals are recovered with plastics or others as mixed materials, the value decreases. In the case of Si, the main barrier is "no proper destination," which is caused by the low value of Si compared to Ag and Cu and the lack of recycling uses. Even if the smelter receives Si together with Ag and Cu, it might not be recycled as a secondary product; however, if Si is separated and recovered with a high purity, it will be necessary to find a high-value end use of the recovered Si. Ideally, it is expected that the Si will be reused for Si PV cells, but further efforts to realize this at large scale are necessary.

Plastics/polymers are also difficult to recycle and are currently mostly discarded and sent to landfills; however, they are an important target for high-value recycling, and a circular economy and a valuable approach for recycling these materials should be developed, with a focus on new products.

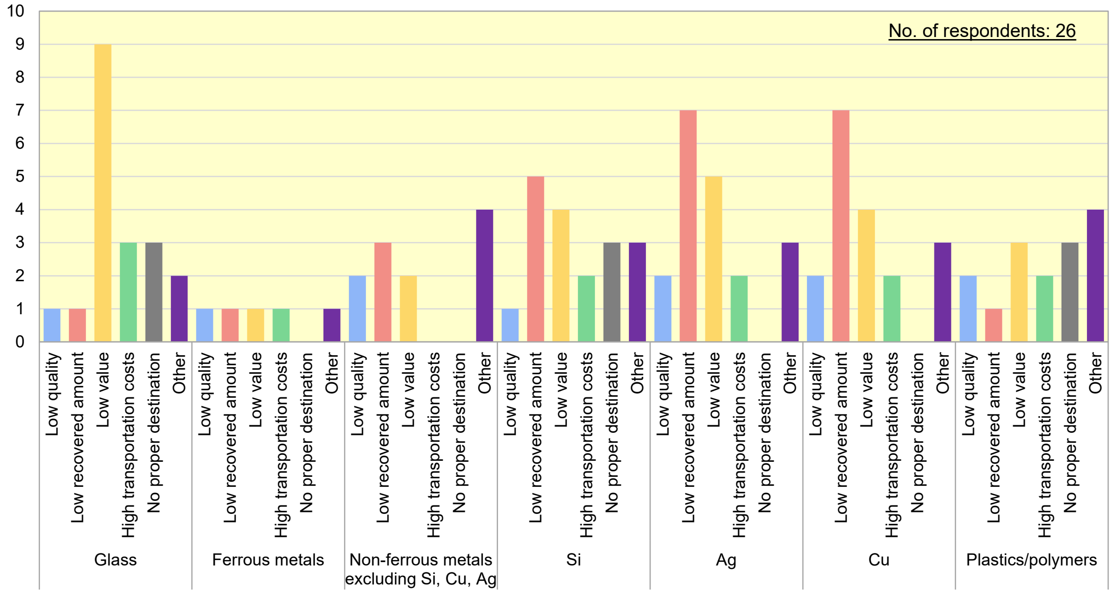


Fig. 3.2-13 Issues or barriers for recovering or recycling materials

4 SUMMARY AND CONCLUSIONS

The PV market is growing rapidly, and further market expansion is expected around the world. With PV deployment increasing exponentially, the number of PV modules that will reach the end of useful life will also greatly increase in the future, accumulating proportionately. In anticipation of the large volume of PV module waste, and to retain PV's position as a clean energy technology, PV module recycling has become a key topic, and various discussions and activities have been conducted and developed by governments, organizations, and companies.

This report summarized an overview of the status of PV module recycling in some IEA PVPS Task 12 countries. The first section of the report presented the regulatory schemes, information on PV module waste, relevant companies, and the PV waste outlook of each region, based on contributions by IEA PVPS Task 12 members. The second section discussed the results of a survey to PV module recyclers in several countries.

4.1 Status of PV module recycling

Europe: Germany, France, Italy, and Spain

In Europe, PV module recycling has been mandated since 2012 through the WEEE Directive 2012/19/EU. All EU member states have homologated the directive into national law, requiring all producers with PV modules in the EU market to either operate their own take-back and recycling scheme or to join what are known as producer compliance schemes. According to the Eurostat statistics, 13 951 tons of PV module waste were collected in 12 countries in 2018.

In Germany, the amount of collected PV modules was 7 865 tons in 2018; 7 708 tons were recovered, from which 6 896 tons were put to recycling and preparing for reuse. All PV modules require a registration and a specific EOL treatment. Business-to-customer PV modules are collected without charge for the customers at municipal waste collection points. Manufacturers must confirm default-free guarantees for these modules. Business-to-business PV modules require a direct take-back/collection but have no default-free guaranties; hence, collection fees could apply for business customers. The take back, recycling, and reuse of EOL modules in Germany is organized by service providers, such as PV CYCLE Germany or take-e-way, which provide full services of the administration, take back, and recycling of EOL modules. The recycling of c-Si PV modules is mainly done by glass recycling companies, and for CdTe PV modules, a specific recycling line is operated by First Solar in Frankfurt (Oder). According to the IRENA/PVPS Task 12 report on EOL PV panels published in 2016, waste projection range in Germany will be between 400 000 tons and 1 million tons in 2030 and increase up to 4.3 million tons in 2050.

In France, the amount of collected PV module waste has multiplied by more than 13 times from 366 tons in 2015 to 4 905 tons in 2019. Soren, the nonprofit eco-organization approved by ministerial decree, has the monopoly on activities related to PV module waste management. Soren manages both the collection and recycling by operating private tendering procedures that enable the centralization of PV waste management on French territory. The distribution of the PV module waste includes c-Si, CdTe, a-Si, CIGS, and flexible PV. The bulk waste stream comprises c-Si and CdTe modules. In 2019, c-Si waste was sent to the recycling facility Triade Electronique (Veolia subsidiary), whereas CdTe waste was sent to Germany, and other PV waste streams were sent to other treatment plants. The projections of the amount of PV waste expected in France will be more than 43 000 tons by 2030 and more than 118 000 tons by 2040. To meet this drastic increase, in February 2021, Soren launched a new tender to implement three new facilities dedicated to PV recycling in France. One facility started operation in 2021, and other two facilities will be operational in 2022.

