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International Energy Agency
**Photovoltaic Power Systems Programme**

Task 12 PV Sustainability

PVPS

# Status of PV Module Recycling in IEA PVPS Task 12 Countries

2025

**Report IEA-PVPS T12-31:2025**

# What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organisation for Economic Cooperation and Development (OECD). The Technology Collaboration Programmes (TCP) were created with a belief that the future of energy security and sustainability starts with global collaboration. The programmes are 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 TCPs 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.” 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.

The 27 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkiye, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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# What is IEA PVPS Task 12?

The goal of Task 12 is to foster international cooperation and knowledge sharing on the sustainable aspects of PV technology, emphasizing environmental and social factors. Its mission is to provide essential information to stakeholders, enhancing consumer and policy-maker confidence in PV systems, and thereby accelerating the shift towards sustainable energy. The objectives of Task 12 are to: (1) Quantify PV electricity’s environmental profile to enhance supply chain sustainability and enable comparisons with other energy technologies. (2) Enhance PV technology and materials circularity through novel analysis, legislative tracking, and technical standards development. (3) Investigate synergies between PV system deployment and its environmental and ecosystem impacts. (4) Identify and tackle both real and perceived social and socio-economic challenges to PV market growth. (5) Share analytical findings with technical experts, policymakers, and the public.

Task 12’s first objective focuses on employing Life Cycle Assessment (LCA) for detailing energy, material, and emission flows across PV life cycles, including human health assessments. The second objective involves advancing the circular economy for PV modules and system components through research and metric development. The third objective is met by evaluating the impact of PV projects on ecosystems, including both standard and integrated systems like agrivoltaics. The fourth objective promotes sustainable practices within the solar value chain and assesses environmental, social, and socio-economic impacts of PV technology. Lastly, the fifth objective engages a wide audience through publications, presentations, and media collaboration, disseminating information and fostering industry-wide sustainable actions.

Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and TotalEnergies. Support from the U.S. Department of Energy and TotalEnergies is gratefully acknowledged.

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**COVER PICTURE**

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INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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**IEA PVPS**
**Task 12**
**PV Sustainability**

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| Ag | silver |
| a-Si | amorphous-silicon |
| ANSI | American National Standards Institute |
| ARENA | Australian Renewable Energy Agency |
| B2B | business-to-business |
| B2C | business-to-consumer |
| BIL | Bipartisan Infrastructure Law |
| c-Si | crystalline silicon |
| C&I | commercial and industrial |
| CdTe | cadmium telluride |
| CEBA | Clean Energy Buyers Alliance |
| CEBI | Clean Energy Buyers Institute |
| CIGS | copper indium gallium selenide |
| CINEA | European Climate, Infrastructure, and Environment Executive Agency |
| Cu | copper |
| DCCEEW | Department of Climate Change, Energy, the Environment, and Water |
| DOE | U.S. Department of Energy |
| DSW | Definition of Solid Waste |
| EAG-VO | Elektroaltgeräteverordnung (Austria) |
| EAK | Elektroaltgeräte Koordinierungstelle (Austria) |
| EAR | Elektro-Altgeräte-Register |
| EC | European Commission |
| EIP | European Innovation Partnership |
| EIT | European Institute of Innovation and Technology |
| EOL | end-of-life |
| EPEAT | Electronic Product Environmental Assessment Tool |
| EPC | Engineering, Procurement and Construction |
| EPR | extended producer responsibility |
| EU | European Union |
| EV | electric vehicle |
| 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) |
| GWh | gigawatt-hour |
| HaDEA | European Health and Digital Executive Agency |
| IEA | International Energy Agency |
| IEMAP | Italian Energy Materials Acceleration Platform |
| IRA | Inflation Reduction Act |
| IRENA | International Renewable Energy Agency |
| ISMC | Iberian Sustainable Mining Cluster |
| JPEA | Japan Photovoltaic Energy Association |
| kW | kilowatt |
| kWp | kilowatt-peak |
| LCA | life cycle assessment |
| MASE | Ministry of Environment and Energy Security |
| METI | Ministry of Economy, Trade, and Industry (Japan) |
| MITERD | Spanish Ministry for the Ecological Transition and the Demographic Challenge |
| MOE | Ministry of Environment (Japan) |
| t/y | tonnes per year |
| MW | megawatt |
| MWh | megawatt-hour |
| MWp | megawatt-peak |
| NDRC | National Development and Reform Commission |
| NEA | National Energy Administration |
| NECP | National Energy and Climate Plan |
| NEDO | New Energy and Industrial Technology Development Organization |
| NREL | National Renewable Energy Laboratory |
| NSF | National Science Foundation |
| NSW EPA | New South Wales Environmental Protection Authority |
| NWR | National WEEE Register |
| OECD | Organisation for Economic Co-operation and Development |
| PARSIVAL | PAnels Recycling to create SIlicon VALue chain |
| PLIM | product lifecycle information management |

| | |
|---|---|
| PROs | producer responsibility organizations |
| PV | photovoltaic(s) |
| PV ICE | PV in the Circular Economy |
| PVPS | Photovoltaic Power Systems Programme |
| R&D | research and development |
| RCRA | Resource Conservation and Recovery Act |
| RIS | Regional Innovation Scheme |
| SEIA | Solar Energy Industries Association |
| SETO | Solar Energy Technologies Office |
| TCLP | Toxicity Characteristic Leaching Procedure |
| TCP | Technology Collaboration Programme |
| TRL | technology readiness level |
| TW | terawatt |
| UNSW | University of New South Wales |
| US | United States |
| WEEE | Waste Electrical and Electronic Equipment |
| WET | Waste Extraction Test |
| WP | Work Programme |

# EXECUTIVE SUMMARY

This report aims to provide an overview the status of PV module recycling in International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Task 12 member countries in two parts. Firstly, regulatory schemes, information on expected PV module waste, recycling companies, and the outlook of each region and/or country are surveyed. Secondly, selected, recent research and development (R&D) projects on PV module recycling technologies supported by national and/or regional public funding are summarised. It updates and expands upon prior Task 12 reports on these subjects (Komoto et al. 2018 & Komoto et al. 2022).

In terms of the status of PV recycling in the selected Task 12 countries included in this report, in Europe, 48 395 tonnes of PV module waste were collected from 18 countries in 2022, according to Eurostat. The European Union (EU) has adopted PV-specific end-of-life (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, without specific consideration of PV. In EU and non-EU countries, policy approaches for accelerating PV EOL management, including supporting technology R&D, have been developed or are in the process of being developed. For instance, in Japan, a discussion for assessing how to handle EOL PV modules has accelerated, and a concept of regulation for promoting a proper treatment such as recycling was drafted in December 2024, including a potential recycling mandate. In South Korea, a PV extended producer responsibility (EPR) regulation has been enforced starting in 2023, whereas in China, PV recycling technology development and practice continues to advance due to the successive release of national incentive policies. In Australia, it is expected that a mandatory product stewardship program to address PV system waste will be implemented by 2025 at the federal level, in addition to state-level discussions. In the United States (U.S.), regulations specific to EOL PV exist in some states. Although there are no U.S., federal regulations specific to PV module recycling, the Environmental Protection Agency initiated a rulemaking effort in October 2023 in which PV modules would be added to universal hazardous waste regulations. This designation would allow for less-stringent collection restrictions and management requirements compared to fully regulated hazardous waste.

Several R&D projects for high value recycling and circulating materials have been implemented in the world. Often focusing on glass-based crystalline Si PV modules, the treatment steps developed by such R&D projects are delamination, metal recovery, and preparation of materials for markets. Novel delamination approaches being developed in R&D projects identified in this report include diamond wire, water jet and infrared lamps. Metal recovery is typically realised through a chemical approach. Advances being addressed in R&D projects identified in this report include environmentally friendly solvents that can replace acids. As for material preparation for markets, recovery rate and purity targets for specific materials such as Si, Ag, glass and polymer are being set. In the case of Si, novel markets being explored include the anode material for lithium-ion batteries and waterglass (or sodium silicate).

It is observed across the countries surveyed that the current low volumes, limitations with available commercial-scale recycling technologies, logistics challenges, and undeveloped markets for recovered materials result in a high-cost, low-revenue scenario of PV module recycling. Further improvement in PV EOL recycling and its associated logistics and secondary market development is needed to meet future material demand at a cost comparable to virgin material manufacture. Key to realizing high-value, low-cost recycling will be expanding from delamination-focused recycling technology to include recovery of all metals and identifying highest value target markets. Circulating recovered materials to new PV cells and modules is appealing as a closed loop solution, but use of recovered PV materials in other industries can be explored as well. How to achieve high purity in recovered materials remains an issue to be solved.

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 information and data in this report were collected in 2024, reflective of the latest year available.

# 1 INTRODUCTION

Photovoltaic (PV) technology 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. PV circularity is an increasingly important topic, requiring proper EOL treatment of PV components. The PV market is growing rapidly, and further market expansion is expected around the world.

Globally, newly installed PV capacity reached approximately 456 gigawatts (GW)/year in 2023, leading to a cumulative capacity of 1 642 GW by 2023 [1] (see Fig. 1-1 and Fig. 1-2). It is expected that 1 terawatt (TW) PV will be annually installed in a couple of years, bringing us into the terawatt-era of photovoltaics.

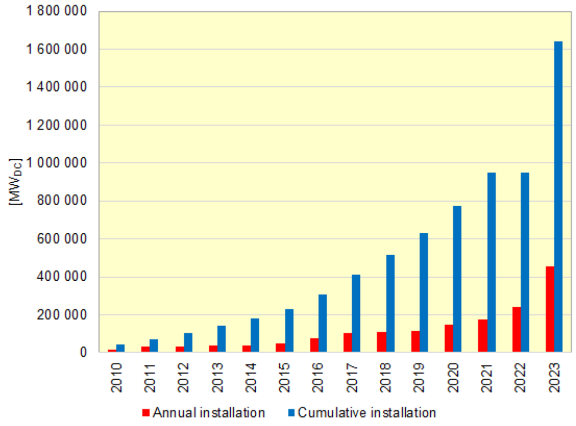



**Fig. 1-1 Trends in PV installations around the world [1]**

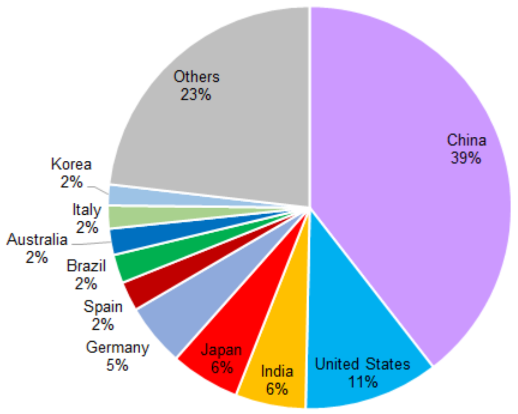



**Fig. 1-2 Regional distribution of the cumulative installation of PV technology at the end of 2023 [1]**

With PV deployment increasing exponentially, the number of PV modules that reach the end-of-life will also increase, accumulating as waste after their operational lifetime. When a product cannot be repaired or reused, according to the common circular economy pathway hierarchy (e.g., [2]) recycling is the next preferable option before disposing of it as waste. In anticipation of the large volume of EOL PV modules, and to retain the PV 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.

In 2016, PVPS Task 12 published a technical report regarding EOL management of PV modules together with the International Renewable Energy Agency (IRENA) [3]. The report showed the estimated cumulative volumes of EOL PV modules around the world (see Fig. 1-3). In the regular loss scenario, an EOL PV module volume of 100 000 tonnes was projected by 2020, with an increase to 1.7 million tonnes by 2030, and 60 million tonnes by 2050. The early loss scenario projection estimated much higher total EOL PV streams, with 850 000 tonnes by the end of 2020, 8 million tonnes by 2030, and a total of 78 million tonnes by 2050.

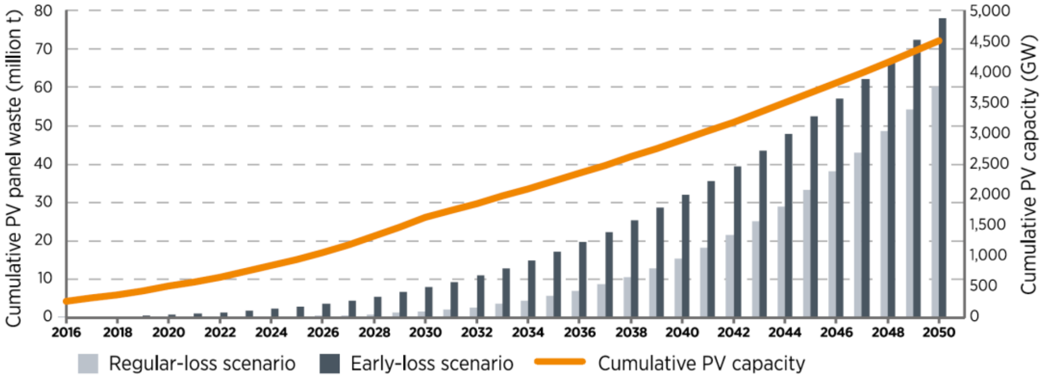



**Fig. 1-3 Estimated cumulative global volumes of EOL PV modules by IRENA/Task 12 in 2016 [3]**

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. This means that EOL PV could increase more quickly in the coming decades.

"World Energy Transitions Outlook 2022" by IRENA [4] projected that EOL PV modules from global cumulative PV projects would increase to 4 million t in 2030, almost 50 million t in 2040, and more than 200 million t by 2050 (see Fig. 1-4). According to the IEA report "Special Report on Solar PV Global Supply Chains" published in July 2022 [5], using a different model, the global cumulative flow of decommissioned PV capacity is estimated to reach around 7 GW by 2030 and could increase to more than 200 GW by 2040 (see Fig. 1-5). This represents 0.4 to 0.6 million t of embodied materials cumulatively by 2030 and 11 to 15 million t by 2040.

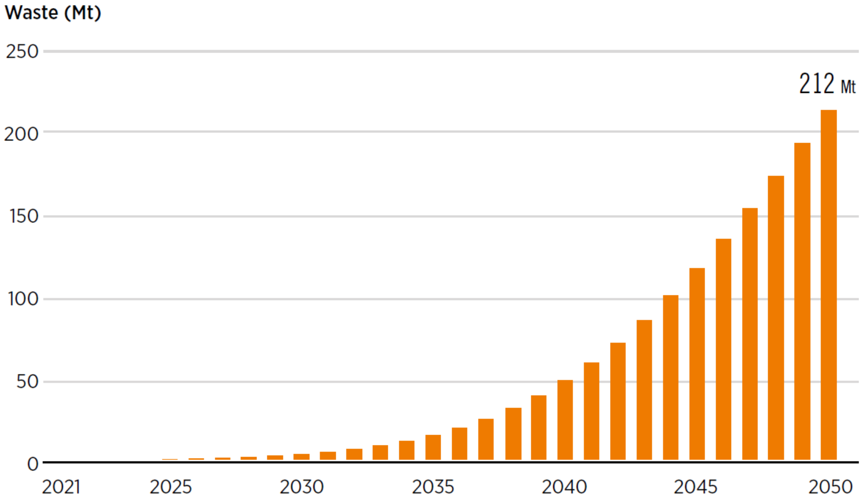



**Fig. 1-4 Projected cumulative EOL PV modules under IRENA's 1.5°C Scenario through 2050 [4]**

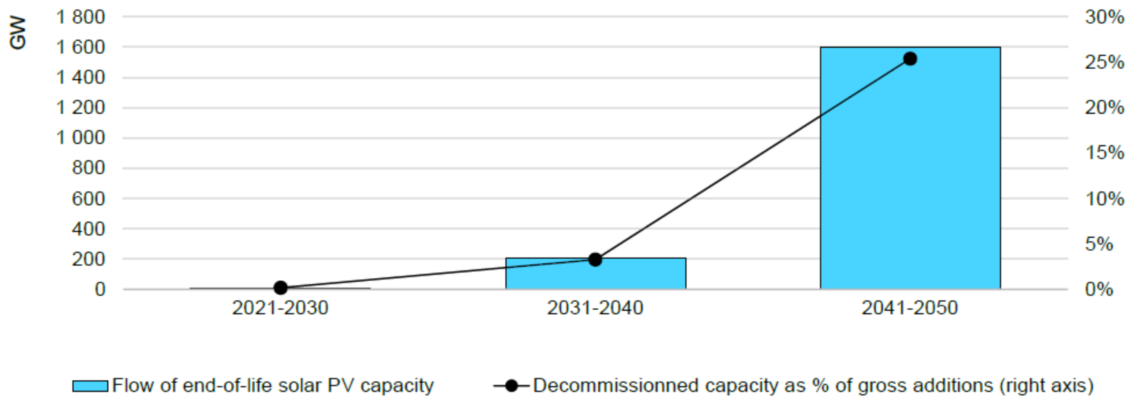



**Fig. 1-5 Expected flows of decommissioned PV capacity, 2020-2050 [5]**

(Notes: Values are based on historical capacity additions as well as additions modelled in the IEA Net Zero by 2050 Scenario. PV module lifetimes before decommissioning are assumed to follow a Weibull distribution pattern, with median lifetimes of 25 years for utility-scale installations and 30 years for distributed.)

(Source: IEA 2022, Special Report on Solar PV Global Supply Chains, page 97)

Responsible EOL management strategies are considered part of being an environmentally favourable electricity generation source. A framework supporting the early development of EOL strategies will foster progress toward comprehensive policies. Integrated regulatory and technological approaches are needed to optimize EOL PV management plans, together with adaptations to the unique conditions of each country or region.

A previous Task 12 report surveying the status of PV recycling in some Task 12 countries published in 2022 [6] concluded:

- The European Union (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 research and development (R&D), have been developed.
- Regarding 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 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.

Since that report was published, the amount of EOL PV module is gradually increasing in the world, relevant regulations have become or are likely to become effective in other regions, and new facilities and equipment for PV module recycling, mainly for delamination, are being operated. Additionally, several R&D projects for high-value recycling and circulating materials have been implemented.

This report provides an overview and update of the status of PV module recycling in two main chapters, based on contributions by IEA PVPS Task 12 members. First, regulatory schemes, information on EOL PV modules and relevant companies, and the outlook of each region and/or country are surveyed. Second, selected, recent R&D projects on PV module recycling technologies supported by national and/or regional public funding are summarized. The data and information were collected in 2024, the latest data available at the time of writing.

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 and as a way for realizing PV circularity.

# 2 STATUS OF PHOTOVOLTAIC MODULE RECYCLING

This chapter examines the status of PV module recycling from the viewpoints of regulatory schemes, EOL PV modules, relevant companies, and overall outlook. Information on following IEA PVPS Task 12 participating countries was surveyed and organized by region:

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

## 2.1 Europe

Before the establishment of world PV markets, PV module recycling was mandated in Europe through Directive 2012/19/EU, the Waste Electrical and Electronic Equipment (WEEE) Directive [7]. The Directive regulates the collection, recovery, and recycling targets for waste from electrical and electronic equipment, including PV modules. Since 2012, all European Union (EU) members have implemented the PV regulation into national law, requiring all PV module manufacturers in the EU market to either operate their own take-back and recycling systems or join existing producer compliance schemes.

The WEEE Directive follows the *producer responsibility* principle, making producers or their authorized representatives responsible for recovering WEEE using the best available techniques. It establishes several obligations and recommendations for Member States and electrical and electronic equipment (EEE) producers, including PV manufacturers. Producers can comply with the Directive through individual or collective compliance schemes. Their obligations include:

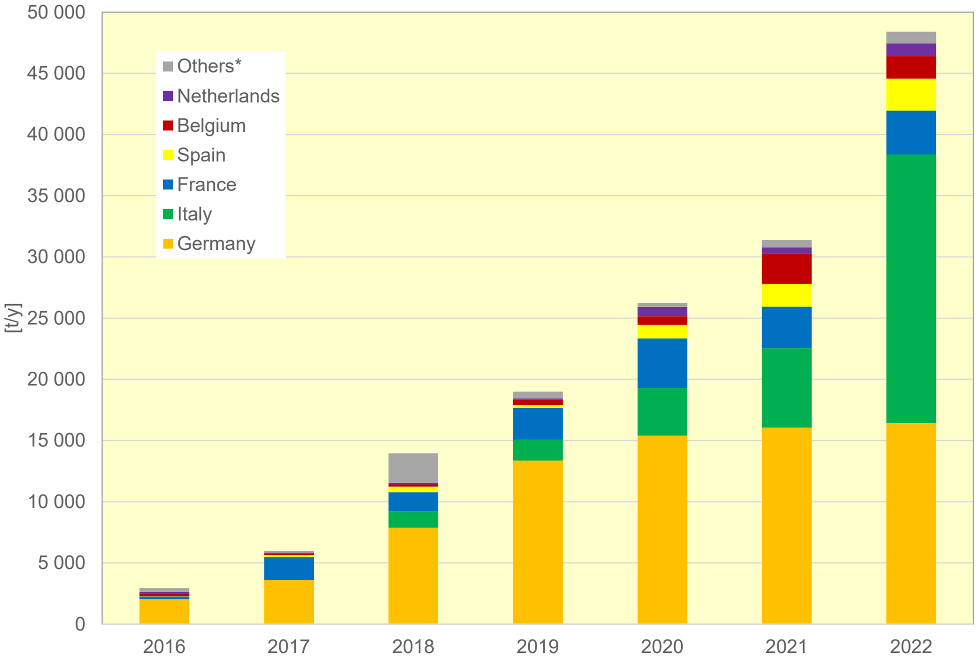
- Comply with the recovery targets defined in the Directive.
- Finance the collection, treatment, recovery and environmentally sound disposal of WEEE from private households.
- Inform users about the need to separate WEEE from other waste, available collection systems, and the potential effects of hazardous substances in EEE. Producers must mark products with a crossed-out wheelie bin to indicate that the equipment requires separate collection.
- Provide free-of-charge information for waste treatment facilities regarding the required preparation for re-use and treatment.
- Report on an annual basis (i) the quantities and categories of EEE placed on the market, (ii) the amount of WEEE collected, prepared for reuse, recycled, and recovered and (iii) separately collected WEEE exported.
- Producers must be registered in the Member State where their products are sold or be registered through their authorized representatives.

According to the WEEE Directive from 2019, the minimum collection rate to be achieved annually is 65% of the average weight of the electrical and electronic equipment placed on the market in the 3 preceding years in the member state concerned or, alternatively, 85% of WEEE generated on the territory of that member state. Also, the minimum recovery rate from collected waste is 85%, and the rate for recycling or preparation for reuse is 80%.

The amendments to the WEEE Directive [8] clarified financial responsibilities for managing PV module waste, addressing concerns over retroactive obligations on producers by ensuring fairness in cost distribution for modules placed on the market before 2012. The changes strengthened monitoring and reporting requirements for PV module waste, streamlined compliance for smaller producers, and introduced a review clause requiring the European Commission to assess the directive’s effectiveness by 2026. These updates aim to improve waste management practices, promote sustainability, and align the directive with EU legal standards.

In parallel with the directive, several European R&D initiatives are driving the improvement of recycling technologies for various PV technology families and recent years, R&D initiatives for realizing PV circularity are being promoted. These initiatives aim to decrease recycling costs, increase the potential revenue streams from the secondary raw materials recovered through the recycling process, and integrate PV recycling into the PV supply chain by securing materials for manufacturing from waste PV components. Also, the European Committee is focusing on the “recyclability index” of PV modules as one of the Ecodesign standards, expected to be enforced into the European market in 2026.

Statistical data of PV module waste under the WEEE Directive are available via Eurostat statistics [9][10]. Fig. 2.1-1 shows trends in PV module waste since 2016. Table 2.1-1 shows some details about year 2022, with 48 395 tonnes of PV module waste collected from 18 countries.




* Austria, Bulgaria, Czech Republic, Denmark, Estonia, Finland, Greece, Malta, Norway, Poland, Portugal, and Slovakia

**Fig. 2.1-1 PV module waste collected under WEEE in Europe (from 2016 to 2018 [9], from 2019 to 2022 [10])**

**Table 2.1-1 PV module waste collected under WEEE in Europe in 2022 [10]**

| [t/y] | Germany | Italy | France | Spain | Belgium | Netherlands | Others* | Total |
|---|---|---|---|---|---|---|---|---|
| a) Waste collected | 16 430 | 21 493 | 3 582 | 2 603 | 1 855 | 1 035 | 947 | 48 395 |
| b) Waste treatment | 16 430 | 21 882 | 5 005 | 2 538 | 1 855 | 1 035 | 811 | 49 556 |
| c) Recovery | 16 017 | 19 354 | 4 395 | 2 284 | 1 289 | 1 035 | 742 | 45 116 |
| d) Recycling and preparing for reuse | 15 195 | 19 340 | 4 210 | 2 279 | 1 267 | 1 025 | 714 | 44 030 |
| e) Recycling | 15 195 | 19 272 | 4 210 | 2 269 | 1 267 | 1 025 | 713 | 43 951 |
| Ratio: (c/b) | 97.5% | 88.4% | 87.8% | 90.0% | 69.5% | 100.0% | 91.5% | 91.0% |
| Ratio: (d/b) | 92.5% | 88.4% | 84.1% | 88.8% | 68.3% | 99.9% | 88.0% | 88.8% |
| Products put on the market | 703 252 | 269 234 | 235 102 | 448 893 | 66 833 | 318 847 | 818 047 | 2 887 209 |

* Austria, Bulgaria, Czech Republic, Denmark, Estonia, Finland, Greece, Malta, Norway, Poland, Portugal, and Slovakia

To date, in Europe, mostly independent private companies have performed the reuse, repair, and refurbishment of PV components without support from the original manufacturers [11]. Because it is still a small-scale and informal sector, limited regulations or standards exist for the testing, certification, and labelling of refurbished PV modules, and little data are available [11]. This creates uncertainty around the regulation of electricity-generating equipment reuse, leading to the recommendation of the Product Environmental Footprint Category Rules (PEFCR) to not consider the reuse of PV systems and assume that PV modules should be disposed of in an inert material landfill [12].

The status of PV module recycling in some European countries is presented in the next sections, regarding relevant regulations and schemes, treatment of EOL PV modules, companies treating EOL PV modules for recycling, and outlook.

### *2.1.1 Germany*

#### (1) Relevant regulations and schemes for EOL management of PV modules

The European WEEE Directive delivers an important legal framework to ensure suitable take-back and recycling of PV modules and has been implemented in German law by ElektroG. The first version of ElektroG was enacted on March 15, 2005, with a major update (ElektroG2) on October 24, 2015, which became obligatory for manufacturers to follow on February 1, 2016. With this update to ElektroG, electrical and electronic equipment manufacturers must take more responsibility throughout the life cycle of their products.

The recovery and recycling rates of WEEE were adopted by ElektroG. For PV modules, the minimum recovery rate is 85%. In this context, the recovery rate includes the preparation for reuse and refurbishment, the recycling of material, and the energy recovery from thermal treatment (e.g., waste incineration). The recycling rate for PV module waste is 80% of mass. These minimum quotas—the 85% recovery rate and the 80% recycling rate of PV mass—are applied as target quotas for Germany.

Since the implementation of the revised WEEE Directive into national law, all manufacturers or authorized representatives that place PV modules on the German market must register the modules with the German WEEE register, Stiftung Elektro-Altgeräte-Register (EAR) [13]. Stiftung EAR, as a joint body of manufacturers, has been assigned sovereign tasks by the Federal Environment Agency (Umweltbundesamt) to ensure the implementation of ElektroG. According to ElektroG, manufacturers of PV modules bear responsibility for the products they place on the market—that is, the manufacturers are responsible for the products' return, logistics, sorting, dismantling, recovery, and recycling. To this end, the manufacturers must provide financial guarantees. Stiftung EAR records the quantities placed on the market and coordinates the provision of waste containers at public locations of the waste management authorities (öffentlich-rechtliche Entsorgungsträger örE) [13].

In Germany, PV modules are classified as business-to-consumer (B2C), dual-use products. Depending on their application—either commercial (business-to-business [B2B]) or private (B2C) use—different regulations apply for the collection and take-back of PV modules. Also, PV modules are classified as Collection Group 6, "photovoltaic modules," and they are assigned to either WEEE Category 4 ("large equipment": any external dimension more than 50 cm) or Category 5 ("small equipment": no external dimension more than 50 cm), depending on their size. The local authorities are responsible for sorting the waste equipment into containers for the respective groups. Small PV modules that are embedded in electronic products, such as calculators, belong to the respective collection groups of the main product.

PV modules from private households can be handed in free of charge at collection points of municipal waste management authorities or points registered by Stiftung EAR. In Germany, however, these are limited to typical quantities that are customary for households, which is defined by the German task force of environmental ministers to ensure the best possible harmonization of waste legislation across the federal states (Bund/Länder-Arbeitsgemeinschaft Abfall [LAGA]) for a maximum of 20 to 50 modules [14]. The collection and further treatment of residential volumes are coordinated by the public legal waste management authorities. The collection of larger quantities is organized by the manufacturers, which can commission haulers to collect the EOL modules directly from the end user and transport them to the appropriate treatment facilities.

#### (2) Amount and treatment EOL PV modules

In Germany, the volume of PV modules placed on the market was 703 253 tonnes in 2022 and 801 921 tonnes in 2023 [15]. According to the EuroStat statistics [9], in 2022, the amount of collected PV modules was 16 430 tonnes, whereas 3 629 tonnes were collected from households, and 12 801 tonnes were collected from other sources. Of the 16 017 tonnes recovered, 15 195 tonnes were recycled.

In Germany, there are two mechanisms for financing the take-back and recycling of PV modules: (1) In the B2C mechanism, PV modules are sold directly to private households or users with similar requirements. (2) In the B2B mechanism, product responsibility is transferred to the end owner of the PV modules for commercial use [3][16].

In the B2C mechanism, there are two levels of financing: Level 1 and Level 2. Level 1 covers collection operations and direct collection and recycling costs. Costs for legacy EOL PV modules, that is, EOL modules from manufacturers that no longer exist, are included here. Level 2 ensures funding for the collection and recycling of future waste. When a manufacturer registers with Stiftung EAR, it assumes the Level 1 costs according to its current market share, and it declares covering the Level 2 costs of its products placed on the market. Manufacturers can operate their own take-back and recycling system or join a cooperative. Among these cooperatives, PV Cycle [17] and take-e-way [18] are the most relevant associations. If a manufacturer leaves the market, other manufacturers must take over its market share.

In the B2B mechanism, manufacturers or authorized representatives must take over the costs for the take-back and recycling of modules that were placed on the market after October 24, 2015. In the case of legacy modules, end users are responsible for the take-back and recycling costs. The B2B mechanism applies to operators of solar parks [3][16].

In recent years, several companies and research projects have developed PV module recycling processes and operated them in pilot demonstration plants. PV module recycling processes are based on mechanical, wet chemical, thermal, and optical mechanisms, or combinations of these. Most pilot recycling plants, however, have not made it to commercial implementation on an industrial scale or have been discontinued after a short time. One main reason has been the comparably low and unstable influx of EOL PV modules, which makes the operation of the recycling plants financially difficult.

### (3) Companies treating EOL PV modules for recycling

Currently, the recycling of Si-based modules uses schemes that are partially adapted from other industries, mainly based on mechanical process schemes from flat glass recycling. The Reiling company group is the most relevant player for the treatment and recycling of silicon (Si)-based PV modules in Germany. Reiling operates 19 recycling sites internationally, with a focus on flat glass and container glass recycling, polyethylene terephthalate plastics, wood, and PV modules. In June 2023, Reiling started operating a recycling plant that exclusively recycles Si-based modules. The recycling plant is located at the competence centre of PV module recycling in Münster. The Münster recycling site is intended to process the majority of the crystalline silicon (c-Si) PV modules [19]. The recycling plant in Münster is operated by continuous processing and is designed for recycling capacities of up to 50 000 t/y to treat increasing EOL PV module volumes in the future.

**PV module recycling facility operated by glass recycling company**

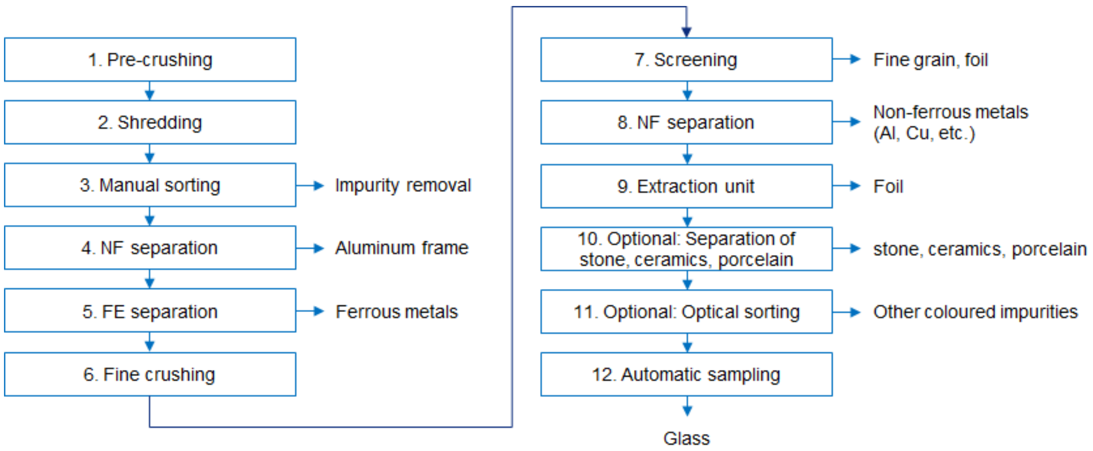
Facility: PV recycling facility owned and operated by Reiling PV-Recycling GmbH & Co. KG

Location: Münster, Germany

Reiling started recycling PV modules around 2010 and can accept all kinds of silicon based PV modules at the glass recycling plants in Osterweddingen, Torgau and Marienfeld, Germany, where are certified in accordance with the ElektroG, but the recycling takes place, with a few exceptions, at the plant in Münster.

The technology used is based on a mechanical treatment originally used for laminated glass from the building and automotive industries. The treatment plants' free capacities were used to process the PV modules in discrete batches. As the EOL PV module stream increased, Reiling performed several R&D projects to improve the mechanical treatment process's yield and efficiency. The results are deployed in the new Münster PV-recycling-plant that started in 2023, with a capacity of 50 000 t/y. In 2024, 11 500 tonnes of PV modules were recycled.

[Treatment process [20]]




After mechanical pre-crushing and shredding steps to extract the aluminum frame, Reiling separates ferrous metals, such as screws, that may be present from the frames. A fine crushing step then makes the glass and foil more accessible for subsequent screening. Reiling then performs a second separation of non-ferrous metals, such as Al and Cu from the interconnectors. They then extract the polymer fraction from the glass. Treatments typically performed for other glass-based products (but optional for PV modules) include separation of stone, ceramics, and porcelain and optical sorting, such as x-ray sortation, to remove coloured impurities. Reiling performs a final quality check.

Reiling has rebuilt and optimised or modernised the plant several times and improved the quality of the glass, increased efficiency and recovered several fractions better. The recovery of silicon and silver is possible. The pilot line for the recovery of silicon was converted in 2025 to recover silicon on an industrial scale. Silver is recovered via the processing industry.


*@Courtesy of Reiling PV-Recycling GmbH & Co. KG*

For non-Si-based thin-film modules, the only existing commercial/industrial-scale recycling plant in Germany is First Solar's recycling plant in Frankfurt Oder, which specializes in recycling cadmium telluride (CdTe) modules. First Solar's established the industry's first global PV recycling program in 2005 [21]. First Solar's Germany recycling plant has a recycling capacity of 10 000 t/y, and it recycles CdTe modules from other European countries too. First Solar's recycling process recovers approximately 95% of a recycled First Solar modules. First Solar's recycling process operates with zero liquid waste discharge and convert most of the incoming PV waste streams into valuable raw materials for other industries, including semiconductor material for use in new solar modules. First Solar's recycling facilities are scalable to accommodate increasing future volumes.

In addition to the currently operating PV module recycling plants, there are further developments and activities that have the potential to extend the available recycling technologies and infrastructure in Germany.

LuxChemtech [22] develops and tests recycling processes for PV by using a combined chemical-physical process. Within the EU-funded research project Photorama [23], LuxChemtech, together with other partners, is developing a pilot line for recycling PV from dismantling and delaminating to metal recovery in an industrial environment. The pilot line includes a three-step process to manage the c-Si-based waste stream and a two-step process to manage the thin-film copper indium gallium selenide (CIGS) waste stream, which allows for recycling valuable materials—silver (Ag), Si (and indium for heterojunction technology), and gallium [24][25].

Further, the companies ImpulsTec [26] and FLAXRES [27][28] are developing alternative processes for breaking up the material composites of PV modules based on physical treatment. The approach of ImpulsTec uses shock wave fragmentation technology (electrohydraulic fragmentation), whereas FLAXRES uses high-intensity light pulse technology. Both technologies show high potential for improving the recycling of various PV technologies because they can be used universally, independent of module type and size. Also, a startup company, Solar Materials, [29] is focusing on recycling technologies of Si-based PV modules using thermomechanical processing, which was founded in the year 2021. Solar Materials is building up a new recycling plant, which will be commissioned around May 2025 and will increase its recycling capacity to more than 10 000 tonnes, or 500 000 PV modules, per year.

### (4) Outlook

According to the IRENA/PVPS Task 12 report on EOL PV modules published in 2016 [3], a projection range of cumulative waste volume in Germany, depending on the scenario of average lifetimes of PV modules, is between 400 000 tonnes and 1 million tonnes for the year 2030 and increases to 4.3 million tonnes in 2050.

On the other hand, based on the actual recorded volume (Eurostat) [9], the official reported collected waste volume in Germany from 2016–2020 totals 42 300 tonnes, which is about twice the estimated volume of the IRENA regular loss scenario (20 000 tonnes) but still considerably less than the estimate for the early loss scenario (200 000 tonnes). Even in the regular loss scenario, however, waste volume will increase twentyfold by 2030, and it will continue to exponentially increase from there.

With regard to PV as part of a sustainable energy system, it is necessary to provide suitable treatment and recycling processes for returned PV module waste streams and to expand the recycling capacities to meet future demand. Because PV modules are made from valuable materials, which differ in their material systems, depending on the PV technology used, suitable recovery and recycling are important to ensure the long-term supply of the required resources and raw materials in the sense of a circular economy. With the increasing complexity of the material systems of future PV technologies and module designs, suitable recycling and recovery of rare materials will become more important.

This makes it important to establish a working take-back and recycling system for PV module waste. The system must provide the necessary recycling capacities and treatment processes at an early stage, and it should be expandable according to expected PV module waste streams.

In view of the current situation of the waste management system and recycling infrastructure in Germany, there is still a high demand for the implementation of industrial-scale PV recycling plants but also for plants that reliably treat the diverse materials from different PV technologies and recover valuable materials to produce new modules or other high-value products. In addition to the technological and infrastructural challenges, it must be ensured that PV module waste is collected via a take-back and recycling system that enables the tracking of waste streams from return and collection to the end of the process. Further, clear processes and responsibilities in the coordination of the recycling system across all treatment stages are of great importance to ensure that modules are collected via the designated collection and recycling channels.

This section, regarding the status of Germany’s PV recycling efforts, is based on the results of two expert workshops [30]. These were held in 2021 and 2022, with approximately 20–25 experts from industry and research along the full treatment chain of EOL PV modules—from production, collection, and take-back coordination to the initial treatment and recycling of recovered materials. The main identified challenges and potential optimization measures are summarized in the following. Participants of the two expert workshops acknowledged that Germany has taken steps to ensure the proper collection and recycling of PV modules. However, there is a clear need for improvement throughout the treatment chain, especially in anticipation of the growing volume of end-of-life module flows. Germany's experience and lessons learned in managing larger volumes of EOL PV modules will be valuable for other countries preparing for similar challenges. The main areas requiring improvement can be summarized as follows [30]:

***Transparency of PV module waste volume***

The volume flows of collected and treated PV module waste reported in official statistics are still less than the expected quantities, so it has been assumed by the workshop attendees that even larger quantities are disposed via alternative routes, bypassing the designated recycling system (e.g., via illegal exports). In addition, material flows after initial treatment (e.g., to secondary material recovery facilities) are nontransparent and hard to trace.

Hence, besides the already existing obligatory reporting of PV module streams according to ElektroG, stakeholders suggest that additional measures are required to enable better tracking of EOL modules throughout the complete treatment chain, such as providing incentives to ensure that PV module waste is returned to official collection points. Further, it should be ensured that private users can return EOL modules at the collection points without additional fees. Currently, quantities are limited to approximately 20 modules. End users could be better informed about their responsibilities regarding how and where PV module waste must be returned.

***Take-back and collection***

Workshop attendees noted that the current collection and take-back system is complex due to the required coordination of PV modules from B2B and B2C use. In terms of take-back logistics, on the one hand, insufficient communication of collection quantities leads to underused transports, and on the other hand, inappropriate presorting leads to frequent redirection of modules that were transported to incorrect initial treatment facilities or recycling plants (e.g., non-Si modules sent to recycling facilities that only treat Si modules). Both aspects lead to high transport costs. Further, involved stakeholders in the collection and further treatment of PV module waste are often not fully aware of their obligations.

It was suggested at the workshops that, to reduce the high share of transport costs of PV module recycling, a collection deadline of 48 hours after reporting the collection quantities could be extended to increase transport utilization. For avoiding extra transport steps related to the redirection of misplaced modules, the following was suggested: appropriate training of the responsible personnel to sort and prepare modules for transport at the public collection points, as well as at the initial treatment facilities. Additionally, labelling of the PV module types at the module manufacturer sites could further ease the sorting. Another measure to reduce transport costs is to reduce distances from collection sites to the initial treatment facilities. In this regard, initial treatment facilities that can treat several or all types of modules could lead to significant improvements.

Workshop attendees suggested that the introduction of a uniform, commercial take-back coordination and collection program of PV module waste from B2B and B2C use could reduce the complexity and provide a clearer framework for the stakeholders involved in EOL management.

***Module recycling***

Workshop attendees noted that German recycling infrastructure and recycling capacities must be rapidly expanded, and recycling processes for all module types are required (not only Si-based and CdTe modules but also CIGS and tandem modules). A main challenge of the current industrial-scale recycling processes is that glass cullet currently fails the requirements to be recycled for high-quality applications and hence is used for lower-quality applications. In terms of Si-based module recycling, not all valuable material fractions (e.g., Si) can be economically recycled with the current process. Recently, a research project demonstrated the technical feasibility of separating materials and producing passivated emitter and rear contact cells from 100% recycled Si from mechanical treatment. The technology for this applied processing, however, is still on a low readiness level.