In Italy, the amount of collected PV modules in 2018 was 1 350 tons. The Italy's energy services manager, the GSE, oversees the definition of instructions for the disposal of modules installed in plants in Italy in FIT schemes. PV modules discarded from plants with a nominal power less than 10 kWp are classified as "domestic WEEE." Those from plants with a nominal power greater than 10 kWp are classified as "professional WEEE". The domestic modules, once they have reached EOL, need to be sent to a national collection center. In the case of professional modules, they must be destined to an entity authorized to manage waste such as PV modules, a transporter, or a national collective system. The plants that benefit from the FIT scheme - or, rather, the modules that comprise the incentivized installed power - must comply with the rules set by the GSE or the PV module holder may be charged 12 EUR per domestic module or 10 EUR per professional module. According to the IRENA/PVPS Task 12 report on EOL PV panels, the waste projection range in Italy will be between 140 000 - 500 000 tons in 2030 and increase up to 2.2 million tons in 2050.

In Spain, the treatment of waste coming from PV modules is in a very preliminary stage. The amount of PV module waste collected in 2019 was 226 tons. The producer (manufacturer, distributor, installer, etc.) is obliged to comply with the obligations of the product design, to adopt the necessary actions to manage the waste of its products, and to fund the cost for this management. The producers must register their products in the national producer registry of electrical and electronic equipment (RII_AEE), managed by the Ministry of Industry, Commerce, and Tourism. The registration can be done individually or through a producer responsibility organization; currently, there are 11 authorized producer responsibility organizations, according to Royal Decree 110/2015. The amount of PV waste in Spain is small, but it will increase in the short to medium term due to the EOL of the first PV plants installed and in the long term due to the aging of plants recently installed and the new ones that will be installed in the coming years.

Asia and the Pacific: Japan, South Korea, China, and Australia

In Asia and the Pacific, there are currently no nationwide schemes dedicated to PV module recycling; however, some countries are implementing various discussions and activities for promoting the proper EOL management of PV module waste.

In Japan, currently, there are no specific regulations for EOL PV modules, so they must be treated under the general regulatory framework for waste management: the Waste Management and Public Cleaning Act; however, in 2018, Ministry of Economy, Trade, and Industry and MOE jointly published the second edition of the guideline for promoting the proper EOL treatment of PV modules, including recycling, as update to the previous edition, which was published in 2016. Also, in May 2021, MOE published a guideline for promoting the proper reuse of PV modules. Although there is no official statistical information on PV waste, it was estimated that 6 300 tons/year of PV waste were generated in 2020; from that, approximately 4 200 tons of modules would be reused, and 2 100 tons of modules would be sent to recycling facilities. Most waste was caused by natural disasters, such as typhoons, floods, and earthquakes. There are at least 29 companies treating PV module waste for recycling; it seems more than half of them use specific equipment for PV module recycling (separating the PV module's structure and components). It is forecasted that the amount of PV module waste will increase to 170 000 - 280 000 tons/year by the mid-2030s. Currently, some projects to find solutions for high-value glass recycling and for low-cost recycling, including the collection and transportation of EOL PV modules, are being carried out.

In South Korea, it is not currently mandatory to treat PV waste; however, PV module waste will be included in the list of items affected by EPR regulations, which will be enforced in the PV industry beginning in 2023, after the collection infrastructure for PV module waste and the development of recycling technologies is established in 2022, which will define PV modules as a unique product group. According to the statistics of the Korea Environment Corporation, the amount of PV module disposed and recycled during 2018 and the first half of 2020 was approximately 540 tons. Three companies use intermediate processes to correctly treat PV module waste; their total nominal treatment capacity is 7 800 tons/year. Several other companies have plans for PV recycling, but there is no detailed schedule for setting up facilities. According to predictions of annual PV module waste estimated by the Korea Environment Institute in 2018, the amount of annual module waste is predicted to reach 9 665 tons in 2023, consistently increasing to 20 935 tons in 2030, and 112 564 tons in 2040. To meet the increasing waste volume, various government-funded R&D projects to develop PV recycling technology have been carried out.

In China, there are no specific policies and regulations on PV module recycling or harmless treatment at the EOL stage. Although there are a variety of methods and feasible technical routes in the recycling of PV modules in China and abroad, the corresponding industrial chain has not been formed in China. In terms of policies and regulations, China is making efforts to study and introduce relevant policies to guide the industry, to require PV module recycling, and to fill the gaps. In recent years, increasing numbers of enterprises have joined the field of PV module recycling. Because of the high cost of PV module recycling, however, including transportation and collection, the economic benefits of PV module recycling are low, and the domestic market has little power to recover PV modules. To meet the demand for recycling, several R&D projects have been implemented. Also, an alliance, the China PV Recycling Center, was established in 2022, and it is expected that their work plan will contribute to achieving the goal of large-scale recycling of PV module waste.

In Australia, the State of Victoria passed legislation banning all electronic waste from landfill, including PV modules, inverters and PV batteries; however, currently, no other Australian state or territory has mandatory regulation on PV module disposal. The EPR principle in Australia is enacted through the Product Stewardship Act 2011. Currently, there are no recycling or product stewardship requirements for PV system components in any state or territory in Australia; however, an activity to evaluate the inclusion of PV systems showed that either voluntary or coregulatory approaches for PV modules might be feasible and are likely to achieve the objectives of the Product Stewardship Act, improving the management of PV modules and opportunities to reuse valuable materials. Currently, the Product Stewardship Centre of Excellence is leading the codesign of the National Product Stewardship for PV systems, with the aim of designing an EPR scheme by June 2022, to be implemented by June 2023. Barriers for recycling include transporting PV modules to a recycling facility and high processing costs. As a result, only a small amount of EOL PV modules are being recycled or refurbished. Despite such circumstances, some companies have started developments for PV module recycling. Also, national-level funding has been granted to develop innovative solutions to enable the sustainable and cost-effective management of EOL PV modules. It is expected that the amount of PV module waste will reach 10 000 tons/year by mid-2020s and to surge after 2030. Because the amount is likely to become large enough by the end of the decade, establishing collection systems is a priority for any recovery pathway. Further, R&D is required to develop advanced processes for high-value recovery and for managing contaminated hazardous residual material.

North America: Unites States of America

In the US, there has been growth in regulations specific to PV module waste across various states to incentivize the expansion of industrial capacity and to manage the expected increase in PV module waste. No US federal regulation specifically regulates PV waste management, but PV waste is covered under the Resource Conservation and Recovery Act. Although the amount of PV module waste is not monitored clearly, c-Si and thin-film PV recyclers in the US operate at various capacities and with different degrees of experience. The potential economic and environmental gains from sustainably managing PV waste have motivated the allocation of R&D funds toward accelerating the scaling of startups focusing on recycling Si PV waste and of industrial firms with experience in recycling non-PV products to expand operations into PV waste management. The amount of PV module waste is projected to reach 5.5 to 10 million tons by 2050. In the coming decades, data that account for the geographic dispersion of PV installation across the US can help recyclers plan to scale up operations and optimally locate recycling facilities to decrease transportation costs. Also, publicly available data on the material and design composition of PV modules will help PV recyclers better adapt and customize recycling technologies to more effectively recycle the expected volume of PV waste.

4.2 PV module recycling in the market

To understand the status of PV module recycling in the market, a survey was conducted. During the survey period, 2020Q4 to 2021Q2, a total of 29 answers were obtained: 6 from Europe (Germany, Spain, and the Netherlands) and 23 from Asia and the Pacific (Japan, South Korea, and Australia); thus, this survey covers a limited number of countries and companies, and the results should not be considered general world trends.

Relevant legislation and take-back management

In Europe, PV module recycling has been mandated through the WEEE Directive 2012/19/EU. EU member states have transposed the PV requirements into national law. Corresponding to the framework, direct collection from the site to the recycling plant, central collection and sorting, and PV CYCLE collection schemes have been applied in some EU countries. In other countries, currently there are no nationwide specific legislations for PV module waste, and direct collection is commonly used; however, discussions for introducing relevant regulations have been implemented.

Waste and PV cells and modules treated in the plant

Most respondents, both in Europe and the Asia/Pacific regions, are treating several waste streams—including metals, glass, and electronic waste—and PV module waste is only one of them. Only three respondents treat only PV module waste. Regarding the PV cell technologies recycled, most respondents treat c-Si PV modules. On the other hand, not many respondents treat CdTe modules or CIGS modules. From the viewpoint of the PV module structure, most respondents treat PV modules with a glass/back sheet structure, with/without a frame, and more than half the respondents treat PV modules with a glass/glass structure. Nine respondents answered they are treating flexible modules.

Treatment technologies for PV modules, their nominal capacity, and the actual amount of treatment

Regarding the treatment technologies for laminated structures, 17 respondents answered that they use only mechanical treatments—for example, shredding, separation by hot knife or wire, or scraping the glass or plastic layer. The other 12 respondents use a combination of multiple technologies. All of them combine mechanical treatments with thermal and/or chemical treatments.

Regarding the current available treatment capacity for PV modules, from among 16 valid answers, 10 plants have capacities less than 1 000 tons/year, whereas the largest capacity is 10 000 tons/year. Comparatively, the current amount treated in the plants is very small. According to 24 respondents, in 23 plants, the amount of PV modules treated was less than 1 000 tons/year; among those, in 14 plants, it was less than 100 tons/year.

Materials recovered from PV modules and estimated average rate of material recovery and recycling

Nonferrous metals and glass are recovered from PV modules at most plants. PV cell materials and polymers/plastics are also recovered. In the case of c-Si PV modules, however, it seems that Si PV cells are recovered together with plastics as mixture materials in many plants.

The estimated material recovery rate from PV modules, according to 25 respondents from among 28 valid responses (self-enumeration), is more than 80% of the materials. On the other hand, the estimated recycling rate from PV modules is less than the recovery rate. Twenty respondents from among the 28 answered that they are realizing more than 80% for the recycling rate. It seems that some polymers/plastics separated from the laminated structure are landfilled or incinerated.

Destination of the recovered or recycled materials

After the treatment at the plant, various materials recovered from PV modules are sent to the next destination for recycling or disposal. Glass is mainly sent to the next processing plant for recycling. Ferrous and nonferrous metals are sent to smelters, the next processing plant, or directly to secondary markets. Metals used for c-Si cells—such as Si, Ag, and Cu—are also sent to smelters, the next processing plant, or directly to secondary markets. In many cases, however, these metals are not separated and are sent to the next treatment as Si cells. Considering the treatment cost and the value of the recovered metals, landfilling might be chosen. For plastics/polymers, there are various destinations. Also, there will be cases when plastics/polymers are treated together with c-Si PV cells without separation.

Potential issues or barriers for recovering or recycling materials

Regarding the potential issues or barriers for recovering or recycling materials, the largest issue for glass is “low value.” The next issues are “high transportation cost” and “no proper destination.” It seems that “no proper destination” could result from situations caused by longer transportation distances or very low values. For other nonferrous metals (e.g., Si, Ag, and Cu), the largest issue is “low recovered amount,” and the second largest is “low value.” In the case of Si, it is “no proper destination.” This is caused by a low value of the Si material itself compared to Ag and Cu. It is also difficult for plastics/polymers to realize effective material recycling, but heat recovery is a promising path. A valuable approach for recycling materials should be developed.

4.3 Conclusions

PV deployment has accelerated more quickly than expected in the early 2010s. This means that, in the coming decades, PV waste will increase faster than anticipated. To meet and optimize the EOL management of PV waste, regulatory and technological approaches should be well integrated, and their potential options should be adapted to the conditions of each country or region.