Workshop attendees suggest a promising approach could be to expand the recycling infrastructure by combining facilities of the established mechanical or mechanical/wet chemical processes with facilities of new process developments using alternative technologies. The main advantages of the established recycling processes (on an industrial scale for Si-based and CdTe modules) are that they are comparably easy to scale and to handle and are independent from PV module dimensions.

Current developments using alternative technologies include interesting approaches to enhance the recycling of valuable materials from different module types. A new recycling process using high-energy light pulses to separate material composites has the advantage of being universally applicable. The compact design also allows for mobile operation; thus, the initial treatment of PV module waste could be operated directly at the location of the disassembly of PV power plants. This could reduce transportation efforts because recovered materials could be forwarded directly to suitable recycling plants. If these processes hold up in practice, they could be a valuable addition to existing procedures.

### 2.1.2 France

#### (1) Relevant regulations and schemes for EOL management of PV modules

In France, the transposition into national law of the directive 2012/19/EU was formalized in 2014 by the Decree n 2014-928 [31] of the French environment Code. The legal requirements are specified within Articles R.543-171-1-R.543-206-4 [32], in which the general provisions of the Article R.543-172 identify a specific category for PV modules, which is listed as category 7.

The producer responsibility organizations (PROs), eco-organizations in France, are responsible for organizing and implementing the extended producer responsibility (EPR). The PROs, as coordinating bodies, attest technical and financial ability to manage the EPR specifications to obtain national certification that accredits their rights to operate as a collective system. The EPR specifications for electrical and electronic equipment were published in the last relative Order in October 2021 [33].

Following legislative evolutions (anti-waste law, February 2020 [34]) and public consultations (2021), the EPR specifications were reframed with additional requirements in October 2021. As the first new requirement, the PRO should develop modulation criteria related to eco-design provisions of electrical and electronic equipment based on reparability, recyclability, hazardous materials, and recycled material content, as related to the anti-waste law. Second, criteria dedicated to PV equipment (Cat. 7) requires PRO to develop a study to identify the critical and valuable raw materials embedded in PV modules to develop related recycling and recovery targets. Both criteria should lead to a proposal from the PRO to the minister for environment. Another important requirement is the provisions relating to reusing and repurposing, including a target of 2% as of 2023.

The collection target is still based on either 65% of the average weight of the products placed in the French market over the last 3 years, or 85% of waste generated while the EPR specifications established new minimum targets in force from 2024 for recovery and recycling, 87% and 82%, respectively.

#### (2) Amount and treatment of EOL PV modules

The nonprofit PRO approved by ministerial decree in France for the treatment of PV waste is Soren [35], which consequently has the monopoly on PV module waste management. Soren manages both collection and recycling by operating private tendering procedures enabling the centralization of PV waste management in France.

The amount of collected PV waste increased drastically from 2015 (366 tonnes), to 2019 (4 905 tonnes), as shown in Fig. 2.1-2. Although the collection from 2020 to 2022 decreased because of the COVID-19 pandemic, the collected waste reached 5 207 tonnes in 2023 in 2023, and 9 477 tonnes in 2024.
The total amount of PV modules treated in 2024 was 7 143 tonnes, from which 86.81% were recycled, 5.07% recovered, and 8.12% disposed of. The average recycling and recovery ratios on the territory are 86.81% and 91.88%, aligning with the legislative criteria.

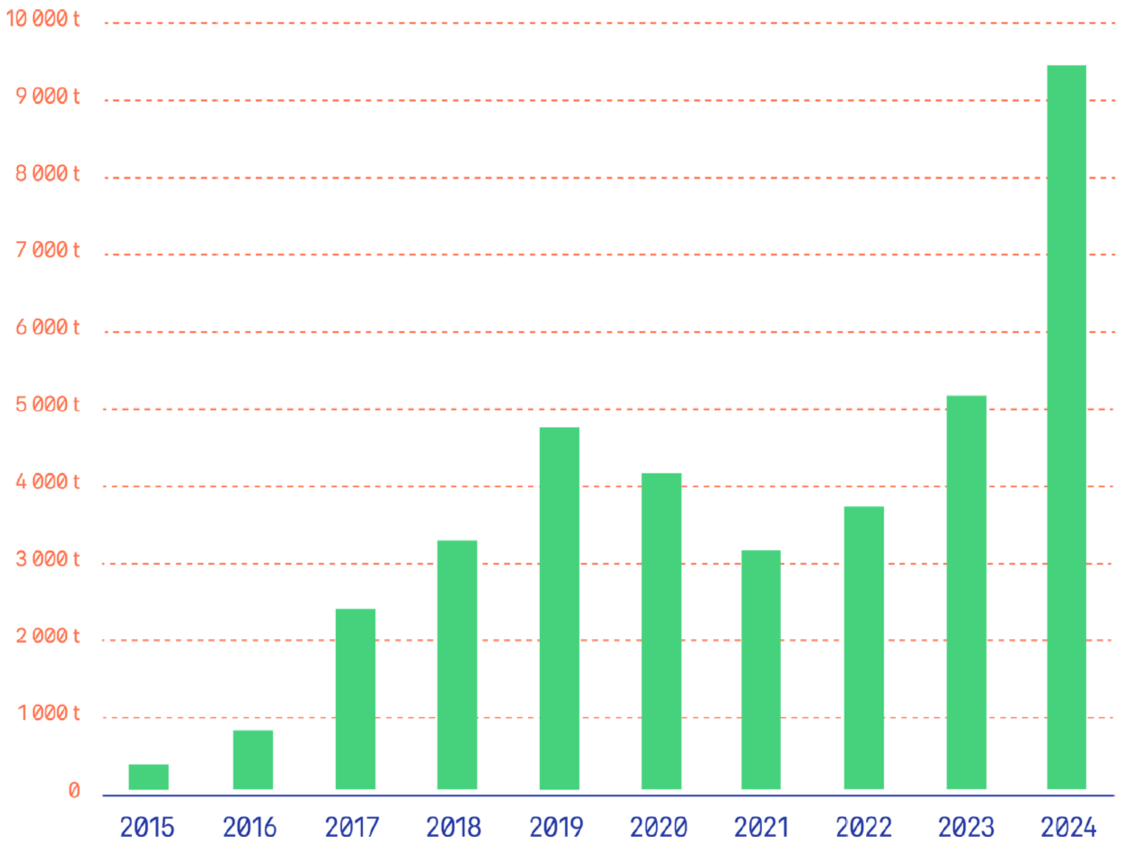



**Fig.2.1-2 Annual volume of PV module waste collected in France [provided by Soren]**

### (3) Companies treating EOL PV modules for recycling

The map in Fig.2.1-3 shows the locations of the nine massification centers in the country that gather the collected PV waste to be redirected to one of three treatment facilities currently mandated: Gallo France in the north and ENVIE 2E Aquitaine and ENVIE 2E Midi Pyrénées, both in southwestern France. PV waste identified as CdTe waste stream is sent to the recycling facility of First Solar in Germany.

**Gallo France** is a recycling operator focusing on ferrous and nonferrous metal recycling being identified as one of the main actors in the field of Western Europe. The treatment center based in Halluin, France, has integrated PV module recycling into their installations since 2021. They are currently recycling PV modules using a grinding/crushing process followed by several sorting processes to separate the components. Aluminium frame and junction boxes are previously removed and recovered. Then, the successive steps allow for the recovery of copper and glass.

**ENVIE2E** Aquitaine in Saint-Loubés is part of the network ENVIE, which operates waste management from collecting and sorting, to treatment and reparation for reuse, for WEEE stream in France. A facility dedicated to PV recycling was designed and built in 2021. The line includes an automated predismantling unit to remove the external components (aluminium frame, junction boxes) and a delamination unit based on the cutting process, using a hot knife. The output fractions—aluminium, junction boxes, glass sheets, laminate multi-layer (PV cells/ backsheet)—are sent to other facilities for further treatments. The ENVIE2E Aquitaine has also set up a line dedicated to module inspection and performance diagnosis for reuse, including several steps of testing (electroluminescence, power, insulation).

**ENVIE 2E Midi Pyrénées** in Portet-sur-Garonne is also part of the ENVIE federation. The PV modules are predismantled (frame, junction box) before being redirected to other recycling facilities for further treatment.

PV waste collected in the north may be redirected to Comet and Recma in Belgium, while ROSI Solar in Rhône Alpes treats output fractions from the facilities of ENVIE2E Aquitaine.

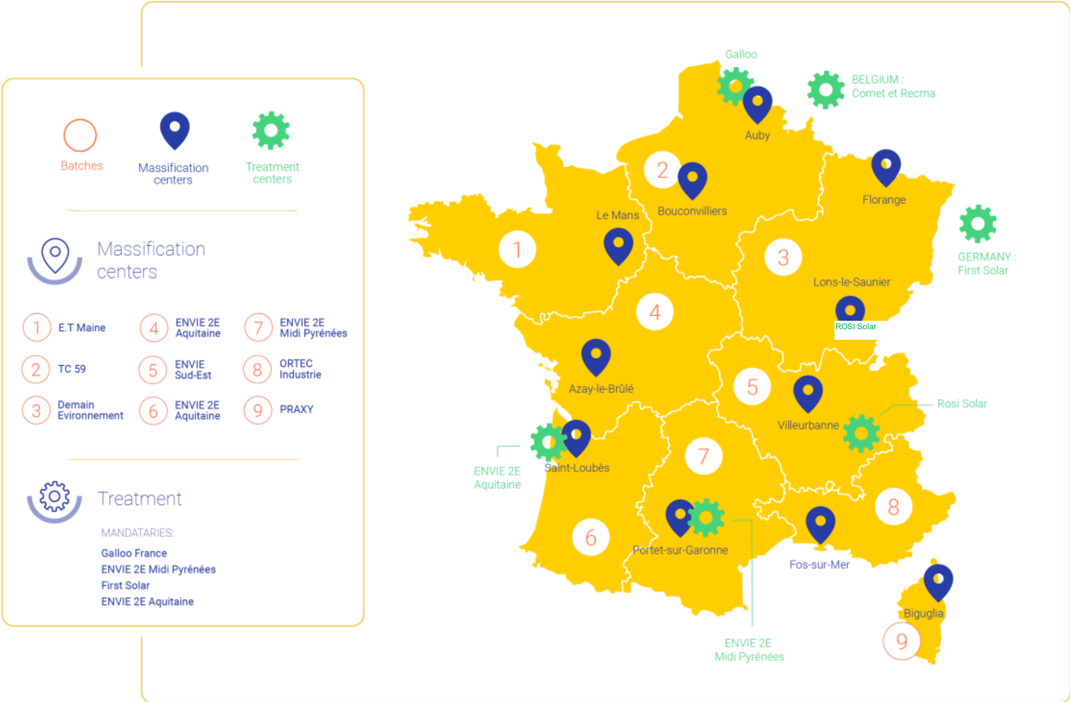



**Fig. 2.1-3 Location of the massification and treatment centers in mainland France [36]**

**PV module recycling facility using a combination of pyrolysis and chemical treatment**

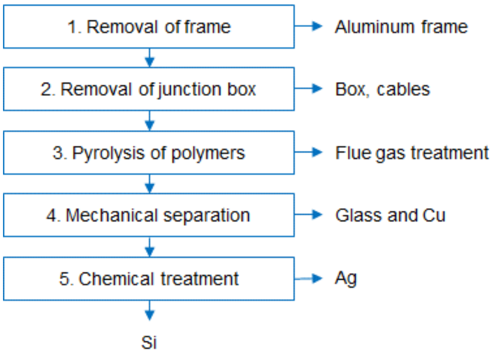
Facility: PV recycling facility owned and operated by ROSI Solar

Location: Auvergne-Rhône-Alpes, France

ROSI is a French startup company founded in 2017 that focuses on recovering raw materials from the solar industry including silicon, silver, copper, glass, and aluminium. The company states on its homepage (www.rosi-solar.com): "ROSI is a company offering innovative solutions for recycling and revalorization of raw materials in the photovoltaic industry. Its technologies allow to recover high purity silicon and other metals currently lost during the production of photovoltaic cells and at the end-of-life of solar panels." Its two main activities are silicon kerf recovery and c-Si PV module recycling.

At present, ROSI partners with Soren and collaborates with ENVIE2E Aquitaine to provide high-value recycling of end-of-life PV modules in France. In spring 2023, ROSI put a PV recycling plant in operation close to Grenoble, France. The plant uses a batch pyrolysis process and a proprietary silicon and silver recovery process. Pretreatment at ENVIE2E Aquitaine to take off glass plates is not a prerequisite of ROSI's process. ROSI can fully treat all kinds of EOL c-Si PV modules in all conditions, including broken, and partially separated modules.

[Treatment process]




After frame, junction box, and cable removal, ROSI performs a thermal treatment step to pyrolyze the polymers. The flue gas is treated with an afterburner to make sure the combustible gases resulting from pyrolysis undergo complete combustion (such as transforming carbon monoxide to carbon dioxide). The gases after the afterburner are then washed by a wet scrubber before being discharged into the atmosphere. The scrubber captures pollutants by absorption, including acid gases of the HF type (because of the presence of fluorine in the backsheet). The pyrolysis of the polymers gives easy access to high-quality and high-yield glass, metals, and solar cell fragments. High-quality clean glass cullet is obtained after pyrolysis. The copper interconnectors and solar cell fragments can be separated using state-of-the-art mechanical separation technology, such as screening or sortation by density. ROSI developed a process to detach the silver fingers and pads from the resulted cell fragments using a proprietary mild chemical etching process that was not disclosed. The silicon obtained is 99.9% to 99.999% pure (3-5N).

***@Courtesy of ROSI Solar***

### (4) Outlook

The projections of PV module waste volume expected in France are illustrated in Fig. 2.1-4, assessed on calculations based on Regulation 2017/699, UNU methodology using Weibull distribution and field data. This shows that more than 43 000 tonnes are expected by 2030 and 118 000 tonnes by 2040.

Soren will launch a new tender process in 2025 to select the recycling operators for the next 5 years.

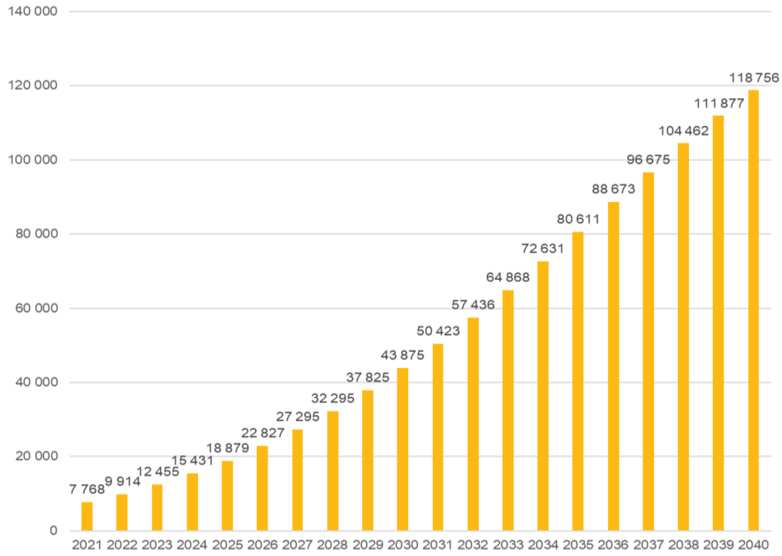



**Fig. 2.1-4 Projection of PV module waste collection targeted in France (2021–2040) [provided by Soren]**

To meet the legal requirements from the EPR specifications, Soren has engaged further in driving national progress on high-value recycling and eco-design development. Soren carried out the study on critical and valuable materials, including the proposal for the recovery and recycling target submitted to the minister of the environment in 2024. Soren has also elaborated the framework and guidelines to support PV suppliers to establish and implement the prevention and eco-design plan legally required in Article 541-10-12 of the environment Code and the 2021 EPR specifications. Eco-modulation based on design requirement (nonrenewable primary resources, recycled material content, recyclability) will be submitted to the minister of the environment. After approval, the eco-modulation will be used to regulate the contribution/EPR fees, depending on the environmental performance of the products.

### *2.1.3 Italy*

**(1) Relevant regulations and schemes for EOL management of PV modules**

The directive 2012/19/EU [7] was implemented in the Italian national regulatory system with the Legislative Decree No. 49/2014 [37]. 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 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 by the criteria listed in the Legislative Decree No. 152/2006 – Environmental Code [38].

Legislative Decree 49/2014 applied to the electrical and electronic equipment categories 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 applies 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 of 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, "producers" also include electrical and electronic equipment importers, even if the product's manufacturer is outside 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) Amount and treatment of EOL PV modules**

According to Eurostat statistics [9], 1 350 tonnes of PV modules were collected in 2018. Modules collected from households totalled only 11 tonnes, whereas modules collected from other sources totalled 1 339 tonnes. In 2022, the amount of collected PV modules in Italy was 21 943 tonnes, consisting of 628 tonnes from households and 21 315 tonnes from other sources, and it was the largest amount in the EU countries.

In October 2023, Italy's energy services manager, GSE (Gestore dei Servizi Energetici SpA), issued new 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 [39] and taking into account the amendments introduced by Law No. 41 of 21 April 2023 [40] and Law No. 87 of 3 July 2023 [41]. The domestic PV modules that reach EOL must be either:

- Sent to a national collection center (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).

For 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 make up 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 out the Annex 8.1 form 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 modules, 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 plant owner 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 Formulario di Identificazione Rifiuti (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 decommissioned (making them eligible for reuse or resale). To ensure the financing of collection, transport, appropriate treatment, environmentally 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 for the disposal of PV modules at the end of the module's service life using the amounts retained. The amount retained by GSE, aimed at ensuring full coverage of the costs of management and environmentally compatible disposal of photovoltaic modules at the end of their life, represents a guarantee for the future implementation of operations relating to:

1. The withdrawal of the PV modules from the installation site, including the dismantling and packaging of the modules
2. The logistics for transferring the PV WEEE from the installation site to the treatment facility (also considering any additional costs resulting from storage)
3. The appropriate treatment of WEEE
4. The recovery and “environmentally compatible” disposal of waste from PV modules.

The share withheld (from the incentives) by the GSE is equal to:

- A value of 10 EUR/module for domestic PV modules (at the 15$^{th}$ incentive year)
- A value of 10 EUR/module for professional PV modules (fee spread over the last 10 years of incentive).

Alternatively, the owner of a PV system can provide a financial guarantee for the collection, transport, adequate treatment, recovery, and disposal of PV modules by joining a collective system shown in Table 2.1-2 and paying a fee of 10 EUR/PV module.

**Table 2.1-2 List of the Italian registered collection systems for the end-of-life management of PV modules [42]**

| Registration Number | Company | District |
|---|---|---|
| IT08021000016 | APIRAEE | TORINO |
| IT10071000026 | COBAT RAEE | ROMA |
| IT08021000023 | CONSORZIO ECOEM | SALERNO |
| IT07111000001 | CONSORZIO ECOLAMP | MILANO |
| IT07121000010 | CONSORZIO ECOPED | MILANO |
| IT22041000041 | CONSORZIO E-CYCLE | PESCARA |
| IT07121000007 | CONSORZIO ERP ITALIA | MILANO |
| IT08011000012 | CONSORZIO RLG | TORINO |
| IT07121000004 | ECOLIGHT | MILANO |
| IT19071000038 | ECO-PV | MILANO |
| IT20071000039 | ERION PROFESSIONAL | MILANO |
| IT20101000040 | ERION WEEE | MILANO |
| IT11031000027 | ESA GESTIONE R.A.E.E. CONSORZIO | FIRENZE |
| IT13121000032 | LA MIA ENERGIA SOCIETA' CONSORTILE A RESPONSABILITA' LIMITATA | ISERNIA |
| IT14011000033 | PV CYCLE ITALIA CONSORZIO | MILANO |
| IT09111000024 | SISTEMA NAZIONALE BATTERIE PILE E ALTRO | MILANO |
| IT14121000037 | WEEE-SAFE PROFESSIONAL | MILANO |

### (3) Companies treating EOL PV modules for recycling

In Italy, there are no recycling plants exclusively dedicated to PV modules because the volume of EOL PV modules is insufficient to create an ad hoc market. However, preparing for coming decades, a couple of companies, such as 9-tech [43] and EcoWeTech [44] have started up a pilot plant and demonstration.

### (4) Outlook

At present, the amount of PV module waste in Italy is low and not enough to create an ad hoc market; nevertheless, a gradual increase in waste volumes is expected in the short-medium term following the decommissioning of the first PV plants installed (see Fig. 2.1-5). PV module waste projections are greatly dependent on the past trend of PV annual installation and the predictions for future installations. Regarding this last point, the current Italian National Energy and Climate Plan (issued in June 2024) sets a target of around 79 GW of installed PV capacity by 2030.