In Europe, the EU has adopted PV-specific waste regulations. In other parts of the world, PV waste is typically handled under each country's legislative and regulatory framework for general waste treatment and disposal; however, policy approaches for accelerating PV EOL management, including supporting technology R&D, have been developed.

Looking at the treatment of PV module waste in the market, regardless of whether there are PV-specific waste regulations, several companies are treating PV module waste for proper EOL management and recycling.

The current low volumes, recycling technologies, logistics challenges, and undeveloped markets for recovered materials result in a high-cost, low-revenue scenarios of PV module recycling. The implementation of further improvements in PV EOL process is needed to meet future demand and to realize high-value, low-cost recycling.

[REFERENCES]

[1] IEA PVPS, Snapshot of Global PV Markets 2022, Report IEA PVPS T1-42:2022, 2022.

[2] IEA PVPS, Trends in Photovoltaic Applications 2021, Report IEA PVPS T1-41:2021, 2021.

[3] OECD/IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector, 2021.

[4] IRENA/IEA PVPS Task 12, End-of-Life Management: Solar Photovoltaic Panels, 2016. Available at https://iea-pvps.org/wp-content/uploads/2020/01/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf.

[5] European Parliament and Council, Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE), EU, Brussels.
Available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0019&from=EN.

[6] Eurostat "Waste electrical and electronic equipment (WEEE) by waste management operations"; online data code: ENV_WASELEE, last update: 9/2/2021 07:00; accessed 08 October 2021.
Available at https://ec.europa.eu/eurostat/en/web/products-datasets/-/ENV_WASELEE.

[7] Deutsche Umwelthilfe, Strengthening circularity in photovoltaics, Challenges and opportunities along the lifecycle, 2021. Available at https://www.duh.de/fileadmin/user_upload/download/Pressemitteilungen/Kreislaufwirtschaft/210310_White_Paper_Strengthening_Circularity_in_Photovoltaics_ENG_FINAL.pdf.

[8] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000029387124.

[9] https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000044096673/

[10] https://www.legifrance.gouv.fr/jorf/article_jo/JORFARTI000029583089.

[11] Data provided from PV Cycle France.

[12] Decreto Legislativo 14 marzo 2014, n. 49. Attuazione della direttiva 2012/19/UE sui rifiuti di apparecchiature elettriche ed elettroniche.

[13] Decreto Legislativo 3 aprile 2006, n. 152. Norme in materia ambientale.

[14] Decreto Legislativo 3 settembre 2020, n. 118. Attuazione degli articoli 2 e 3 della direttiva (UE) 2018/849, che modificano le direttive 2006/66/CE relative a pile e accumulatori e ai rifiuti di pile e accumulatori e 2012/19/UE sui rifiuti di apparecchiature elettriche ed elettroniche.

[15] Real Decreto 110/2015, de 20 de febrero, sobre residuos de aparatos eléctricos y electrónicos. (Royal Decree 110/2015 of January the 20th on Waste of Electrical and Electronic Equipment).
Available at https://www.boe.es/eli/es/rd/2015/02/20/110.

[16] Ley 22/2011, de 28 de julio, de residuos y suelos contaminados. (Law 22/2011 of July 28th on waste and contaminated soil). Available at https://www.boe.es/eli/es/l/2011/07/28/22.

[17] Ley 7/2022, de 8 de abril, de residuos y suelos contaminados para una economía circular. Available at: https://www.boe.es/buscar/act.php?id=BOE-A-2022-5809&p=20220409&tn=1.

[18] Data provided by the Ministry of Ecological Transitions and Demographic Challenge. Available at https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/flujos/responsabilidad-ampliada/.

[19] Real Decreto 27/2021, de 19 de enero, por el que se modifican el Real Decreto 106/2008, de 1 de febrero, sobre pilas y acumuladores y la gestión ambiental de sus residuos, y el Real Decreto 110/2015, de 20 de febrero, sobre residuos de aparatos eléctricos y electrónicos. (Royal Decree 27/2021 of 19 January amending Royal Decree 106/2008 of 1 February on batteries and accumulators and the environmental management of their waste, and Royal Decree 110/2015 of 20 February on waste electrical and electronic equipment). Available at https://www.boe.es/eli/es/rd/2021/01/19/27.

[20] Directive (EU) 2018/849 of the European Parliament and of the Council of 30 May 2018 amending Directives 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment.
Available at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L0849&from=ES.

[21] Real Decreto 208/2022, de 22 de marzo, sobre las garantías financieras en materia de residuos. Available at https://www.boe.es/buscar/doc.php?id=BOE-A-2022-5809.

[22] Resolución de la dirección general de calidad y evaluación ambiental por la que se publican los objetivos mínimos de recogida separada de residuos de aparatos eléctricos y electrónicos (raee) que deberán cumplir los productores en el año 2022. Available at: https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/report_resolucionobjetivosproductores2022_tcm30-538960.

[23] UNEF 2020 and 2021 Annual Report. Available at https://unef.es/informacion-sectorial/informe-anual-unef/.

[24] Disposición 5106 del BOE núm 77 de 2021. Resolución de 25 de marzo de 2021, conjunta de la Dirección General de Política Energética y Minas y de la Oficina Española de Cambio Climático, por la que se publica el Acuerdo del Consejo de Ministros de 16 de marzo de 2021, por el que se adopta la versión final del Plan Nacional Integrado de Energía y Clima 2021-2030.
Available at https://www.boe.es/boe/dias/2021/03/31/pdfs/BOE-A-2021-5106.pdf.

[25] J.D. Santos, M.C. Alonso-García. Projection of the photovoltaic waste in Spain until 2050. Journal of Cleaner Production 196 (2018) 1613-1628. Available at https://doi.org/10.1016/j.jclepro.2018.05.252.

[26] J.D. Santos, M.C. Alonso-García, N. Vela. Update of the Projection of the Photovoltaic Waste in Spain until 2050. Pro. Of the 36th EU PVSEC, September 2019, Marseille, France, pp 1234-1240. ISBN: 3-936338-60-4, Paper DOI: 10.4229/EUPVSEC20192019-4AV.2.50.

[27] Japanese Ministry of Environment. Guidelines for promoting recycling of solar power generation equipment, second edition, 2018. Available at https://www.env.go.jp/press/files/jp/110514.pdf.

[28] Japanese Ministry of Environment. A guideline for promoting proper reuse for PV modules. May 2021. Available at https://www.env.go.jp/press/files/jp/116525.pdf.

[29] Japanese Ministry of the Economy, Trade and Industry. Interim report of working group for a securement of cost of waste management of photovoltaic systems, December 2019. Available at https://www.meti.go.jp/shingikai/enecho/shoene_shinene/shin_energy/taiyoko_haikihiyo_wg/pdf/201901210_01.pdf.

[30] Japanese Ministry of the Economy, Trade and Industry, Jan. 2021. Available at https://www.meti.go.jp/shingikai/santeii/pdf/20210127_1.pdf.

[31] Japanese Ministry of the Economy, Trade and Industry, Review meeting for a proper installation and management of renewable energy power generation, 21 April 2022. Available at https://www.meti.go.jp/shingikai/energy_environment/saisei_kano_energy/pdf/001_04_00.pdf

[32] Japan Photovoltaic Energy Association. A list of intermediate processors which can treat PV modules properly, updated in May 2022. Available at https://www.jpea.gr.jp/wp-content/uploads/220526_recycle.pdf.

[33] Japanese Ministry of the Economy, Trade and Industry, Committee for a mass-introduction of renewable energy and future electricity networks, 21 November 2018. Available at https://www.meti.go.jp/shingikai/enecho/denryoku_gas/saisei_kano/pdf/010_03_00.pdf.

[34] NEDO, A master plan for development of technologies to promote photovoltaic power generation as main power source (FY2020-2024).

[35] Recycling scheme of future wastes including PV panel waste is prepared (in Korean), Press release from Ministry of the Environment, 2018.

[36] EPR enforcement is from 2023 with a two-year delay (in Korean), newspaper of Solar Today, 2018.

[37] Expansion of reuse and recycling of PV panel wastes (in Korean), Press release from Ministry of the Environment, 2019.

[38] Enforcement rule of the act on resource circulation of electrical and electronic equipment and vehicles (in Korean), National law information center, 2020.

[39] PV panel waste is a big problem, no regulation on environmental pollution (in Korean), KBS broadcasting news, 2018.

[40] Statistics provided by Korea Environment Corporation.

[41] Photo courtesy of Yoonjin Tech.

[42] South Korea to introduce new rules for PV recycling, PV magazine, 2020.

[43] Photo courtesy of WonKwang S&T.

[44] Photo courtesy of Chungbuk Technopark.

[45] Management status and improvement plans of waste solar panels (in Korean), Korea Environment Institute, 2018.

[46] NTIS website (https://www.ntis.go.kr/).

[47] Special science and technology report of national key R & D projects in the 13th five year plan: Research Report on the status quo of crystalline silicon photovoltaic module recycling at home and abroad, 2020.

[48] http://www.chinapv.org.cn/com_news/415.html.

[49] L Zhang, et al., “Projection of Waste Photovoltaic Modules in China Considering Multiple Scenarios”, 2022, https://doi.org/10.1016/j.spc.2022.07.012

[50] Arup, “Circular photovoltaics - Circular business models for Australia’s solar photovoltaics industry,” 2020.

[51] J. Milbank, “Recycling solar”, 2019. Available at https://renew.org.au/renew-magazine/sustainable-tech/recycling-solar/.

[52] N. FILATOFF, “Arup report outlines potential of PV and the circular economy”, PV Magazine, 2020.

[53] L. Chaplin, N. Florin, and E. Dominish, “Photovoltaic Stewardship: accessing international experience”, 2018.

[54] Equilibrium, “PV Systems Stewardship Options Assessment Second Phase Stage Eight – Final Report”, vol. 3031, no. March, 2019.

[55] W. and the E. Department of Agriculture, “Partnering for a sustainable environment Partnership Call: product stewardship scheme for photovoltaic systems”, no. January, 2021.

[56] D. Mathur, R. Gregory, and T. Simmons, “End-of-Life Management of Solar PV Panels”, 2020.

[57] R. Wakefield-rann, N. Florin, N. Harford, D. Wigley, and T. Pollock, “Scoping study for photovoltaic panel and battery system reuse and recycling fund”, 2020.

[58] Sustainability Victoria, “PV Panel Reprocessing: Research into Silicon-Based Photovoltaic Cell Solar Panel Processing Methods, Viable Materials Recovery and Potential End Market Applications”, 2019.

[59] Sustainability Victoria, “National approach to manage solar panel, inverter and battery lifecycles,” 2020. Available at https://www.sustainability.vic.gov.au/About-us/Research/Solar-energy-system-lifecycles.

[60] “PV Industries”. Available at https://www.pvindustries.com.au/.

[61] T. Dawson, “Electrical Connection magazine features PV Industries”, 2020.

[62] “A positive disruption – Scipher Technologies is turning to innovation as it strives to be the pre-eminent e-waste recycler in Australia”, in press, Waste Management Review Magazine, June 2022.

[63] “NSW EPA awards Solar Professionals almost $1 million to develop a first-of-its-kind solar recycling facility”, Solar Professionals, August 2021. Available at https://solarprofessionals.com.au/wp-content/uploads/2021/08/210831_Solar-Professionals-receives-NSW-EPA-grant-of-almost-1-million_FINAL.pdf.

[64] “Reclaim PV Recycling”. Available at https://www.reclaimpv.com/.

[65] N. FILATOFF, “Australia’s first large-scale solar panel recycling operation amps up collection of precious ‘waste’”, PV Magazine, 2021.

[66] S. Vorrath, “‘First of its kind’ solar panel upcycling plant on cards after federal grant win”, 2020.

[67] “Solar Recovery Corporation” Available at https://www.resourcerecyclingaustralia.com/.