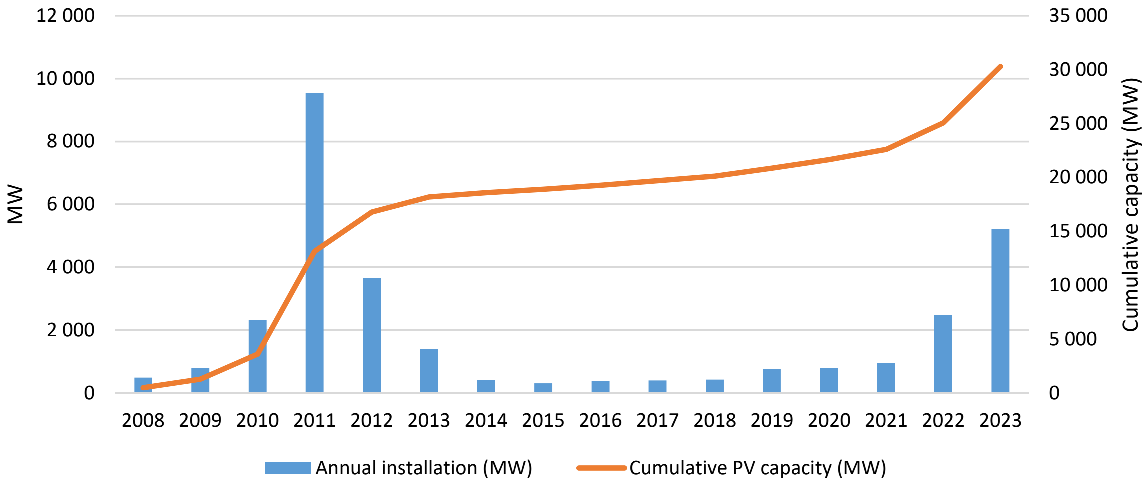



**Fig. 2.1-5 Trends in PV installation in Italy [45]**

According to the IRENA/IEA PVPS Task 12 report on EOL PV modules published in 2016 [3], 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 tonnes for the year 2030 and is expected to increase to 2.2 million tonnes in 2050.

### *2.1.4 Spain*

#### (1) Relevant regulations and schemes for EOL management of PV modules

In Spain, the WEEE Directive 2012/19/EU was transposed into the Royal Decree 110/2015 of 20 February 2015 [46]. This Royal decree repeals *inter alia* the former royal decree on electrical and electronic waste, and 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. The registration can be done individually or through a PRO. If the system is collective, each producer contributes a quota to the systems based on the number of products they put in the market per year. If it is individual, the producer assumes all the EOL costs. Currently, there are 12 authorized PROs in agreement with the Royal Decree 110/2015 obligations: AMBILAMP, ECOASIMELEC, ECOFIMÁTICA, ECOLEC, ECOLUM, ECO-RAEE'S, ECOTIC, ERP, REINICIA, SUNREUSE, ECOECHE, and FUNDACIÓN ECOTIC CLIMA [47]. 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 toward the administrations and consumers.

Royal Decree 110/2015 includes in the scope PV modules (with a dimension larger than 50 cm) and as per amendments of Royal Decree 208/2022, PV modules have a dedicated category for them—namely, Category 7. Within this category, specific subcategories are defined, distinguishing between 7.1-Silicon non-hazardous PV modules; 7.2-Other non-hazardous PV modules; and 7.3-Hazardous PV modules.

During the first quarter of each year, the Spanish Ministry for the Ecological Transition and the Demographic Challenge (MITERD) releases the WEEE collection targets that collective systems must achieve for the current year. The targets for individual systems are directly communicated to each producer. These targets are determined based on the amount of products placed in the market over the preceding 3 years (65% of the average mass of electrical and electronic equipment placed on the market (POM) in the 3 previous years; or 85% of WEEE produced in the Member State).

In January 2023, the Waste Coordination Commission specified that the treatment of photovoltaic modules should not be limited exclusively to thermal treatments or equivalent techniques but may also contemplate other typologies, such as mechanical or chemical treatments [48]. Later, in September 2023, the MITERD published a technical note listing the general requirement common to all facilities that perform specific treatment of WEEE, the mass balance and specific procedures for the treatment of WEEE with a section for Si PV modules and another for CdTe PV modules [49].

#### (2) Treatment and amount of EOL PV modules

The amount of PV module waste collected yearly is still small in Spain. Table 2.1-3 shows the amount of electrical and electronic equipment put on the market in Category 7, PV modules, and Table 2.1-4 shows the WEEE collected in this category.

**Table 2.1-3 WEEE Category 7 (Category 4.b up to 2018): PV modules placed on the market in Spain [50]**

| Year | Put on the market (tonnes) |
|---|---:|
| 2017 | 1.53 |
| 2018 | 21.85 |
| 2019 | 83.26 |
| 2020 | 221.99 |
| 2021 | 169 438.28 |
| 2022 | 448 893.13 |
| 2023 | 629 213.58 |

**Table 2.1-4 WEEE Category 7: PV modules (4.b up to 2018) collected [51]**

| Year | Total collected (tonnes) | Treated (tonnes) | Recovery (tonnes) | Preparing for reuse and recycling (tonnes) |
|---|---|---|---|---|
| 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 |
| 2020 | 1 102.91 | 1 067.43 | 917.6 | 906.08 |
| 2021 | 1 865.87 | 2 359.05 | 2 079.38 | 2 079.38 |
| 2022 | 2 603.33 | 2 537.95 | 2 284.19 | 2 279.03 |

According to the last publication of the MITERD [52], out of the 12 authorized PROs, only 9 collective systems that had targets for PV module waste collection in 2024 are as shown in Table 2.1-5.

**Table 2.1-5 Collective and individual systems target for PV module waste in 2024 [52]**

| Collective Systems | Minimum Professional Objective (tonnes) |
|---|---|
| ASOCIACIÓN AMBILAMP | 1 191.11 |
| ASOCIACIÓN REINICIA | 654.73 |
| ECOASIMELEC | 203 710.88 |
| ECO-RAEE'S | 35.16 |
| ECOTIC | 6 325.21 |
| EUROPEAN RECYCLING PLATFORM RAEE, S.L. | 10 738.64 |
| FUNDACIÓN ECOLEC | 30 742.88 |
| SUNREUSE ASSOCIATION | 2 562.03 |
| INDIVIDUAL SYSTEMS | 14 340.78 |
| TOTAL | 270 301.41 |

Despite those collection targets, it is estimated that approximately 22 000 tonnes of PV module waste were processed in 2023. As the industry matures and early installations reach their end-of-life, waste volumes are projected to rise sharply, reaching around 34 000 tonnes by 2030 and escalating to an estimated 150 000 tonnes by 2050 (see [4]).

### (3) Companies treating EOL PV modules for recycling

There are several recycling facilities authorized for the treatment of PV modules, some of them authorized recently as listed below:

**Solar Recycling (Valencia).** Web page: https://solarrecycling.es/reciclaje/. The steps they offer for the treatment of PV modules are:

1. Removal of junction box (separation of all interior elements)
2. Dismembering aluminium frames
3. Glass module separation
4. Separation of silicon wafer and plastic.

Their authorization is for 510 t/y.

**Reciclajes Pozo Cañada SL (Pozocañada, Castilla la Mancha):** They began operation in 2022. They do a mechanical process with the separation first of the electrical connection, frame and glass, then the plastic, Si, and other fraction are separated with a valorisation rate of 95%. Their annual capacity is 4 000 t/y. They treat glass-plastic backsheet and glass-glass modules.

**FCC ÁMBITO, S.A (Zaragoza, Aragón):** https://www.fccambito.com/-/noticias/inauguracion-planta-cadrete. They do mechanical treatment and announced 95% valorisation in the test. They have an agreement with Iberdrola to promote PV recycling and perform research in material recuperation within the PV4INK project, funded by MCIN/AEI/10.13039/501100011033 and by European Union NextGenerationEU/PRTR, 2022-2025. Their annual capacity is 3 840 t/y. They are authorized only to treat Si PV cells.

**La Hormiga Verde, (Villafranca de los Barros, Extremadura):** They do a mechanical process with the separation first of the electrical connection, frame and glass, then the plastic, Si, and other fraction are separated with a claimed valorisation rate of 98%. Their annual capacity is 800 t/y. They treat glass-plastic backsheet and glass-glass modules. They are expecting to increase substantially their capacity by means of a current separator equipment acquired in 2025.

**ROSI (Teruel, Aragón):** They plan to begin operations in 2025. Currently, the facility only holds authorization for storage, with further processing capabilities anticipated upon full operational launch. The projected annual capacity is 10 000 t/y. Once operational, the plant will likely focus on advanced recycling processes aimed at optimizing material recovery rates.

**Medenasa (Ateca, Zaragoza):** Operated by the WIREC Group, Medenasa acquired the Ateca plant and began operations with a process line similar to that of Reciclajes Pozo Cañada SL. The facility employs a mechanical process equipment to separate electrical connections, frames, glass, plastic, silicon, and other fractions. The valorisation rate is expected to align with industry standards. Their annual capacity is 2 000 t/y, and they are authorized to treat silicon-based PV modules.

**CERFO:** Authorization for a plant in Albalate del Arzobispo (Teruel) with a treatment capacity of 1 000 t/y, though they are doing the administrative procedure for an increase in the capacity up to 9 000 t/y. Their plan is to begin the operation in 2026.

### (4) Outlook

The amount of PV waste in Spain is currently small, but it will increase in the short to medium term when the first PV plants installed reach EOL and in the long term due to 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. 2.1-6 presents the cumulative PV capacity from 2007 to 2023. 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 2019–2023 compared with the previous years. This change is in line with the new actions to achieve climate neutrality.

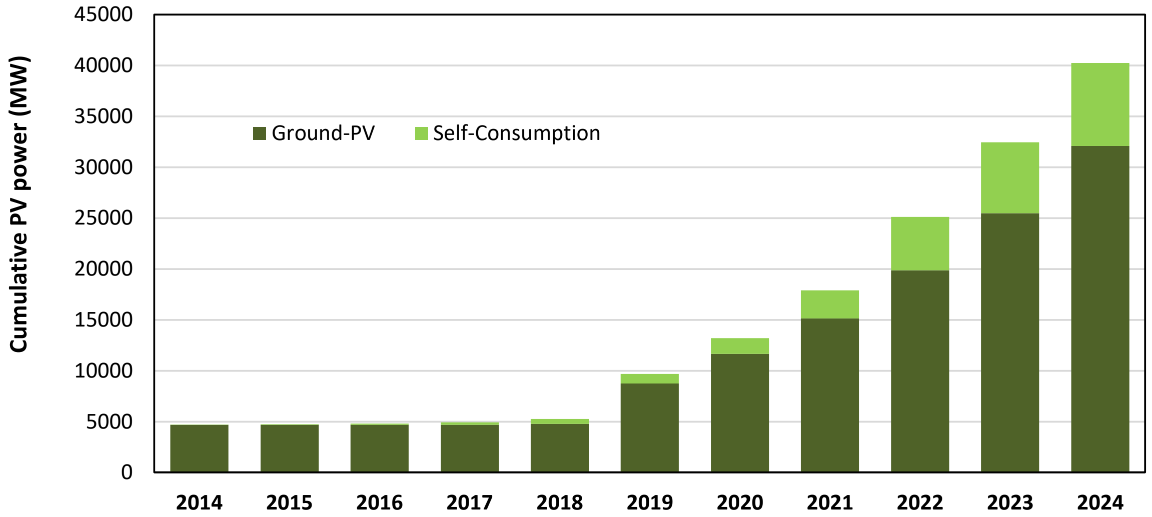



**Fig. 2.1-6 Cumulative PV capacity in Spain during 2007–2023 [53] (2023 data provided by UNEF)**

In March 2021, the final version of Spain's integrated National Energy and Climate Plan (NECP) 2021–2030 [54] was published. This plan foresees an increase in renewable energy capacity, with a target scenario of 39 GW of installed PV capacity by 2030. The NECP was recently reviewed in 2023, updating the targets for renewable energy penetration with an objective of 76 387 GW by 2030 [55]. This review of the NECP was supported by the European commission in January 2024.

Some scientific studies have forecasted PV waste in Spain based on different projections [56][57][58]. In these papers, several degradation scenarios and PV projections are used to calculate the PV waste in 2030 and 2050, together with the annual evolution of PV waste, both cumulative and annually generated. Although the first two references only do the calculations for Spain, the third one also incorporates other countries. This last paper is an update of the former calculations. For Spain, the study bases its 2030 forecast on the original NECP target of 39 GW. Nevertheless, the study also presents a sensitivity analysis, in which several upward and downward considerations are assumed. A more recent study updates the PV waste calculations in the 27 EU countries considering the reviewed NECPs, what causes a substantial increase in cumulative PV waste by 2050 [59].

### *2.1.5 Belgium*

#### (1) Relevant regulations and schemes for EOL management of PV modules

The EOL management of PV modules in the EU member states has been regulated by the WEEE Directive since 2012 [7], which was amended in 2023 [8]. The WEEE Directive foresees that 85% of modules should be recovered and 80% prepared for reuse and recycled. In Belgium, some aspects of the Directive were transposed into national law through the Royal Decree of 12 October 2004 and the Royal Decree of March 17, 2013.

In Belgium, legal compliance with waste management requirements, including the collection and treatment of WEEE is complex since regional legislation for Flanders [60], Wallonia [61] and Brussels [62] apply. The WEEE Directive is transposed into regional law in each of these regions through distinct legislation, with regional authorities responsible for its implementation:

- For the Brussels Capital Region: the Ordinance on waste materials of 6 June 2012 [63] and the Order of the Brussels Capital Regional Government of December 2016 [64]. Brussels Environment is the authority for waste management.
- For the Flemish Region: the Material Decree of 23 December 2011 [62] and the Flemish Regulation on the Management of Material Cycles (VLAREMA) of 17 February 2012 [65]. The Public Waste Agency of Flanders (OVAM) is the authority for waste management.
- For the Wallonia region: the decrees of March 10$^{th}$, 2005 [66], and the decree of September 23$^{rd}$ 2010 [67]. The Public Service of Wallonia (SPW) is the authority for waste management.

Organizations like Recupel and PV Cycle work together within the framework of extended producer responsibility (EPR) to manage waste and recycling for various types of electrical and electronic equipment and PV modules. In Belgium, PV Cycle [68] and Recupel [69] are compliance schemes, i.e., organizations that support producers in meeting their obligations defined under the WEEE Directive. Both are members of ROUND [70], the Belgian alliance of extended producer responsibility organizations. Founded in 2024, ROUND brings together several organizations responsible for managing various waste and material streams.

Recupel operates in Belgium, managing the collection, recycling, and disposal of general electrical and electronic equipment (EEE) waste, including household appliances and consumer electronics, by offering a collective solution for producers to fulfil their legal requirements. PV Cycle focuses on the PV industry across Europe, providing a specialized compliance scheme for the recycling and proper disposal of end-of-life of PV modules. Both schemes simplify the process for producers by handling the logistical, financial, and regulatory aspects of waste management, ensuring compliance with environmental regulations while promoting sustainable recycling practices. The key differences from Recupel and PV Cycle are summarized in Table 2.1-6.

**Table 2.1-6 Key differences between institutions responsible for photovoltaic (PV) modules in Belgium**

| Aspect | PV CYCLE | Recupel |
|---|---|---|
| Activities | Focuses on PV module producers | Covers all producers of EEE in Belgium, including PV modules |
| Collection points | Collection points across Europe, including Belgium | Collection points for all types of WEEE, including PV modules, in Belgium |
| Geographic Scope | European | Belgium (Flemish and Walloon regions) |
| Main Services | Collection and recycling of PV modules | Collection and recycling of all electronic waste |
| Revenue | Fees paid by PV module manufacturers and importers to cover collecting, recycling, and disposing of end-of-life PV module costs | Revenue through fees paid EEE producers based on the amount and type of products they place on the Belgian market. |

Since July 1, 2023, PV CYCLE has established a new environmental contribution rate structure for producers following eco-modulation principles: hard-to-recycle modules pay a higher contribution than easy-to-recycle modules. This ensures better alignment with the actual costs of collection and processing. For the most common modules, silicon with aluminium frames, the environmental contribution decreased from 2 EUR per module to 1.5 EUR per module. The full tariff structure can be found on the PV CYCLE Belgium [71].

Besides, the producers' responsibility, a specific recycling fee for consumers also exists. In the Flanders region, consumers installing new PV modules must pay a one-time recycling fee [8]. The fee is directed to a fund that aims to ensure the free collection and recycling of discarded PV modules. Since July 2017, the contribution amount is 2 EUR per module (excluding VAT) [72].

### (2) Treatment and amount of EOL PV modules

Similar to the number of available PV modules in the Belgium market and the share of PV energy generation in the country, PV module waste collection and treatment in Belgium has also increased steadily in recent years (Fig. 2.1-7). Currently, the main data source for the evaluation of total PV modules and statistics on waste in Belgium is Eurostat [9][10], which includes data for (WEEE) according to several waste management operations.

From 2016 to 2022, about 6 000 tonnes of PV module waste was collected, mostly from households. About 99% of the collected PV module waste underwent treatment in an EU member state. In 2022, 1 855 tonnes of PV module waste were collected and treated. About 70% of the collected PV module waste was recycled, and the remaining part underwent other final disposal strategies, including energy recovery. According to PV Cycle, 95% of the PV modules collected are classic c-Si modules. The remainder are CIS or CIGS modules (containing copper, indium, gallium, and selenium) and CdTe modules (containing cadmium and tellurium) [73][74].

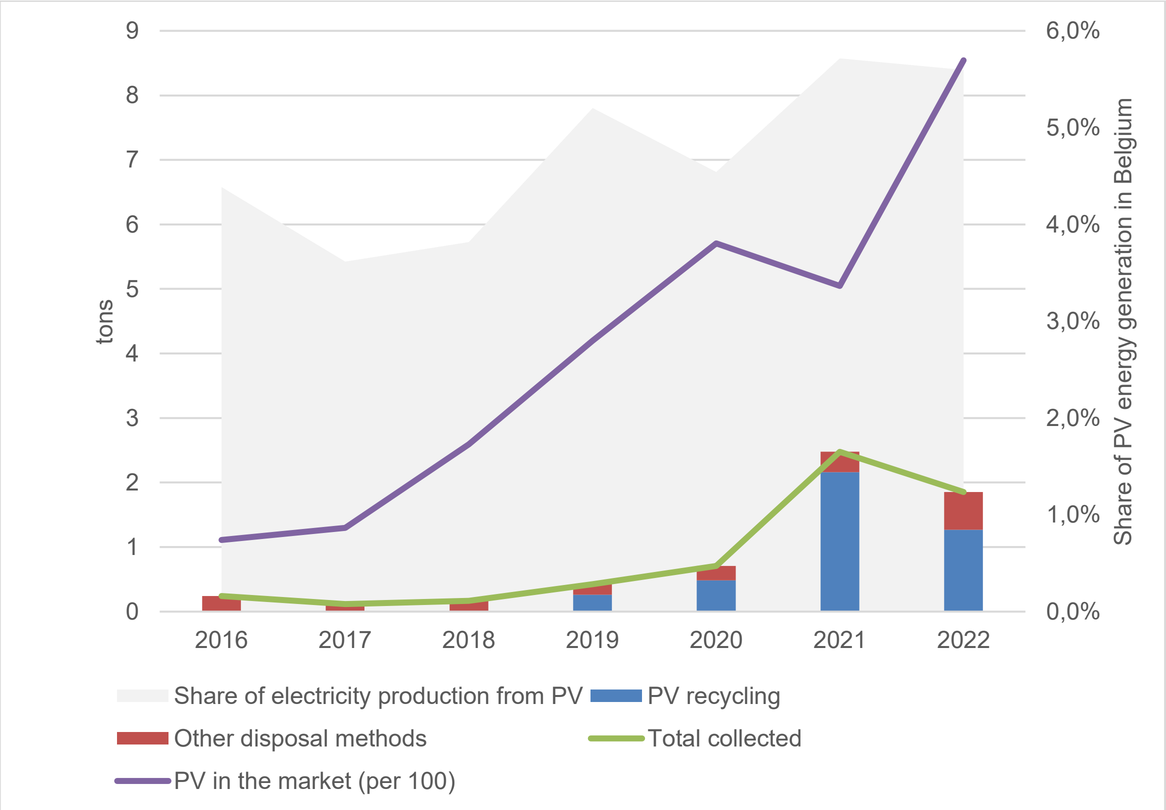



**Fig. 2.1-7 Photovoltaic modules by waste management operations for Belgium Source [9][10][75]**

### (3) Companies treating EOL PV modules for recycling

Table 2.1-7 presents a non-exhaustive compilation of the companies involved in the collection and recycling of PV modules in Belgium. In 2023, 658 tonnes of PV modules were recycled by PV Cycle, with the distribution per region equivalent to 86% for Flanders, 13% from Wallonia and 1% from Brussels [76].

There are two ways to dispose of PV modules in Belgium. For small quantities (up to 40 modules), PV CYCLE Belgium offers a network of collection points spread throughout Belgium (Fig. 2.1-8). This network grew to a total of 88 collection points in 2023. These points are mainly companies that sell PV modules themselves and make space available for the reception and temporary storage of discarded PV modules. For larger quantities, PV CYCLE Belgium collects the modules free of charge at the location where they are released. In 2023, 31% of discarded PV modules were collected through the network of collection points [73].