[68] Andrea Steffen, “Australia’s First Solar Panel Recycling Facility Is Now Operational”, Intelligent Living, 2021. Available at https://www.intelligentliving.co/australias-first-solar-panel-recycling-facility/

[69] B. HENWOOD, “UNSW awarded more than $7m for renewable energy research and development”, 2020.

[70] NSW EPA, “Circular solar trials - expression of interest”, 2020.

[71] N. FILATOFF, “NSW Government recycling trials to seed a circular solar economy”, PV Mag., 2020.

[72] S. Mahmoudi, N. Huda, and M. Behnia, “Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia”, Resour. Conserv. Recycl., vol. 146, no. April, pp. 192–205, 2019, doi: 10.1016/j.resconrec.2019.03.039.

[73] N. Mathur, S. Singh, and J. W. Sutherland, “Promoting a circular economy in the solar photovoltaic industry using life cycle symbiosis”, Resour. Conserv. Recycl., vol. 155, no. August 2019, p. 104649, 2020, doi: 10.1016/j.resconrec.2019.104649.

[74] PV Industries, “How long do solar panels last”, 2021. Available at https://www.pvindustries.com.au/faq/how-long-do-solar-panels-last/.

[75] Tan, V., Dias, P.R., Chang, N. and Deng, R., 2022. Estimating the Lifetime of Solar Photovoltaic Modules in Australia. Sustainability, 14(9), p.5336.

[76] "Installers to play key role in UNSW solar module recycling strategy", David Carroll, PV Magazine, Dec 23, 2021. Available at https://www.pv-magazine-australia.com/2021/12/23/installers-to-play-key-role-in-unsw-solar-module-recycling-strategy/.

[77] Washington State Legislature Wash. Rev. Code § 70A.510.010 - Photovoltaic Module Stewardship and Takeback Program. Available at https://app.leg.wa.gov/RCW/default.aspx?cite=70A.510.

[78] Department of Toxic Substances Control (DTSC) Final Regulations: Photovoltaic (PV) Modules – Universal Waste Management.
Available at https://dtsc.ca.gov/regs/pv-modules-universal-waste-management/ (2021).

[79] Curtis, T. L.; Garvin, H.; Buchanan, H.; Smith, L. A Circular Economy for Solar Photovoltaic System Materials: Policy Considerations and Case Studies; NREL/TP-6A20-74550; National Renewable Energy Laboratory: 2021.

[80] Curtis, T. L.; Heath, G.; Buchanan, H.; Shaw, S.; Kaldunski, B. Solar Photovoltaic Recycling: A Survey of U.S. Policies and Initiatives; NREL/TP-6A20-74124. Golden, CO; National Renewable Energy Laboratory: 2021.

[81] Department of Environmental Quality, N. C. Final Report on the Activities Conducted to Establish a Regulatory Program for the Management and Decommissioning of Renewable Energy Equipment. Available at https://files.nc.gov/ncdeq/documents/files/DEQ_H329%20FINAL%20REPORT_2021-01-01.PDF (2021).

[82] CSA Group, Photovoltaic (PV) Recycling, Reusing, and Decommissioning - Current Landscape and Opportunities for standardization. 2020.

[83] Ravikumar, D., Seager, T., Sinha, P., Fraser, M.P., Reed, S., Harmon, E. and Power, A., Environmentally improved CdTe photovoltaic recycling through novel technologies and facility location strategies. Progress in Photovoltaics: Research and Applications 2020, 28, (9), 887-898.

[84] Ravikumar, D., Sinha, P., Seager, T.P., Fraser, M. P., An anticipatory approach to quantify energetics of recycling CdTe photovoltaic systems. Progress in Photovoltaics: Research and Applications 2016, 24, (5), 735-746.

[85] Sinha, P., Raju, S., Drozdiak, K., Wade, A., Life cycle management and recycling of PV systems. PVTech 2018, 47-50.

[86] Sinha, P., Cossette, M., Ménard, J-F., End-of-Life CdTe PV Recycling with Semiconductor Refining. In 27th European Photovoltaic Solar Energy Conference and Exhibition, 2012; pp 24-28.

[87] recyclepvsolar Solar Recycling Simplified. Available at https://recyclepv.solar (2021).

[88] We Recycle Solar National PV Disposal Provider. Available at http://werecyclesolar.com/about-us/ (2021).

[89] Solarrecycle.org, Vendors at a glance. Available at https://5c97398d-8e70-4dc9-934c-1f0bf4539dbe.filesusr.com/ugd/30ffda_41e42e43c9cd483b940003ef04f51e26.pdf.

[90] TG Companies Building a Sustainable Future. Available at https://www.tg-companies.com (2021).

[91] Solar Energy Industries Association (SEIA) SEIA National PV Recycling Program. Available at https://www.seia.org/initiatives/seia-national-pv-recycling-program (2021).

[92] Echo Environmental Solar panel recycling. Available at https://echoenvironmental.com/solar-panel-recycling/ (2021).

[93] Green Century Recycling Business Services. Available at https://greencenturyonline.net/electronics-recycling-services/business-services/ (2021).

[94] Cascade Eco Minerals The next generation of PV recycling. Available at https://www.cascadeecominerals.com (2021).

[95] Tao, M.; Fthenakis, V.; Ebin, B.; Steenari, B.-M.; Butler, E.; Sinha, P.; Corkish, R.; Wambach, K.; Simon, E. S., Major challenges and opportunities in silicon solar module recycling. Progress in Photovoltaics: Research and Applications 2020, 28, (10), 1077-1088.

[96] Heath, G. A.; Silverman, T. J.; Kempe, M.; Deceglie, M.; Ravikumar, D.; Remo, T.; Cui, H.; Sinha, P.; Libby, C.; Shaw, S.; Komoto, K.; Wambach, K.; Butler, E.; Barnes, T.; Wade, A., Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nature Energy 2020, 5, (7), 502-510.

[97] Domínguez, A., Geyer, R., Photovoltaic waste assessment of major photovoltaic installations in the United States of America. Renewable Energy 2019, 133, 1188-1200.