**Table 2.1-7 Key players in the photovoltaic market in Belgium**

| Name | Location | Website | Observation |
|---|---|---|---|
| Comet Group | Rivage de Boubier 53<br>6200 Châtelet | https://www.cometgroup.be/ | Already operating with mechanical recycling lines. |
| Maltha | Kerkstraat 26, 3920 Lommel | https://www.maltha-glassrecycling.com/nl-nl/ | Glass recycling plant. |
| Out of Use | Lochtemanweg 40<br>B-3580 Beringen | https://outofuse.be/en | Specialized in testing and preparation for the reuse/refurbishment of diverse WEEE. |
| PV CYCLE | Brand Whitlocklaan 114, 1200 Sint-Lambrechts-Woluwe | https://pvcycle.be/study-of-re-used-pv-modules/ | Management body for PV modules established under the Environmental Policy Agreement on Solar Modules. |
| Recma | Rue du Téris 45<br>4100 Seraing | https://www.recma.be/ | Collection of end-of-life PV modules. |

**Fig. 2.1-8 Available PV cycle collection points for PV modules.[73]**

### (4) Outlook

In 2020, the production of renewable energy in Belgium achieved 376 GWh, of which 129 GWh were produced via photovoltaic systems [77]. In 2023, in Belgium, the current installed capacity for PV systems was about 10 GWp, an increase of 1.8 GW from 2022, and the total energy production reached 11% of the total electricity consumption [78].

The geospatial potential for rooftop PV in Belgium is estimated at 118 GWp [79], showing still a potential for growth in the country's PV installations. In the Flemish region, from June 2025, PV modules will be mandatory on buildings with an energy consumption higher than 1 GW/year [80][81].

Additionally, the report "Scenarios for a Climate Neutral Belgium by 2050" [82] demonstrates that PV energy will be indispensable across all pathways to achieving climate neutrality in Belgium. Despite differences in their ambition, all scenarios agree on the need of scaling PV capacity significantly to achieve the climate goals [83].

For 2030, the Belgian contribution to the European target amounts to a renewable energy share of 21.7% in 2030. The Belgium National Climate Action Plan [84] combines different targets for solar energy in 2030:

- In the Flemish region, it is expected an increase PV installed capacity to 8.9 GW.
- In Wallonia: a goal of producing 5.1 GWh of PV electricity.
- The federal government aims to accelerate investments to explore the 1 GWp potential of floating PV energy.
- The Brussels government did not state an explicit target regarding PV.

In addition to these goals, the Belgian federal government launched a package to estimate the energy transition [85] from 2022 onwards. Measures within this package affecting PV systems include:

- Tax reduction on PV modules, solar thermal collectors and heat pumps.
- Funding to deploy PV on national railway stations (in connection with EV smart charging) and on federal buildings.
- Support the deployment of large-scale floating PV systems.
- Reduced time needed to obtain permits and licences for onshore PV and wind generation projects.

The expected increase in solar energy installations in Belgium suggests that the country may face challenges related to the growing volume of PV module waste in the coming decades. As PV modules typically have a lifespan of 20-30 years, Belgium is likely to experience a significant rise in PV module waste as more installations reach their end-of-life. Managing this waste will require investment in recycling technologies to handle obsolete modules and recover valuable materials like silicon and silver. The country faces global challenges associated with managing the end-of-life of PV modules, including:

- Complex recycling processes due to the variety of materials used in modules, such as silicon, glass, and metals, which complicate efficient recycling.
- The lack of standardization in PV module designs.
- Raising consumer awareness about proper disposal and ensuring active participation in recycling schemes like PV Cycle.
- The high cost of end-of-life management and recycling processes.
- Data quality and availability issues, as reliable data on the quantity, types, and conditions of PV modules in use is often lacking, making it difficult to track waste volumes and plan effective recycling and recovery strategies.

On a national level, Belgium faces additional challenges, such as the need for improved collection infrastructure, especially in rural areas, to facilitate the effective disposal and recycling of old modules. Without sufficient collection points and a well-established infrastructure to manage the growing volume of PV module waste, handling this waste stream becomes increasingly difficult.

Another key challenge is the fragmented regulatory framework in Belgium. While the WEEE Directive provides general regulations for the recycling and disposal of PV modules, each region (Flanders, Wallonia, and Brussels) can implement its own variations on how these regulations are applied. This creates inconsistencies in compliance, collection systems, and different fees for consumers and producers across regions. The lack of harmonization can lead to confusion among installers, producers, and consumers about their specific responsibilities and obligations. These regulatory challenges may slow the development of a cohesive and efficient national framework for managing PV module waste.

Regulatory pressures, particularly from the WEEE Directive, will play a significant role in driving the growth of PV module waste management in Belgium. As compliance with the directive mandates higher recycling and recovery rates, Belgium will be incentivized to develop a more robust framework for managing PV module waste. This will ensure that as PV installations continue to grow, the modules are efficiently decommissioned and recycled. The evolving regulatory landscape will also drive investment in recycling technologies, the development of better collection infrastructure, and initiatives to increase consumer education. Addressing these challenges will be crucial to ensuring that PV modules are disposed of sustainably as the industry expands.

### *2.1.6 Netherlands*

#### (1) Relevant regulations and schemes for EOL management of PV modules

In the Netherlands, Stichting Open (OPEN Foundation) implements the legal producers responsibility for electronic appliances that are put on the Dutch market on behalf of all producers of electrical appliances, including PV modules. These activities include collection, sorting and recycling activities, plus awareness campaigns. Since 1 March 2021, the OPEN Foundation is responsible for reaching the collection target of 65% of all e-waste appliances with its partners or 85% of WEEE generated. Under the flag of Wecycle, the OPEN Foundation continues to run campaigns to encourage consumers and companies to separate and hand in e-waste at one of the 13 000 Wecycle collection points. The logistics are arranged via pickup services from these local recycling centers, but also from installers of larger PV projects.

Since July 1st 2023, the so-called “producers” (which are mostly importers in the Netherlands) need to pay a waste management contribution (“afvalbeheerbijdrage”) when importing PV modules in the Netherlands. This contribution is 0.04 EUR/kg of PV module [86]. This budget should guarantee the collection and recycling of PV modules for a period of 5 years, ending in 2026. Negotiations are ongoing between the Dutch national government and Stichting Open for new arrangements for the period after 2026.

For PV module recycling, members in Stichting Open include, among others, Holland Solar (branch organization) and Zonne-energie Recycling Nederland (ZRN), part of Holland Solar, but focusing on PV module recycling [87].

#### (2) Treatment and amount of EOL PV modules

The National (W)EEE Register (NWR) reports the volumes of discarded electric and electronic appliances every year in July (Regeling afgedankte elektrische en elektronische apparatuur [AEEA]). For PV modules, the results reported in 2023 are shown in Table 2.1-8.

**Table 2.1-8 Historical collected PV module waste volume based on the national WEEE register (“regeling AEEA”) [88]**

| | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|
| PV module waste (t) | 131 | 200 | 776 | 493 | 1 036 | 1 381 |

Until 2025, Dutch PV module waste is not treated on a large scale within the Netherlands but is mainly transported to Belgian facilities. However, Stichting Open has started selecting partners to handle PV module recycling. The aim is to process EOL PV modules to enable the reuse of raw materials for new PV modules or other high-value applications. Therefore, Stichting Open has initiated a tendering procedure for the recycling of PV modules [89].

Stichting Open has divided the partner selection into lots for two technology readiness levels (TRLs), to allow both large-scale recycling based on current processes and new developments through an “innovation program [90]:

[Lot 1: Established Market Players (reliable recycling techniques)]

This lot seeks up to two market parties that can deliver sufficient processing capacity to handle the majority of future EOL PV module flows. The focus lies on reliable recycling techniques with a TRL of 7 or higher. Of the resulting materials, at least glass, silver, copper, and aluminium should be of sufficient quality for high-quality reuse. It is hereby specifically required that glass will be used as a glass product and not as a downgraded building component. Stichting Open expects that operation within this lot can start at the end of 2025. Stichting Open states that “they expect to be working very close together with French and/or German partners, thereby reaching or even surpassing the current technology levels in these countries.”

- Volume of lot 1: 2 000 tonnes in 2026, growing to 22 000 tonnes by 2032 (80% of expected material flows).

[Lot 2: Emerging Technologies]

This lot provides an opportunity for market parties with promising but unproven recycling options to further develop their concepts into fully fledged recycling methods, which should offer better results than lot 1. Based on the results from this lot, Stichting Open plans to renew the tender annually through an "innovation program" allowing new developments to participate in the Dutch PV recycling efforts.

- Volume of lot 2: 400 tonnes in 2026, increasing to 4 400 tonnes by 2032 (20% of expected material flows).

### (3) Outlook

Various sources [90][91][92][93] report on the quantity of PV module waste in the future. It is hard to give a precise prediction, since this number is influenced by a large number of factors, including installation volumes, time to end-of-life (for the modules in the Netherlands) and export to other countries after national end-of-life.

Three figures have been collected that present an indication of the range of predictions. Fig. 2.1-9 has been derived from the recycle tender of Stichting Open (see previously) and contains both historical (NWR) and predicted numbers [91][92].

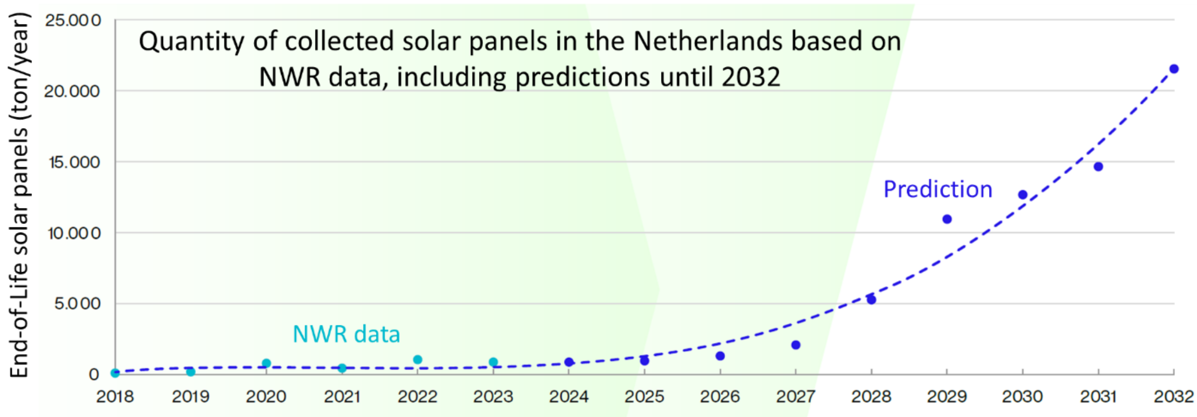



**Fig. 2.1-9 Volume of collected PV modules in t/y based on NWR data. Historical numbers are displayed in green, and predictions until 2032 in blue [90]**

Fig. 2.1-10 describes scenarios for a more distant future (2033–2050) and includes the potential effect of export from the Netherlands [91]. The red line represents a scenario without export, whereas the green line assumes that 30% of the PV modules installed in solar parks are decommissioned and exported after a service time of 15 years.

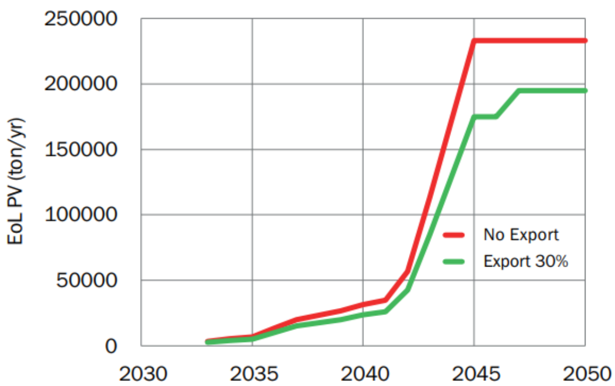



**Fig. 2.1-10 Long-term prediction of volume of collected PV module waste in t/y in the Netherlands between 2033 and 2050, showing the impact of export [91]**

Fig. 2.1-11 shows a third prediction based [92] using the PV ICE model [93] from NREL. It implements a material flow model with degradation rates instead of Weibull distributions, resulting in longer PV lifetimes. Here, the mass of the various materials in the modules, like glass and aluminium, is displayed separately.

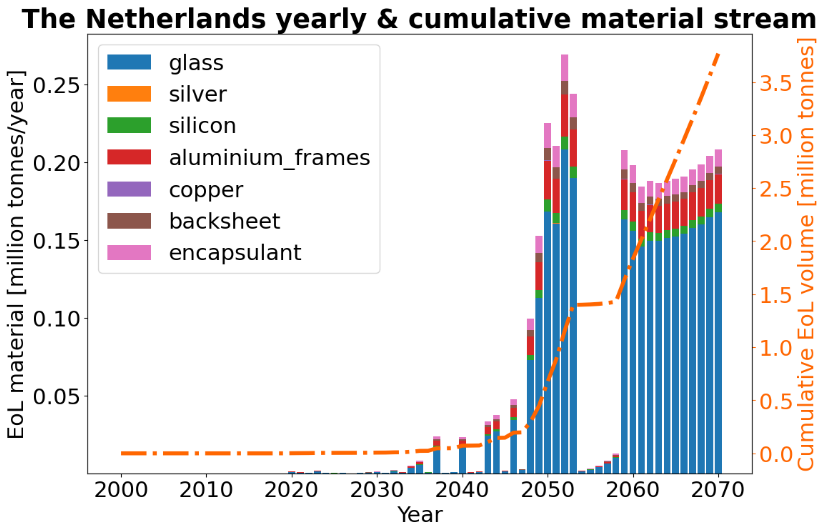



**Fig. 2.1-11 End-of-life volume of PV modules, calculated based on degradation rate, assumptions, based on PV module datasheets with lifetime increased to 35 years and lower degradation rates of 0.5%/year, lead to the jumps around 2055 [92]**

In order to create an overview, all data are plotted logarithmically in Fig. 2.1-12. This figure presents an outlook until 2053 for the Netherlands. Looking at the figure, the expected amount of PV module waste will be more than 10 000 t/y around 2030 and will reach more than 100 000 t/y around 2050.

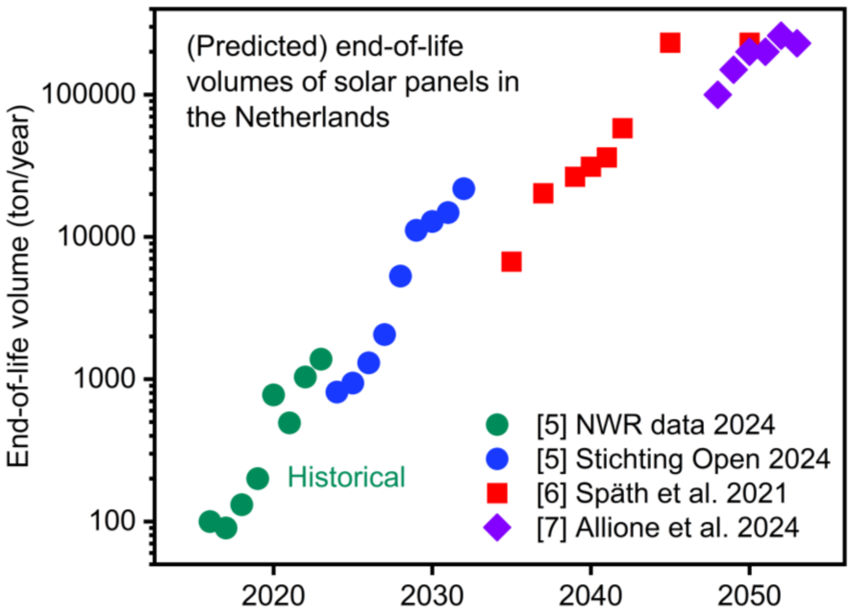



**Fig. 2.1-12 Outlook of PV module waste in the Netherlands**
(Combined data on end-of-life volumes from sources [90], [91] and [92] on a logarithmic scale. For source [91] the scenario without export has been selected.)

### *2.1.7 Austria*

#### (1) Relevant regulations and schemes for EOL management of PV modules

In Austria, the "Elektroaltgeräteverordnung" (EAG-VO) was established to enforce the European WEEE directive, focusing on managing the disposal of PV modules since 2014. This directive outlines how waste is categorized, specifies the required waste collection volumes, and assigns responsibility for these tasks. Due to the EPR for electronic waste, it also defines who is considered a producer of PV modules: the entity that places the product on the Austrian market for the first time. This includes Austrian manufacturers as well as importers and resellers. In Austria, all PV modules are considered B2B products; hence, the associated waste is classified as professional waste.

Moreover, the EAG-VO distinguishes between PV modules installed before and after 1 July 2014. For modules installed before this date, the responsibility for funding the collection and treatment of old modules lies with the producer of the new modules in replacement cases, or with the owner if no replacement occurs. For modules installed thereafter, the producer bears full responsibility for end-of-life costs. In addition to this scheme, commercial users have the option of entering into separate financing arrangements.

The EAG-VO has a separate “collection and treatment category” for PV modules, which comes with specific recycling targets. These targets mandate that 85% (in weight) of PV modules are recovered, and 80% have to be prepared for reuse and recycling.

#### (2) Treatment and amount of EOL PV modules

The Elektroaltgeräte Koordinierungstelle (EAK) compiles data on the quantity of electronic waste, which includes PV modules, entering the market in Austria, as well as the amount collected, recycled, and recovered, subsequently reporting this information to the EU. The integration of PV modules was initially limited until recent years. Up to 2008, in total, only 32.3 MWp of PV capacity was installed in Austria. Then in the years 2009 until 2018, the implementation increased only very slowly from 20.2 to 186.2 MWp annually [94]. Consequently, the volume of (EOL) modules remains relatively low.

Since 2016, PV modules have been categorized separately and aggregated by the EAK [95] (see Fig. 2.1-13). In 2023, 62 tonnes were collected, accounting for a mere 0.04% of all electronic devices. However, it must be stated that these are only the officially reported numbers. It is assumed by experts working in the field that a significant number of modules is either classified in the wrong waste category or not reported at all. This is due to the fact that (1) waste treating companies still charge a fee for EOL modules and (2) there is only a small amount of companies that can treat PV modules properly. Moreover, it is still possible because most EOL modules come from the time before the WEEE directive was in place or the producers of the modules are no longer on the market or do not know of their responsibility.

The official retrieval of EOL modules is typically managed by compliance schemes such as Elektro Recycling Austria, UFH or the European Recycling Plattform Austria GmbH. Producers contribute a fee, to these compliance schemes, which then organize the take-back process. They have several waste collecting points and collaborate with recycling facilities in Austria.

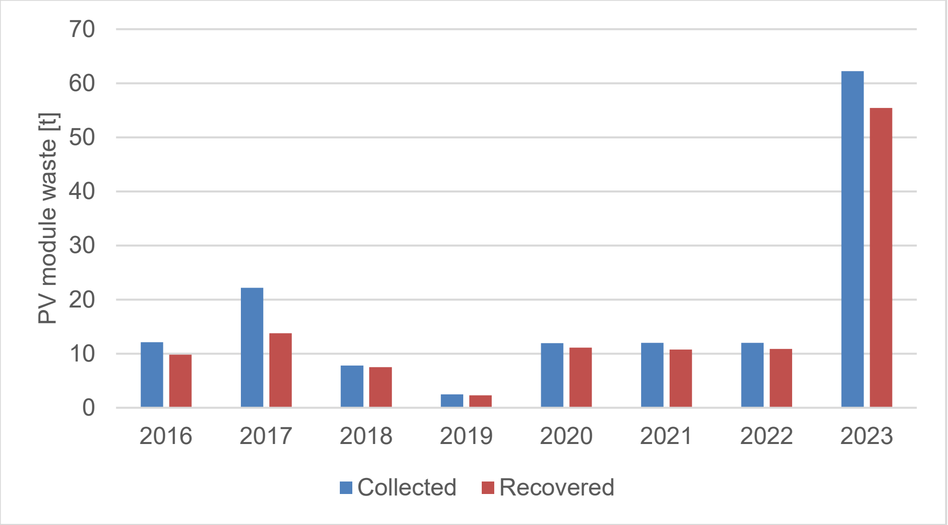



**Fig. 2.1-13 PV module waste collected and recovered in Austria from 2016 until 2023, official data from EAK reports in the specific years [95]**

### (3) Companies treating EOL PV modules for recycling

Because of the low waste volumes, there are no specific recycling plants only treating PV modules in Austria. To be allowed to gather and treat EOL modules, companies need to apply for a permit. Since 2022, PV modules have their own number and are no longer part of general waste large electronic equipment. Most companies easily got the permit for the new number. This results in a list of 147 companies that are legally allowed to treat EOL modules [96]. However, most of or nearly all of them are not treating modules in reality.

Several electronic waste recycling facilities can treat silicon-based modules on a pilot scale level. Currently, modules are stored until reaching a sufficient volume before undergoing treatment. MGG Metran has a legal compliant, that they achieve the recycling quota set by the EU and treat all parts of the modules at the company. They treat the modules with a mechanical treatment, a multistage crushing and separation of glass, plastics, and metals. Most of the other companies only remove frame and junction box and then send it to another (glass-) recycling company in Austria or Germany, where more specific infrastructure is available. Fig. 2.1-14 marks all the companies treating PV modules in Austria which were willing to share information for this report. They are listed below:

- Kerschner Umweltservice und Logistik GmbH
- MGG Metran Rohstoff Aufbereitungs GmbH
- Peter Seppele Gesellschaft m.b.H
- Saubermacher Dienstleistungs- Aktiengesellschaft.

The execution of the treatment steps varies from company to company. As waste volumes are rising, several recycling facilities have already indicated their interest of entering the PV recycling market.