[98] (EPRI), E. P. R. I., Solar PV Module End-of-Life: Options and Knowledge Gaps for Utility-Scale Plants. 2018.

[99] TamizhMani, G., Shaw, S., Libby, C., Patankar, A. and Bicer, B., Assessing Variability in Toxicity Testing of PV Modules. In IEEE 46th Photovoltaic Specialists Conference (PVSC), 2019; pp 2475-2481.

[100] ASTM International, ASTM E3325-21 - Standard Practice for Sampling of Solar Photovoltaic Modules for Toxicity Testing. Available at https://www.astm.org/e3325-21.html

[101] ASTM International, ASTM WK74146 - New Practice for Toxicity Testing of Photovoltaic (PV) Modules by Waterjet Cutting Method for Use with EPA Method 1311. Available at https://www.astm.org/DATABASE.CART/WORKITEMS/WK74146.htm (2021)

[102] "Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan", March 2022. Available at https://www.energy.gov/sites/default/files/2022-03/Solar-Energy-Technologies-Office-PV-End-of-Life-Action-Plan.pdf

[103] DuPont Issues 2019 Global PV Reliability Study. Available at https://www.dupont.com/news/20190618-dupont-issues-2019-pv-reliability-study.html (2019).

[104] Aryan, V.; Font-Brucart, M.; Maga, D., A comparative life cycle assessment of end-of-life treatment pathways for photovoltaic back sheets. Progress in Photovoltaics: Research and Applications 2018, 26, (7), 443-459.

[105] International Technology Roadmap for Photovoltaic (ITRPV), International Technology Roadmap for Photvoltaic (ITRPV) 2019 Results. 2020.

[106] Einhaus, R.; Madon, F.; Degoulange, J.; Wambach, K.; Denafas, J.; Lorenzo, F. R.; Abalde, S. C.; Garcia, T. D.; Bollar, A. In Recycling and Reuse potential of NICE PV-Modules, 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), 2018/06//, 2018; EU Horizon 2020: 2018; p 4.