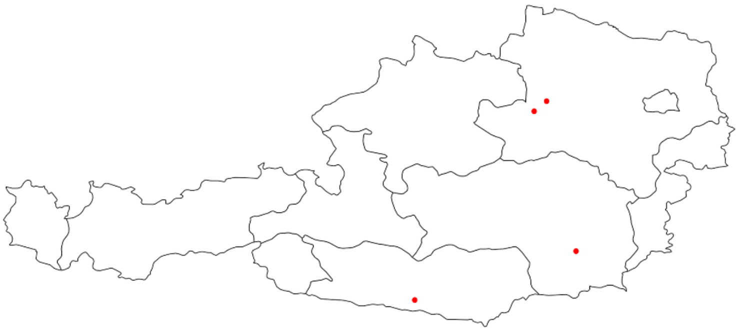


**Fig. 2.1-14 Map of companies treating PV EoL modules in Austria**

### (4) Outlook

Since 2019, PV implementation in Austria has increased rapidly, influencing future waste volumes. Although it is difficult to predict annual installation in the future, an average 2 GWp of installation from 2024 until 2040 is assumed in accordance with PV Austria [97].

In 2020, waste projections were made for Austria [98] according to the methodology developed by IEA PVPS Task 12 and IRENA in 2016 [3]. However, the long-term forecast must be treated with caution, as in 2020 an annual deployment of 400 MW was assumed [98], which has now been increased to 2 GWp/year (Fig. 2.1-15).

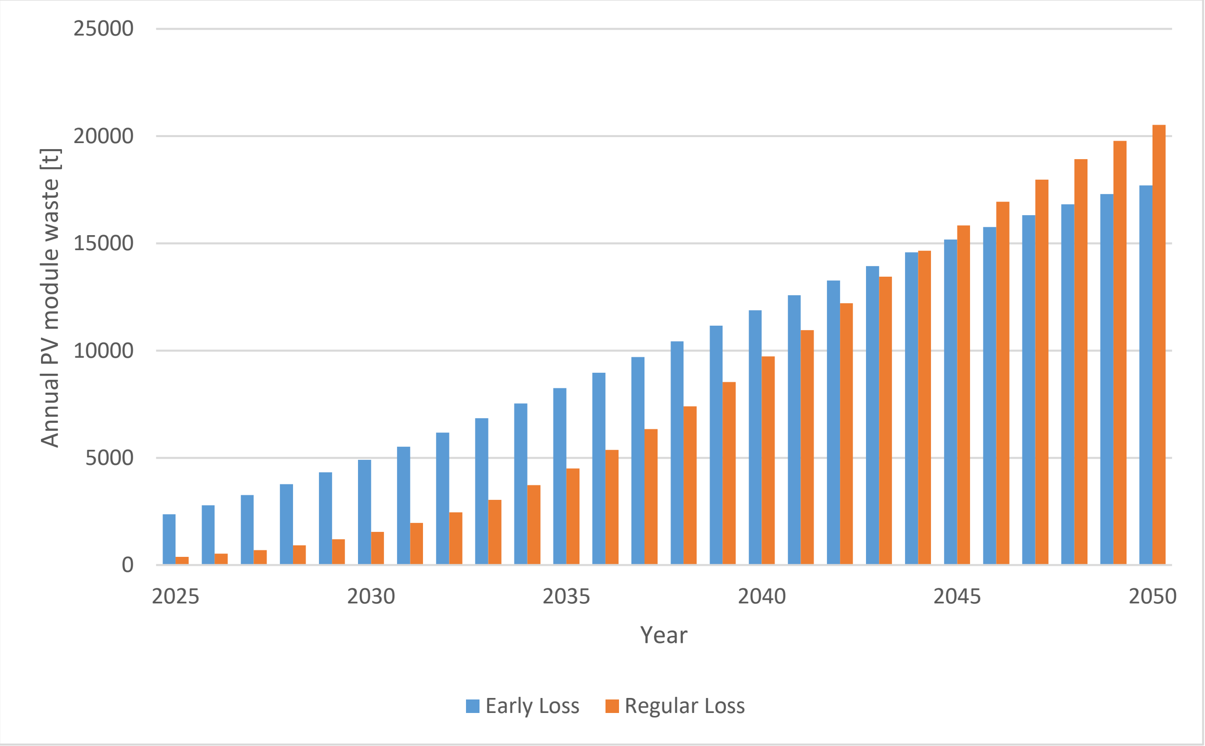



**Fig. 2.1-15 Waste prognosis in Austria adapted from Dobra et al. in 2020 [98]**

Currently, there are R&D activities in Austria to improve the treatment of PV module waste such as "PVReValue." As more waste is expected in the future, there's increasing interest in recycling, even for economic reasons. That could help to implement recycling plants, specifically designed to treat PV modules also in small countries such as Austria.

### *2.1.8 Sweden*

Sweden's installed PV capacity has consistently grown since 2000. The capacity reached approximately 100 MW in 2015. New capacity installations became noteworthy in 2019 with approximately 287 MW, then accelerated by adding approximately 400 MW in 2020 and 500 MW in 2021, leading to the cumulative installed PV capacity reaching approximately 1.6 GW. By 2022, the installed PV capacity in Sweden surpassed 2 GW. This follows a strong growth trend in the PV market and significant new installations in 2023 when more than 1 GW of new capacity was added. As of mid-2024, Sweden's installed PV capacity has exceeded 4.4 GW [99][100][101].

From the PV module waste management perspective, it is important to state most of the PV installations in Sweden comprise small-scale residential and commercial systems, with more than 50% of the installations having capacities under 20 kW, and solar parks larger than 1 MW accounting for about 8% of total installed capacity. In the first half of 2024 alone, 460 MW of PV capacity was installed. The residential sector led with 270 MW, whereas commercial projects added 190 MW [101][102].

Fig. 2.1-16 represents the solar energy supply in Sweden since 2010 and the Swedish Energy Agency forecast until 2027 [103][104]. The graph clearly shows from 2019 to 2024, there was an exponential increase in PV capacity and the assumption is linear installation growth for the next few years.

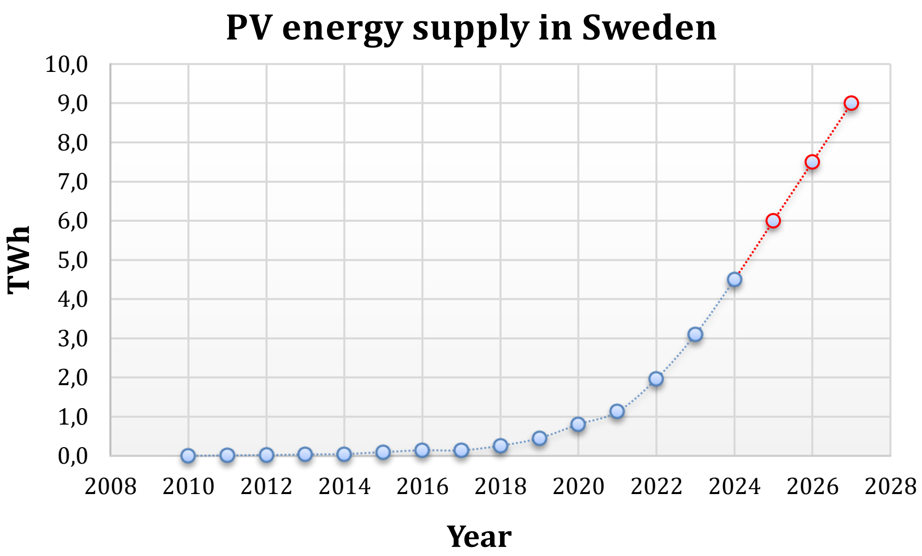



**Fig. 2.1-16 Solar energy supply in Sweden since 2010 and forecast [103][104]**

The Swedish Energy Agency's solar energy statistics (black squares), extrapolation of two mathematical fits (yellow dashed line and black dotted line), three long-term future scenarios (blue, green, and purple dashed line), as well as the solar industry target (asterisk), are given in Fig. 2.1-17 [105].

There has been a significant increase in PV installation since 2020, and the trend is expected to continue to reach the decarbonization goal. Given the extended service life of PV modules, a significant volume of PV module waste is not expected to enter the waste management system until after 2040. Consequently, the current levels of PV module waste generated remain insufficient to sustain an industrial-scale recycling process.

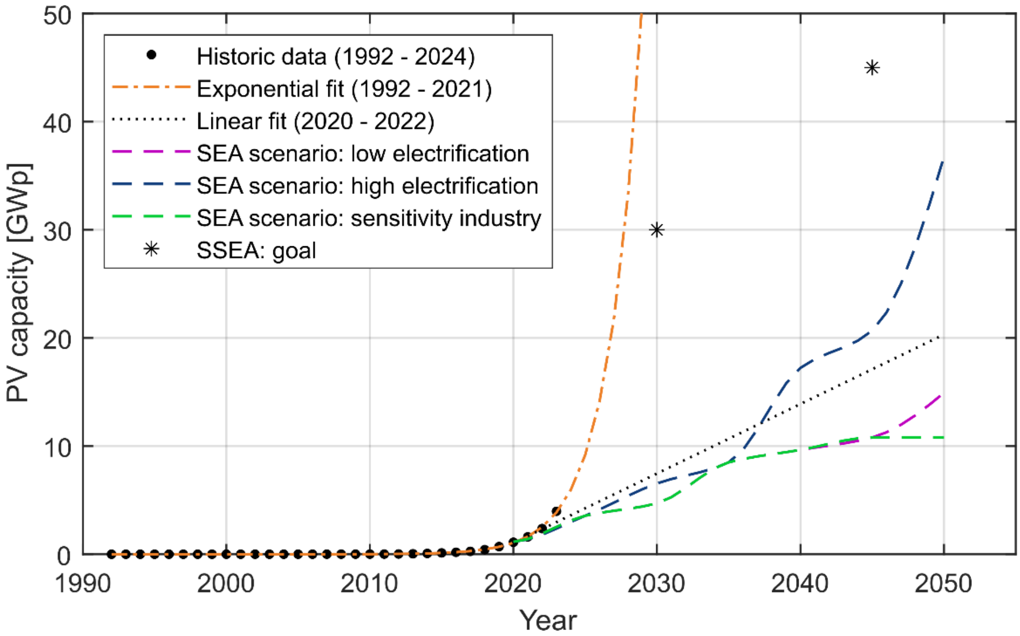



**Fig. 2.1-17 Forecast for cumulative PV capacities in Sweden considering different scenarios [105]**

As stated, as of 2020, the cumulative installed PV capacity is unimportant in volume, and thus, considering the PV modules' service life, the current waste stream is negligible. As one of the member states of the European Union, Sweden follows the WEEE Directive 2012/19/EU, in which PV modules have been under the scope of WEEE since February 2014. As an action to the WEEE Directive, Sweden has implemented EPR policies, which make producers responsible for the entire life cycle of their products—including the collection and disposal of PV modules. Currently, data on decommissioned PV modules are integrated into the WEEE waste stream for collection and processing.

Given the substantial residential installation of PV modules in Sweden, the role of individual owners in ensuring proper waste collection is significant. The country's decentralized and capillary collection network for PV module waste includes on-site, local, and mobile WEEE recycling points, all managed by municipalities. Key players in this system are El-Kretsen AB and Recipo Ekonomisk förening "Recipo Economic Association," which have the permitted WEEE collection. They collect waste from both municipalities and industries. The household collection is coordinated in collaboration with municipal authorities. The collection from the business sector is managed in partnership with municipalities and contracted transporters.

Although there are several actors in WEEE recycling in Sweden, because of the negligible PV module waste volume, industrial processing is limited. NG Metall AB in Katrineholm accepts PV module waste for recycling. In addition, Stena Recycling AB and Ragn Sells have expressed interest in PV module recycling.

### *2.1.9 Switzerland*

In Switzerland, the disposal of electrical appliances—including PV modules—is regulated by the Ordinance on the Return, Taking Back, and Disposal of Electrical and Electronic Equipment [106]. The collection of PV modules is financed through an advanced recycling contribution, which is paid by the buyer at the time of purchase. The central scheme for the recycling of PV modules is managed by SENS eRecycling [107], a foundation dedicated to the collection and recycling of electronic waste. SENS eRecycling is a member of Swiss Recycling and the global competence center for e-waste, the WEEE Forum.

There are no recycling facilities for PV modules available or under development in Switzerland. KWB Planreal AG is so far the sole company commissioned by SENS eRecycling for the collection of PV modules in Switzerland. They collect and store the modules before transporting them to Germany for mechanical recycling by the Reiling Glass Recycling GmbH & Co. KG. Their process involves the mechanical recycling of certain materials and the use of others for energy recovery.

The amount of PV module waste in Switzerland has varied over time with an increase since 2021 (see Fig. 2.1-18).

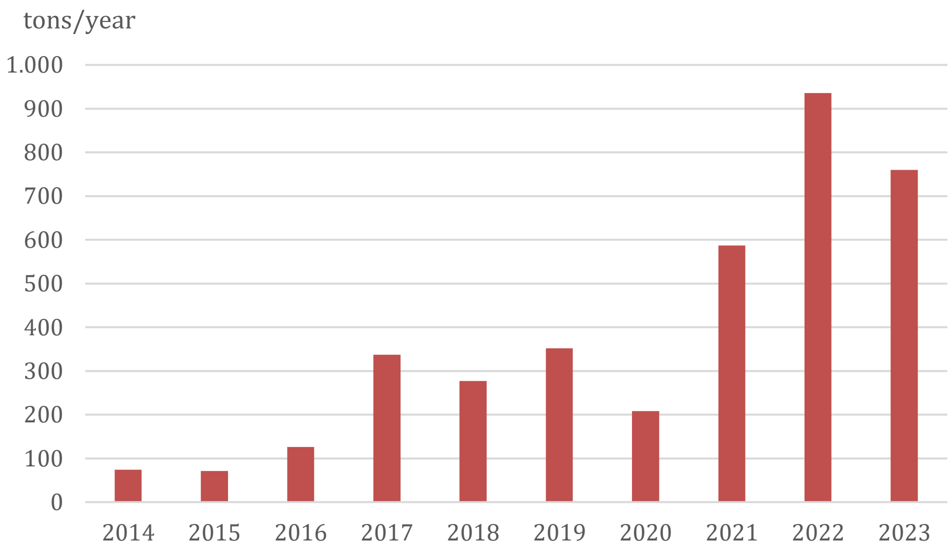



**Fig. 2.1-18 Amount of PV module waste from Switzerland 2014–2023, based on data from SENS eRecycling**

Forecasting future PV module waste is challenging because of various influencing factors. Projections based on calculations by Czajkowski et al. [108] and the Swiss PV Circle estimate the annual amount of PV module waste from Switzerland to reach around 4 000 tonnes in 2030, around 11 000 tonnes in 2040, and around 22 000 tonnes by 2050.

The reuse of PV modules is being explored through the Swiss PV Circle [109] project led by SENS eRecycling, Swissolar, and the Bern University of Applied Science (see Fig. 2.1-19). Some PV modules are already being reused within Switzerland, while others are exported for further use, primarily outside Europe. The Swiss PV Circle project aims to extend the service life of PV modules by developing business models around reuse. To this end, a platform is being developed that enables the early determination of the applicable cycle strategy through comprehensive data management. This data-based assessment will be supported by a standardized test procedure that determines the reuse potential of PV modules. In this way, tested second-hand modules can be put on the market at a lower price and only those modules that are no longer functional can be recycled.

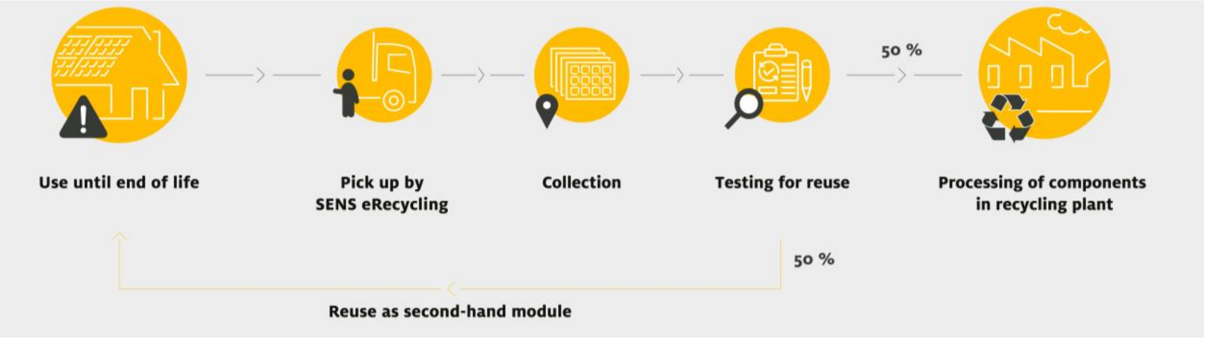



**Fig. 2.1-19 PV modules reuse and recycling system as developed within Swiss PV Circle project** [109]

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

This section presents the status of PV module recycling in Japan, South Korea, China, and Australia, e.g., IEA PVPS Task 12 participating countries in the Asia and Pacific region.

### *2.2.1 Japan*

#### (1) Relevant regulations and schemes for EOL management of PV modules

Currently in Japan, EOL PV modules 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 handlers, handling of industrial waste including landfill disposal, and so forth. To support the proper EOL treatment, the Ministry of Economy, Trade, and Industry (METI) and the Ministry of Environment (MOE) have jointly assessed how to handle EOL PV modules. In August 2024, the 3$^{rd}$ edition of the guideline for promoting proper EOL treatment for PV modules including recycling [110] was published by MOE as an update to the 2$^{nd}$ edition published in December 2018. The guideline covers basic information such as relevant laws and regulations on decommissioning, transportation, reuse, recycling, and industrial waste disposal. Further update to the guideline is under discussion. In addition, in May 2021, MOE published a guideline for promoting the proper reuse of PV modules [111].

A review meeting on how to dispose of and recycle renewable energy power was jointly organized by METI and MOE in 2023, and an interim report was published in January 2024 [112]. The report summarized the current status of EOL management of PV modules and showed a basic direction for a proper EOL management: i) coexistence with locality, ii) collaboration of stakeholders of whole life cycle, and iii) effective activities and minimization of social cost. In addition, required actions for PV were extracted as shown in Table 2.2-1.

**Table 2.2-1 Required actions for proper EOL management of PV [112]**

| Rapid action | To be discussed continuously |
|---|---|
| - Registering information on hazardous materials (As, Pb, Cd, and Se), and requiring to use PV modules such information is registered (effective from April 2024)<br>- Promoting reuse and recycling by active dissemination of existing relevant guidelines<br>- Requesting PV owners to maintain safety after operation (before decommissioning) | - Developing a scheme for<br>: Getting information on EOL management such as owner change and hazardous materials<br>: Implementing delivery and taking over of PV module waste<br>: Promoting reuse<br>: Securing cost of proper EOL management<br>: Avoiding “left unattended” after ending operation |

Rapid actions shown in Table 2.2-1 are already active. In parallel, to cover other issues needed to be discussed continuously, a committee and a working group for PV recycling were established and organized jointly by METI and MOE in summer 2024. As a result of discussion, a concept of regulation for promoting proper treatment of EOL PV modules such as recycling, from viewpoints of “Things,” “Cost,” and “Information,” was drafted; and required steps as shown in Table 2.2-2 were proposed in March 2025 [113].

The concept is proposing to mandate recycling of EOL PV modules, to establish a payment scheme as shown in Fig. 2.2-1, and to manage the scheme by an independent/third-party organization.

**Table 2.2-2 Required steps for proper EOL management of PV [113]**

| Things (= promotion) | Cost | Information |
|---|---|---|
| - Long-term use of PV equipment for reducing waste<br>- Promoting reuse<br>- Promoting recycling<br>: Development of implementing structure and high-value recycling<br>: Adjustment and effectiveness of decommissioning and transportation of PV modules<br>- Countermeasure against leaving and illegal dumping of EOL PV equipment | - Securing a cost for decommissioning by owners<br>: Deposit, redemption, and estimation<br>- Securing a cost for recycling<br>: Payment by producers, delivery to owners, and estimation | - Getting necessary information<br>: Information on implementing proper disposal and recycling<br>: Information on implementation status of recycling<br>: Information on management of PV equipment after the EOL<br>: Information on cost for disposal and recycling<br>- Management of information |

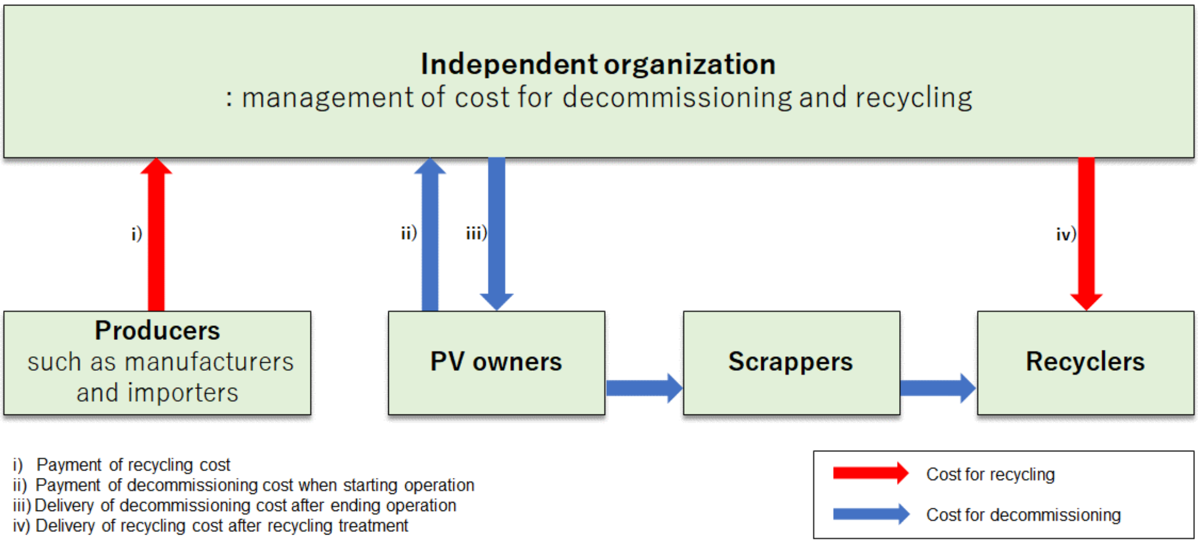



**Fig. 2.2-1 Proposed scheme for payment of decommissioning and recycling costs [114]**

### (2) Treatment and amount of EOL PV modules

Although there is no official statistical information on PV module waste, MOE investigated EOL management and waste of PV modules [115]. As shown in Fig. 2.2-2, it was estimated PV module waste collected was 2 079 tonnes in 2022, and among that, 1 638 tonnes were recycled and 441 tonnes were reused. Until 2020, two-thirds of collected modules were reused, which were decommissioned after natural disasters without any (or little) damage. The amount of PV modules recycled during the period was approximately 2 000 t/y. It seems approximately 10% of the weight was landfilled as residue after recycling (delamination) processes.

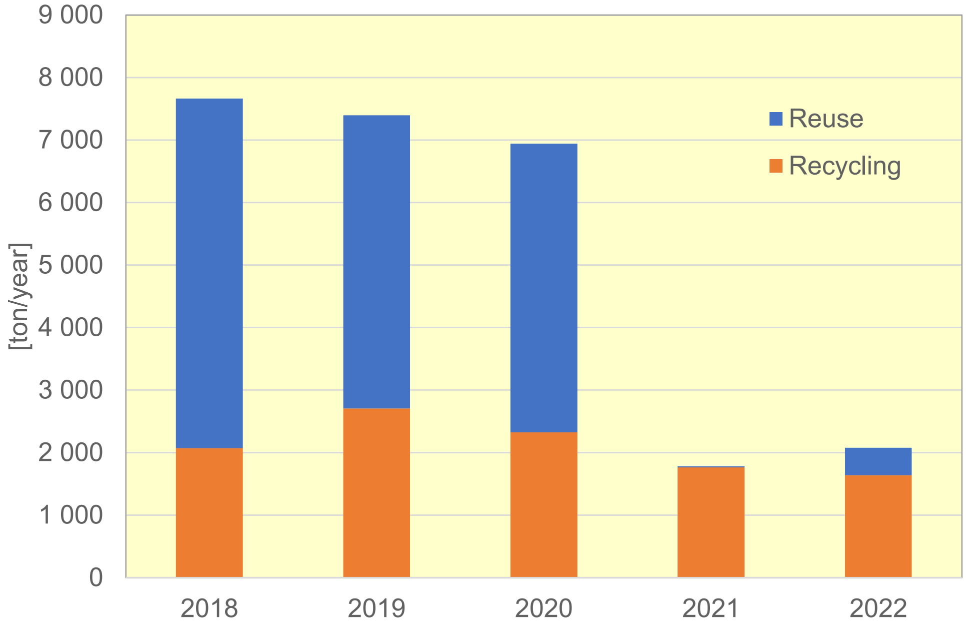



**Fig. 2.2-2 PV module waste collected and treated in Japan [115]**

### (3) Companies treating EOL PV modules for recycling

Table 2.2-3 shows a list of companies accepting PV modules for recycling in Japan [116]. The list was developed by the Japan Photovoltaic Energy Association (JPEA), and it is updated regularly however, it should be noted the table provides information to support and promote EOL treatment but does not cover all companies and facilities in Japan. In addition, JPEA lists companies that can dismount PV modules from residential systems and treat those properly [117], and the list is updated regularly as well.

More than half the companies listed in Table 2.2-3 have installed specific equipment for PV module recycling (separating PV modules’ structure and components). Several types of technology are used for PV module recycling, as shown in Table 2.2-4. Although the most common approach is a mechanical method, various technologies are used, whereas some companies use a thermal method such as pyrolysis. However, because the amount of PV module waste is relatively small, the operation rate of these companies is low.

The other companies are intermediate processors of more common kinds of industrial waste whose main function is to separate bulk materials. According to METI/MOE [114], the capacity of facilities that can treat PV module waste for recycling and include companies not listed in Table 2.2-3 is more than 70 000 t/y.

**Table 2.2-3 Examples of companies that can properly treat PV modules in Japan [116]**

| Name | Location | Name | Location |
|---|---|---|---|
| Matec Inc. | Ishikari, Hokkaido | Ecoenel Inc. | Fujinomiya, Shizuoka |
| Seinan Corporation | Hirosaki, Aomori | Maruryo Automobile Transport Co., Ltd | Shizuoka, Shizuoka |
| Mitsuba-Shigen Co., Ltd. | Towada, Aomori | Recycle Tech Japan | Nagoya, Aichi |
| Kankyo Hozen Service Co., Ltd. | Oshu, Iwate | Mizutani Chemical | Tobishima, Aichi |
| MEK/MK Co., Ltd | Sendai, Miyagi | Aichi Kaiun Co., Ltd./Chuden Sozaiterrace LLC | Gamagori, Aichi |
| Dowa Eco-System Co., Ltd. | Odate, Akita | Earth Construction Co., Ltd. | Toin, Mie |
| Moriya | Higashine, Yamagata | Eco Advance | Iga, Mie |
| Takaryo corporation | Minamisoma, Fukushima | Kinki Denden Yuso Ltd. | Neyagawa, Osaka |
| Shirakawa Syouten | Koriyama, Fukushima | Hakuto Total Recycle System Co., Ltd. | Tottori, Tottori |
| Nisso Metallochemical Co., Ltd. | Taito, Tokyo/Aizu, Fukushima | Earth Suppoer, Inc. | Matsue, Shimane |
| Arrows | Chikusei, Ibaraki | Hirabayashi Metal Co., Ltd. | Okayama, Okayama |
| Mitsukaido Sangyo | Joso, Ibaraki | Uchida Industry Co., Ltd. | Kurashiki, Okayama |
| Kankyo Tsushin Yuso | Ushiku, Ibaraki | Kangai | Kurashiki, Okayama |
| Um-Welt-Japan Co., Ltd. | Yorii, Saitama | JFE Bars & Shapes Corporation | Kurashiki, Okayama |
| Re-Tem Corporation | Chiyoda, Tokyo/Ibaraki | Sunada Co., Ltd. | Higashihiroshima, Hiroshima |
| Hamada Co., Ltd. | Minato, Tokyo and Takatsuki Osaka | Cocco Co., Ltd. | Kure, Hiroshima |
| Tokyo Power Technology Ltd. | Koto, Tokyo | Kaneshiro Sangyou | Matsuyama, Ehime |
| Toko Metal Co., Ltd. | Ota, Tokyo | NPC Incorporated | Matsuyama, Ehime |
| J&T Recycling Corporation | Kawasaki, Kanagawa/Isesaki, Gunma | Recycle Tech Co., Ltd. | Kitakyushu, Fukuoka |
| Hokuriku Giotec | Niigata, Niigata | SAKIN Eco Recycle (Sagakinzoku corporation) | Saga, Saga |
| Harita Co., Ltd. | Takaoka, Toyama | Kyoeikyushu Co., Ltd. | Usa, Oita |
| Shinshu-Takeei | Suwa, Nagano | Kyusyuhokusei Co., Ltd. | Kobayashi, Miyazaki |

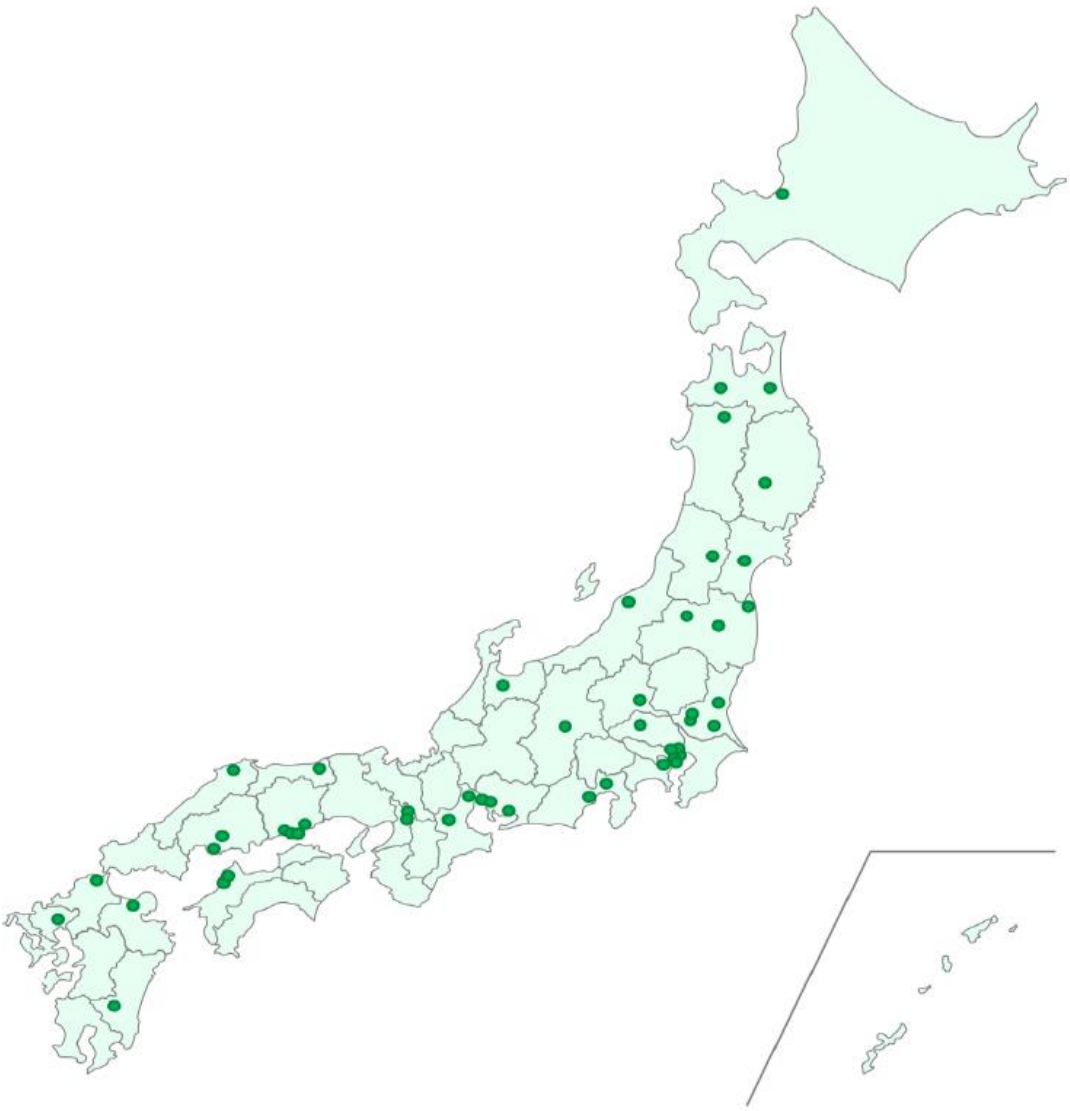


**Fig. 2.2-3 Map showing location of companies that can properly treat PV modules in Japan [116]**

**Table 2.2-4 Examples of PV module delamination technologies operated/demonstrated in Japan**

| Method/Technology | | | Materials recovered |
|---|---|---|---|
| Thermal | Pyrolysis | | Recovery of cover glass and metals without polymer adhesion |
| Mechanical | Glass separation | Hot knife/separator | Separation of unbroken cover glass and polymer/Si cell layer |
| | Glass scraping | Compression roller/particle blasting/hammering | Separation of glass as particles and polymer/Si cell layer |
| | Polymer/cell layer scraping | | Separation of unbroken glass and scraped polymer/Si cell layer |
| | Shredding/sorting (conventional process for separating bulk materials) | | Shredded pieces of PV module components |

**PV module recycling facility using a combination of various delamination technologies**

Facility: PV recycling center, owned and operated by Hamada Corporation

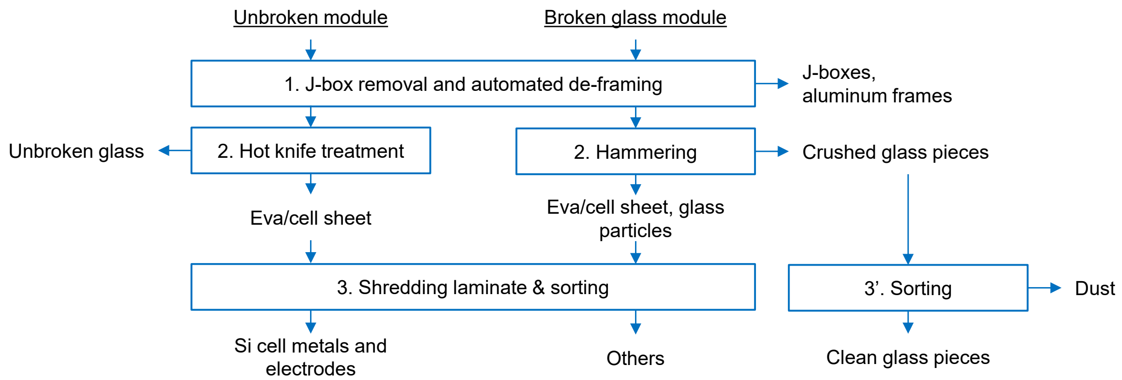
Location: Kyoto, Japan

At the PV recycling center in Kyoto, Japan, owned and operated by Hamada Corporation, two delamination technologies are used in combination. Nominal treatment capacity of each piece of equipment is 10.8 tonnes per day, corresponding to 480 modules (supposing 8 hours of operation with 1 minute per module treatment), respectively; 21.6 tonnes of PV module waste per day can be treated in this facility.

Unbroken modules are treated by hot knife equipment, and unbroken glass and the polymer/Si cell layer (sheet) are recovered separately. Unbroken glass is sent to and used for glass product. The polymer/Si cell layer is crushed and sorted, and Si cell pieces, copper ribbons, and polymer particles are recovered. Metals are sent to a metal refinery company, and polymers are sent to another company and recycled thermally. An expected material recovery rate after treatment is more than 99%.

Glass broken modules are treated by hammering equipment, and crushed glass pieces and the polymer/Si cell layer are recovered. Crushed glass is sorted to remove impurities, and a dust including small glass particles is wasted in a landfill. Polymer/Si cell layer adhering to small particle glass pieces is crushed and sorted. Si cell pieces, copper ribbons, and polymer particles are sent to the next destination along with recovered materials for unbroken glass treatment. In this equipment, an expected material recovery rate is approximately 85%–90%.

[Treatment process]




### (4) Outlook

It is forecasted that the amount of PV module waste will increase to 220 000–340 000 t/y by the mid-2030s, as shown in Fig. 2.2-4 [118].

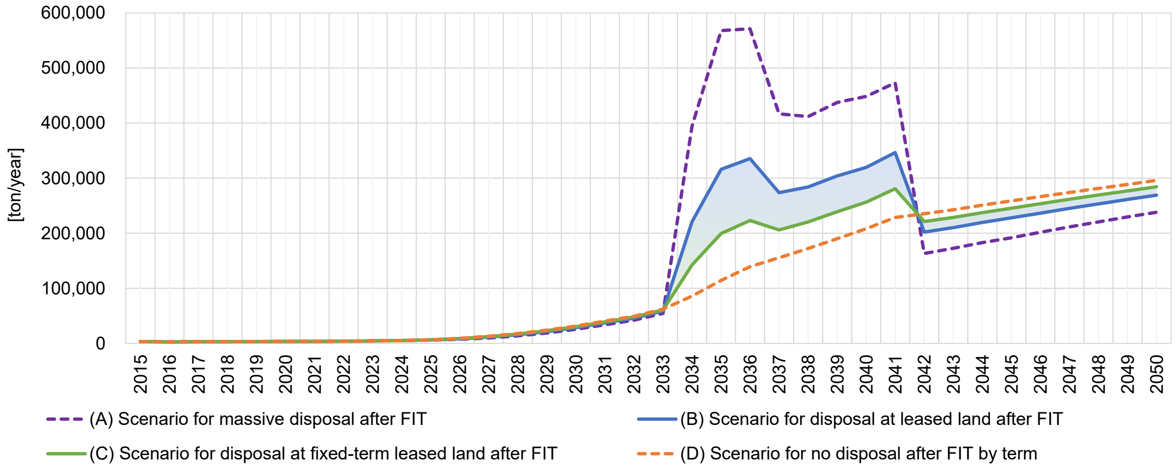



**Fig. 2.2-4 Forecast of the amount of PV module waste in Japan [118]**

A challenge to achieve a high-value recycling business is to find high-value products for the glass and metals recovered from EOL PV modules. R&D projects to find solutions for high-value recycling are conducted under the New Energy and Industrial Technology Development Organization (NEDO) project [119].

As for PV glass recycling, AGC corporation—a world-leading glass manufacturing company—is demonstrating a recycling of PV cover glass to flat-plate glass. PV cover glass cullet was blended into raw materials (including conventional glass cullet) of flat-plate glass production, although a rate of blended PV glass cullet is not open to the public. In October 2023, in its first demonstration, blended PV glass cullet including 24 tonnes of PV glass cullet recovered by Shinryo Corporation, using a commercialized pyrolysis technology, was recycled to figured glass (patterned/rolled-out glass) [120]. In March 2024, in a second demonstration, blended PV glass cullet including 5 tonnes of PV glass cullet recovered by Tokuyama Corporation, using pyrolysis technology, was recycled to float glass [121].

In addition, the number of PV systems installed in Japan is dominated by residential PV systems. To achieve a low-cost recycling business, developing efficient collection and transportation of PV module waste and recycling those are agendas. To this end, Tokyo Metropolitan Government has started a subsidy scheme to promote PV module recycling wasted from residential systems [122].

In 2023, the Solar Panel Reuse and Recycling Association was established to promote the reuse and recycling of decommissioned PV modules [123]. The association's members are companies treating EOL PV modules and equipment for recycling. Although it is a fledgling organization, it is expected to lead an enterprise activity for the proper EOL management of PV modules.

### *2.2.2 South Korea*

#### (1) Relevant regulations and schemes for EOL management of PV modules

In October 2018, the Ministry of Environment announced a legislative notice to expand the EPR system to 23 items, including PV module waste. Subsequently, 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. However, because of insufficient infrastructure for PV module recycling, the enforcement for PV modules was postponed for 3 years and only began on January 1, 2023 [124]. In this rule, PV modules are classified as a separate product group from existing waste groups, such as temperature exchangers, displays, communication/office equipment, and general electrical/electronic devices. PV module manufacturers are required to pay a fee of KRW 727 per kilogram if they fail to fulfill their PV module recycling obligations from 2023 onward, whereas PV module sales companies that do not comply with PV module waste collection obligations are charged KRW 94 per kilogram.

Because the Ministry of Environment had authorized the nonprofit organization E-Cycle Governance as the exclusive operating body for PV module waste EPR, beginning in January 2023, the practical collection and recycling of PV module waste are being conducted by E-Cycle Governance [125]. Companies that perform collection and recycling register as members of E-Cycle Governance, carrying out operations and receiving subsidies based on their processing performance.

With the implementation of EPR in January 2023, the Korean government, at the 14th State Affairs Ministers' Meeting presided over by Prime Minister Han Duck-Soo, reviewed and confirmed the "Plan to Strengthen Management of PV Waste Panels," jointly prepared by the Ministry of Environment and the Ministry of Trade, Industry, and Energy under the coordination of the Office for Government Policy Coordination [126]. This plan aims to encourage recycling consideration from the module production stage, enhance safety management during PV facility dismantling, and establish collection and processing systems tailored to various scales and situations. In addition, it seeks to reduce PV module waste by assessing reusability before recycling, improve statistical systems related to PV module waste, and strengthen management and service infrastructure to achieve a recycling/reuse rate of more than 80% within 3 years through the six detailed strategies shown in Table 2.2-5.

On June 27, 2024, the Ministry of Environment held a Circular Economy New Technology and Service Review Committee meeting and granted regulatory exemptions for a pilot project on the on-site recycling of PV module waste [127]. The "Circular Economy Regulatory Sandbox," introduced earlier in 2024, provides exemptions or temporary permits within limited zones for new technologies, services, or products—waiving or delaying existing regulations for a set period. If the pilot results show the technology or service is stable and environmentally safe, the relevant regulations may be revised or improved.