APPENDIX – RESULTS OF QUESTIONNAIRE BY REGION

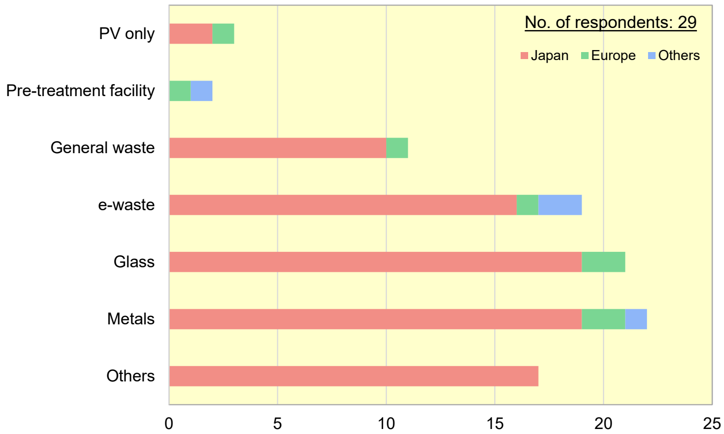


Fig. A-1 Waste treated in the respondents' plants

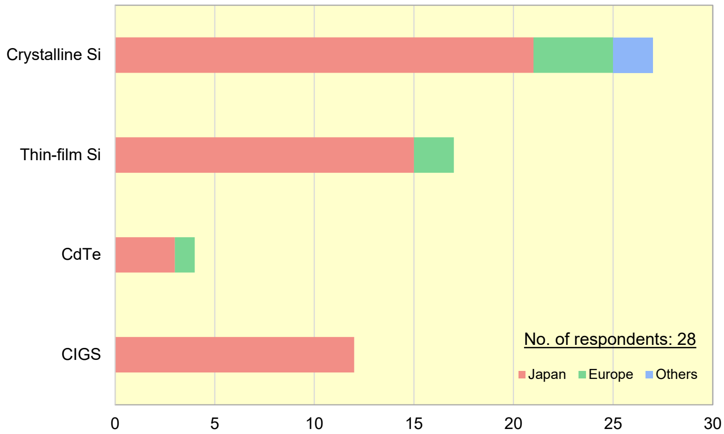


Fig. A-2 PV cell technologies treated in the respondents' plants

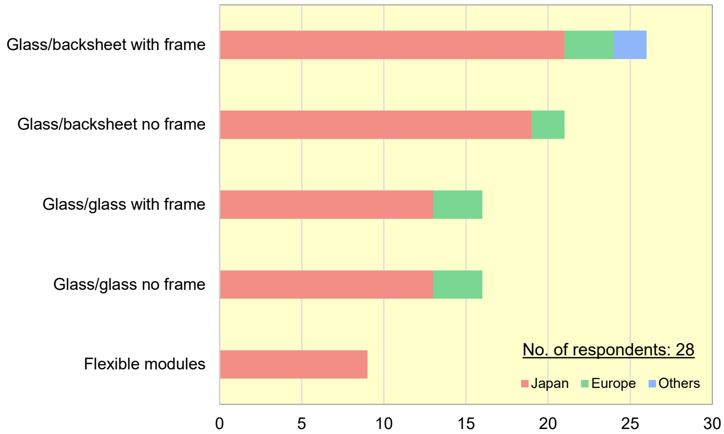


Fig. A-3 PV module structures treated in the respondents' plants

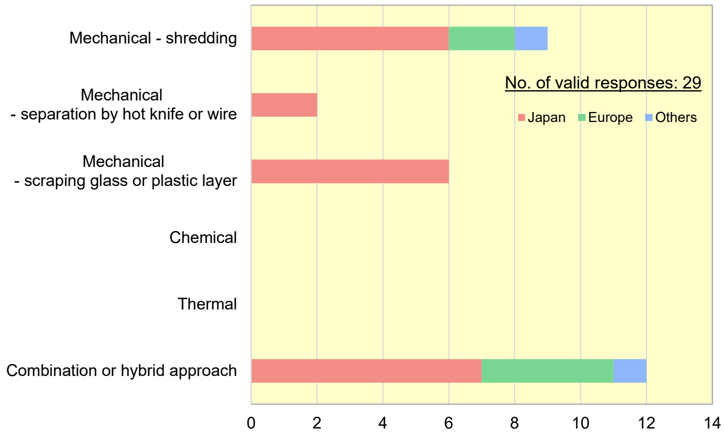


Fig. A-4 Treatment technologies for PV modules

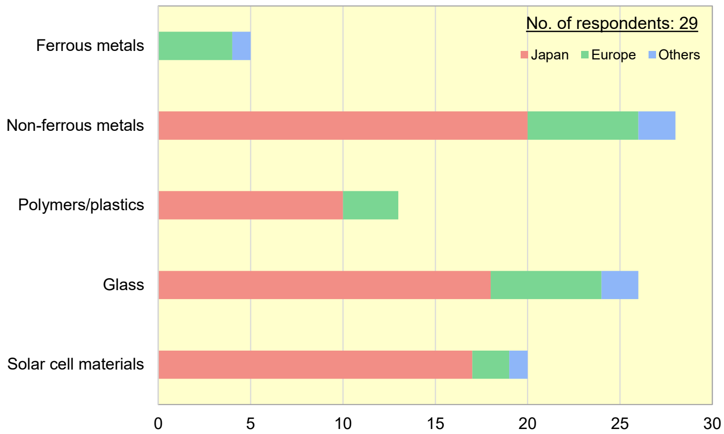


Fig. A-5 Materials recovered from PV modules at the plants

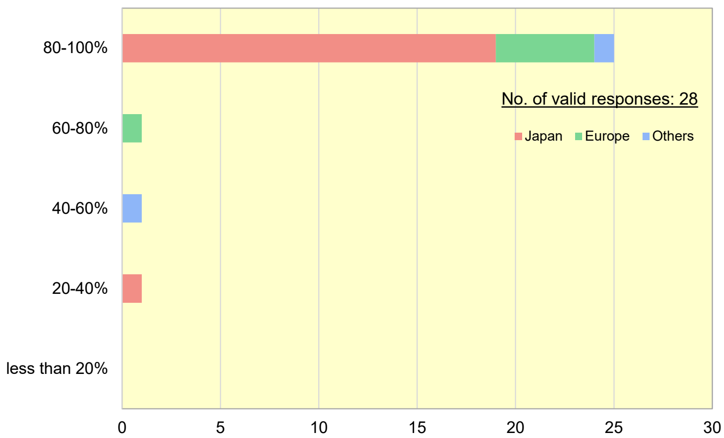


Fig. A-6 Material recovery rate from PV modules at the plants

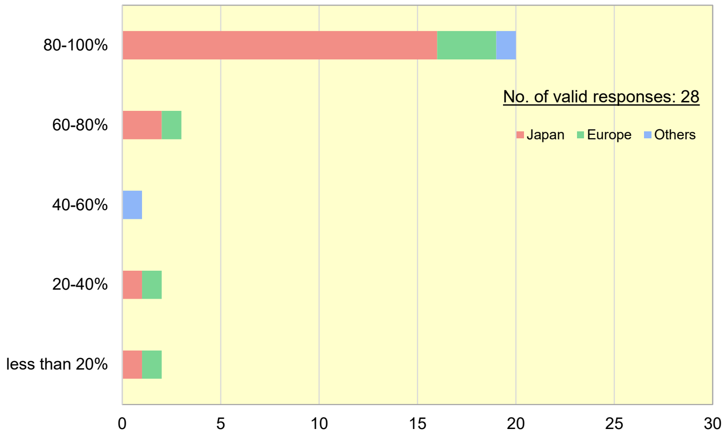


Fig. A-7 Material recycling rate from PV modules at the plants

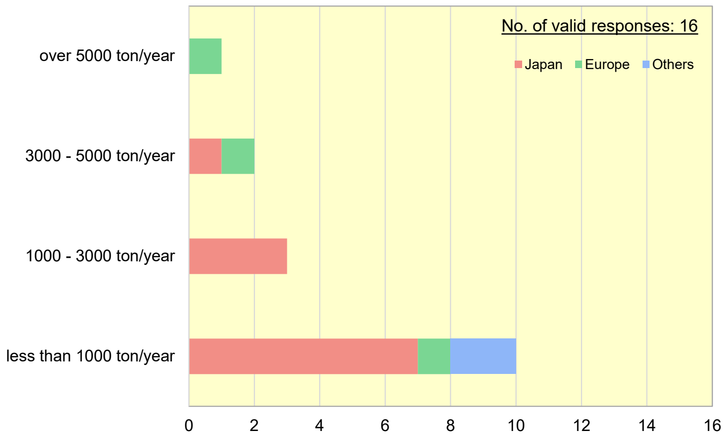


Fig. A-8 Available treatment capacity for PV modules

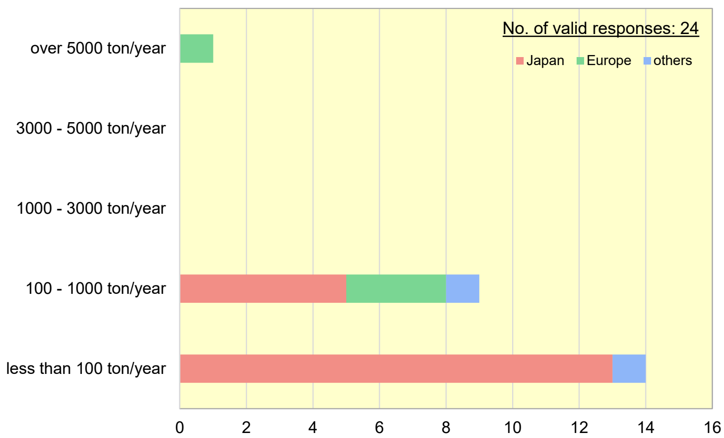


Fig. A-9 Current amount of PV modules treated

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