The on-site recycling service for PV module waste, submitted by Won Kwang S&T, involved a pilot project in which container-mounted equipment would be used at the site to separate, transport, and recover valuable resources from PV module waste by material. However, because there were no standards for installing mobile waste treatment facilities or criteria for licensing such facilities, the project could not be implemented. Currently, PV module recycling is generally permitted at licensed facilities only. Allowing on-site processing carries the risk of recycling companies selectively removing only valuable resources and potentially abandoning the rest, causing environmental pollution. With the granting of this regulatory exemption, the pilot project will assess transportation efficiency, environmental impacts such as noise and vibration, and safety management measures throughout the process. If commercialized, this project is expected to significantly reduce the transport volume of PV module waste, which is projected to surge by 2028 - lowering transport costs for waste generators, preventing the abandonment of PV module waste, increasing the recovery rate of valuable resources, and promoting recycling overall.

**Table 2.2-5 Strategies for achieving a recycling/reuse rate of more than 80% [126]**

| |
|---|
| Manufacturing Stage: Promoting Resource-Circulating Module Production and Technology Development |
| - The plan encourages the design and production of PV modules that facilitate recycling from the manufacturing stage. It also promotes R&D to enhance recycling technologies, including advanced recycling for next-generation PV modules. This involves i) developing production technology using low-carbon, resource-circulating materials, ii) designing products for easy reuse and recycling, and iii) advancing technologies for recycling valuable resources. Furthermore, the use of portable performance inspection equipment will be expanded. |
| Dismantling Stage: Strengthening Safety Management in Dismantling |
| - Because PV facilities can still generate power from modules even after they are disconnected from the power system, there is a risk of electric shock or fire during dismantling. To prevent accidents, safety management will be reinforced during the dismantling process. |
| Collection Stage: Establishing Collection Systems Based on Waste Volume and Disaster Situations |
| - In the collection stage, tailored collection systems will be established based on the scale and form of PV module waste generation, with measures in place to handle mass occurrences of PV module waste because of natural disasters. PV module waste generated on a small scale, such as from households or farms, will be collected through a "household PV module waste recovery system" operated by the cooperative association, whereas modules generated in large quantities from power plants or public institutions will be dismantled by specialized companies and then collected through the cooperative. In case of mass generation because of natural disasters, regional Future Waste Resource Collection Centers will manage storage across the country. |
| Processing Stage : Establishing Regional Collection and Recycling Systems |
| - In the recycling processing stage, the number of recycling facilities will be expanded from two to seven, with dedicated recycling systems established across five main regions (Seoul Metropolitan Area [including Gangwon], Chungcheong, Yeongnam, Honam, and Jeju). In addition, to reduce logistics costs associated with PV module collection and recycling, intermediate collection facilities will be set up in each of the 17 provinces nationwide. By 2025, approximately 200 collection points will be established and operated as basic municipal collection systems. However, new installations will be minimized, with existing public collection centers used to build cooperative systems with local governments. |
| Waste Reduction : Establishing a Basis for Reuse of Usable Modules |
| - To reduce PV module waste generation, guidelines will be developed for the reuse of modules that are still functional. Reuse criteria will be presented—covering factors such as exterior condition, power generation, and insulation performance—to encourage the consideration of reusability before recycling. The mandatory collection amount under the EPR system will be calculated based on the quantity designated for reuse. |
| Strengthening Management and Service Infrastructure<br>: Improving Statistical Systems and Information Provision |
| - With the EPR system for PV modules in effect since 2023, plans are in place to collaborate with related agencies to manage and use information related to PV modules (e.g., installation, replacement, decommissioning, export, and recycling). |

### (2) Treatment and amount of EOL PV modules

In 2023, the first year of EPR implementation, 688 tonnes of PV module waste were recycled. This figure significantly exceeded the Ministry of Environment's target of 159 tonnes by more than fourfold. The target, 159 tonnes, was determined based on the average amount of PV module waste generated over the previous 3 years (2020–2022), calculated as 149.4 tonnes, with an adjustment factor of 0.25 applied according to regulations [128]. The recycling quota for PV module waste in 2024 has been set at 212 tonnes, calculated by applying a 2024 adjustment factor of 0.2 to the average waste generation between 2021 and 2023 [129]. However, as of April 2024, recycling had already reached 363 tonnes, surpassing the 212 tonnes quota, with projections indicating it could reach 1 250 tonnes by the end of the year [130]. The government, noting EPR is still in its early stages for PV module waste, believes it is premature to revise the quota calculation method. It plans to review the recycling quota system once relevant statistics are more established in 5–6 years; therefore, a significant increase in recycling quotas is unlikely in the near term.

**Table 2.2-6 Annual PV module module recycling quotas and treated volumes [128][129][130]**

| Year | a) Target quota (tonnes) | b) Treated volume (tonnes) | c) Achievement rate (%: b/a*100) |
|---|---|---|---|
| 2020 | - | 37.4 | - |
| 2021 | - | 261.1 | - |
| 2022 | - | 149.7 | - |
| 2023 | 159 | 688 | 432 |
| 2024 | 212 | 1 250(e) | 589 |

### (3) Companies treating EOL PV modules for recycling

The nonprofit organization E-Cycle Governance, authorized by the Ministry of Environment as the exclusive operator of the EPR for PV module waste, registers recycling companies as members after a screening process. Registered companies perform recycling activities and receive subsidies based on their recycling processing performance. Although companies can perform recycling without joining E-Cycle Governance, collecting the subsidies would be challenging - making profitability difficult. Currently, a network of specialized PV recycling companies has been established across five regional centers, with a nationwide recycling capacity of 14 725 tons per year as of the end of 2023 (Table 2.2-7) - sufficient to handle PV module waste generation for the next few years. If the domestic market for PV module waste grows beyond the capacity of current members, additional members are typically recruited.

**Table 2.2-7 List of PV module recycling companies registered with the E-Cycle Governance association [130]**

| Region | Company name | Location | Capacity (t/y) |
|---|---|---|---|
| Metropolitan area | Won Kwang S&T | Incheon | 4 500 |
| Gyeongsang region | Yoonjin Tech | Kyeongbuk | 2 400 |
| Chungcheong region | Chungbuk Technopark | Chungbuk | 4,080 |
| Honam region | Seokchung Korea | Jeonbuk | 2 145 |
| Jeju region | JRC | Jeju | 1 600 |

### (4) Outlook

The projection for PV module waste generation in South Korea was initially based on a scenario developed by the Korea Institute of Energy Research in 2015 and was updated in 2020 as shown in Fig. 2.2-5. This scenario was designed to be as objective as possible, drawing on domestic and international deployment data, information from manufacturers, field surveys and interviews at PV plants, status reports on module waste, analysis of both domestic and international scenarios, and expert consultations. The final scenario for PV module waste generation incorporates module lifespans of 15, 20, 25, and 30 years, with weights assigned according to manufacturing period and warranties typical of installation years. To reflect advances in module manufacturing technology and the trend toward lighter modules, the scenario categorizes modules based on their production year: pre-2000 (114.6 kg/kW), 2001–2010 (88.7 kg/kW), and post-2011 (73.3 kg/kW).

According to this updated scenario, more than 1 000 tonnes of PV module waste are expected to be generated annually from 2024 onward. This figure is anticipated to surge in 2028, reaching nearly 10 000 tonnes, with a steady increase thereafter—surpassing 25 000 tonnes annually from 2033 onward.

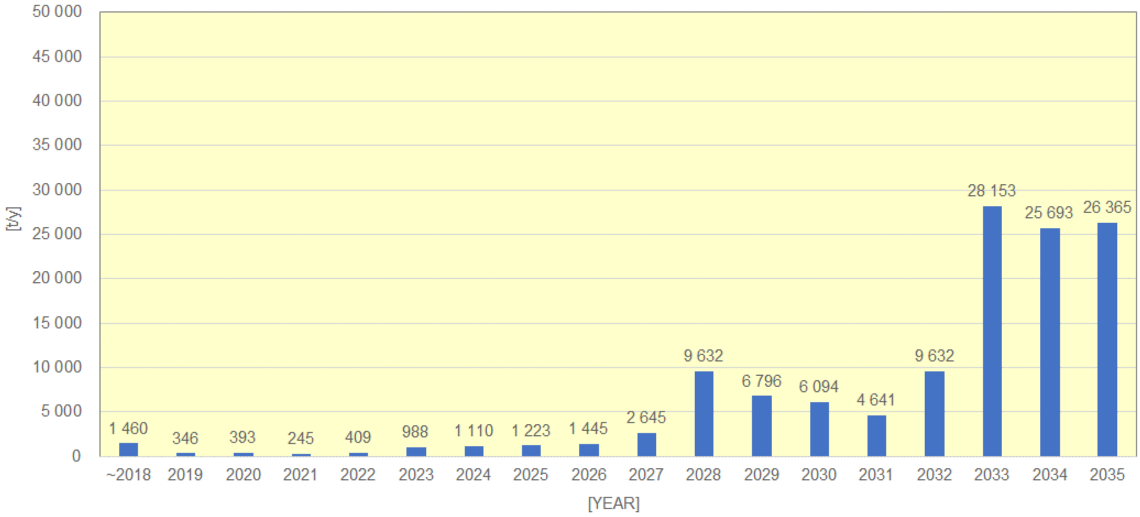



**Fig. 2.2-5 Forecast of the amount of PV module waste generated in South Korea [131]**

### 2.2.3 China

#### (1) Relevant regulations and schemes for EOL management of PV modules

China's PV industry has achieved rapid development, maintaining the largest PV module production in the world for the last 18 years. New PV installed capacity has ranked first in the world for the last 12 years, and cumulative PV installed capacity has ranked first in the world for the last 10 years.

China is a major market for global PV applications. With the accelerated upgrading of the PV industry and technology, China is about to witness a wave of recycling for a large number of PV power generation equipment. As the "last mile" in the PV supply chain, the recycling and circulation of EOL PV modules serve as the ultimate guarantee for achieving a green closed loop in the PV industry chain, bringing new opportunities and challenges to the development of the industry.

From 2023 to 2024, China's PV recycling and circulation industry continued to improve because of the successive release of national incentive policies for it, the continuous improvement of the technology, and the large increase in the number of recycling enterprises. The key policies are summarized as follows.

On August 17, 2023, the National Development and Reform Commission, in collaboration with five other ministries, jointly issued the “Guidelines to Promote the Recycling of EOL Wind and PV Equipment.” This document represents the first systematic policy framework in China aimed at the recycling of EOL wind and PV equipment, providing direction and guidance for it. The document outlines two phased goals: By 2025, a basic responsibility mechanism for the disposal of EOL equipment from centralized PV power plants should be established; by 2030, a technical system for the full-process recycling of PV equipment should be basically mature [132].

On January 11, 2024, the State Council issued the “Guidelines to Comprehensively Promote the Development of the Beautiful China,” which outlined target pathways, key tasks, and significant policies. In terms of promoting the green transformation, the document proposes a crucial measure: Accelerate the establishment of a waste recycling system to promote the recycling of waste materials such as used wind turbine blades, PV modules, power batteries, and express packaging [133].

In January 2024, the Ministry of Ecology and Environment published the “Catalogue of Solid Waste Classification and Codes” aimed at enhancing the standardization, precision, and digitalization of solid waste management practices. It is worth noting in the latest version of the Catalogue, the waste code（900-015-S17） for decommissioned PV modules (including decommissioned PV modules generated during production, rebuilding, and EOL PV) was released for the first time [134].

On March 7, 2024, the State Council released the “Action Plan to Promote the Large-scale Renewal of Equipment and Trading-in of Consumer Goods,” which aimed to promote large-scale equipment renewal and technological transformation in key areas of energy. The National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) organized the preparation and unveiled the “Action Plan to Promote Large-scale Equipment Renewals in the Energy Sector,” focusing on thermal power, wind power, and PV and hydro power, with a focus on achieving equipment renewal and technological transformation and rebuilding, to accelerate the construction of a clean, low-carbon, safe, and efficient energy system [135].

In addition to national policies, more than 20 provinces (cities and municipalities) have successively issued several provincial measures to promote large-scale equipment updates, putting forward relevant requirements and goals for the recycling and reuse of end-of-life PV modules.

#### (2) Treatment and amount of EOL PV modules

China has seen rapid growth in both annual new installations and cumulative installations of PV capacity. At the same time, a large number of PV technology upgrade and rebuilding projects have emerged. Therefore, the scale of EOL PV in China may be even larger, and the peak of decommission will arrive earlier.

As for the amount of PV module waste, there is currently no released official data available in China. In terms of treating with PV module waste, some large-scale centralized PV power plants in the west will pile up them in a centralized manner, whereas the other part of the PV module waste will be dismantled and recycled by a PV module recycle company.

To better clarify the scale of the existing domestic EOL PV market and provide more accurate prediction data and decommission distribution, the ECOPV PV Recycle Industry Development Center (PV Recycle Center) organized a project to predict the scale of EOL PV in China. After more than a year of data collection, discussion, research, and comparison, the project team finally completed a comprehensive set of prediction models, methodologies, and forecasting results.

[Data Collection and Forecasting of China's PV Installation]

By consulting reports and data published by official channels such as the National Energy Administration, State Grid, and the National Renewable Energy Centre, PV Recycle Center has compiled the annual installed capacity data for China since 2000. The work on capacity forecasting is divided into two phases: The short-term forecast focuses on the period through 2030, whereas the long-term forecast extends to 2050. According to predictions from the Energy Research Institute of the National Development and Reform Commission, China's cumulative installed PV capacity is expected to reach 4 000 GW by 2050. Based on this forecast, the project has set a cumulative installed capacity target of 4 000 GW for 2050 and calculated the annual installed capacity through 2050.

[EOL PV Module Scale Prediction Model and Parameters]

The innovation of this prediction lies in segmentation of various climatic regions, including arid hot zones, warm temperate zones, cold temperate zones, subhumid hot zones, and humid hot zones. For each distinct resource climate zone, PV Recycle Center established varying α scale parameters based on demonstration data, reflecting the aging degradation specific to those regions. Regarding the β shape parameter, PV Recycle Center has adopted different scenarios of "early loss" and "regular loss" from IEA and IRENA to set the parameter values.

[National Forecast Results of the Scale of EOL PV Modules]

Based on forecasting research, China's cumulative EOL PV module volume is projected to reach 1 million tonnes in 2030, 12 million tonnes in 2040, and 55 million tonnes in 2050 under the regular loss scenario. Under the early loss scenario, these figures are expected to increase to 4 million tonnes, 23 million tonnes, and 66 million tonnes (Fig. 2.2-6), respectively (with waste generated during production included in the calculation at a rate of 0.05%).

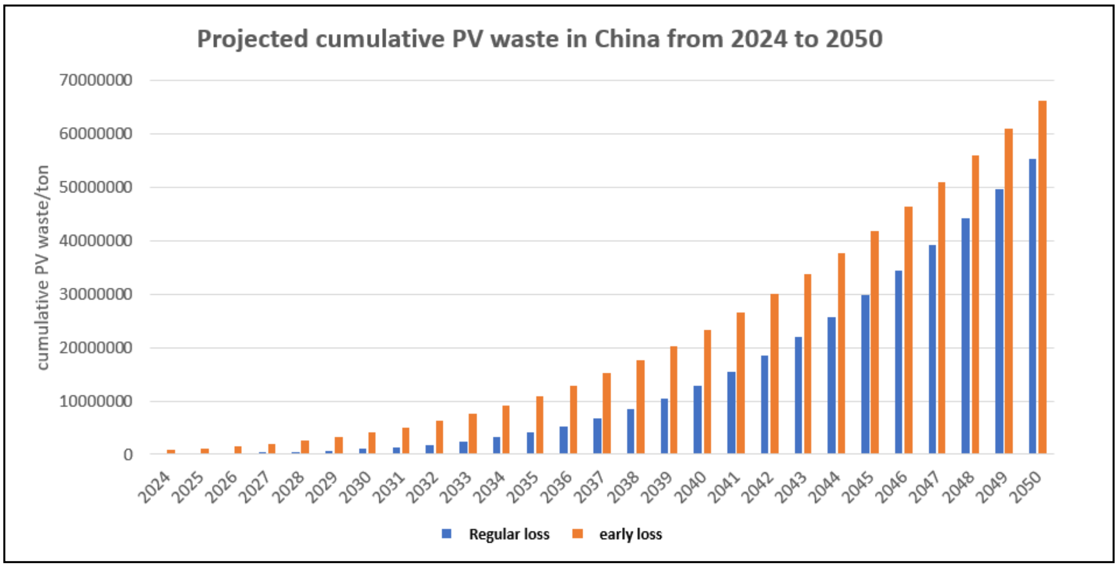



**Fig. 2.2-6 Forecast of the scale of end-of-life PV in China (Source: ECOPV PV Recycle Industry Development Center) [136]**

### (3) Companies treating EOL PV modules for recycling

PV Recycle Industry Development Center was established in February 2022. As a national and nonprofit cooperative organization, it has nearly 100 members. The Center focuses on the PV recycling industry, leverages collective strength, integrates resources, fosters collaboration, and actively engages in a wide range of activities—including technology innovation and assessment in PV recycling, research and demonstration of key recycling equipment, market development and cultivation, formulation and promotion of standard systems, policy and regulation research and proposal formulation, international exchange and cooperation promotion, and exploration of investment, financing, and business models. Since its inception in 2022, the Center has annually compiled and released the “White Paper on PV Recycling and Circulation in China” and organized the annual Technical Forum on PV Equipment Recycling and Circulation.

China's PV recycling industry is developing quickly, and several key enterprises dedicated to clean recovery and recycling have emerged, combined and introduced in the Table 2.2-8. And Fig. 2.2-7 shows location of typical PV modules recycling companies in China.

**Table 2.2-8 Typical PV modules recycling companies in China**

| Name | Location | Name | Location |
|---|---|---|---|
| State Power Investment Corporation Limited (SPIC) | Xining, QingHai Province | Changsha Mining and Metallurgy Research Institute Co., Ltd. | Changsha, Hunan Province |
| JinkoSolar Co., Ltd. | Shangrao, Jiangxi Province | Nantong RIYIXIN Electronic (Suzhou)Co.,Ltd. | Nantong, Jiangsu Province |
| Yingli Energy (China) Co., Ltd. | Baoding, Hebei Province | Shaanxi Van-Solar Energy Technology Co., Ltd. | Xi'an, Shaanxi Province |
| Changzhou Ruisai Environmental Technology Co., Ltd. | Changzhou, Jiangsu Province | Jereh Environmental Technology Co., Ltd. | Yantai, Shandong Province |
| RESOLAR Energy Technology (Shanghai)Co., Ltd. | Shanghai | Ycergy (Suzhou) Technology Co., Ltd. | Suzhou, Jiangsu Province |
| DAS Intelligent Eco Co., Ltd. | Quzhou, Zhejiang Province | | |

**Fig. 2.2-7 Map showing location of typical PV modules recycling companies in China**

The enterprises in the above table have constructed PV module recycling lines, among which the pilot line of module recycling of Huanghe Hydropower Development Co., Ltd. adopts independently researched and developed industrialized crystalline silicon PV module recycling technology and equipment. The company has formed a "high-quality comprehensive recycling" process technology route centering on the "mechanical dismantling process, thermal cutting process, heat treatment process, and chemical purification process." The pilot line adopts self-developed industrialized crystalline silicon PV module recycling technology and equipment (Fig. 2.2-8). The PV module recycling equipment developed by the company can efficiently recycle complete modules and broken modules, and has formed a full-process PV module recycling industrialization process technology plan and equipment integration plan from EOL PV module frame, junction box and backsheet removal to glass separation, welding tape screening, and silicon material purification. It has applied 90 patents, received 49 patents including 11 invention patents, and compiled 11 standards. In addition, the company has been selected as "National Catalogue of Advanced and Applicable Process Technology and Equipment for Comprehensive Utilization of Industrial Resources" and the list of the first (set) of major technical equipment in the field of energy.

In the next stage, Huanghe Company and State Power Investment Corporation PV and Energy Storage Industry Innovation Center will continue to develop advanced technology for module recycling in an encompassing way, develop the advanced double-glass module recycling technology and high-quality recycling and processing capacity, and continuously improve the effectiveness of recycling treatment and enhance the automation and intelligence level of the module recycling line.

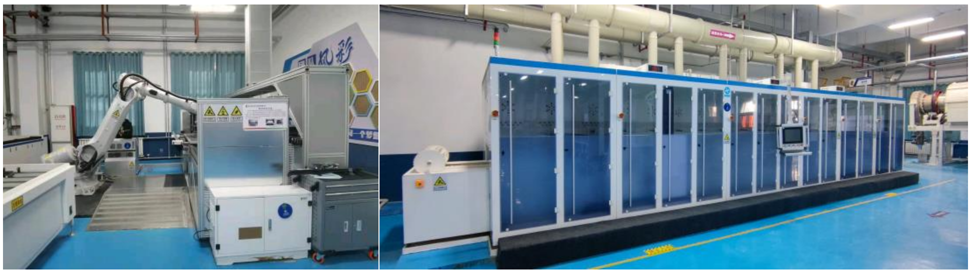


**Fig. 2.2-8 State Power Investment Group company self-developed module recycling equipment**

Changzhou Ruisai Environmental Technology Co., Ltd. adopts special equipment for dismantling PV module peripheral parts by a mechanical method, stripping cover glass by a grinding method, dismantling PV laminates efficiently by a thermal method, and separating high-purity mixture, and so on. The company has a pilot line (Fig. 2.2-9) for dismantling EOL PV modules by a grinding method with an annual capacity of 3 000 tonnes, a pilot line for dismantling EOL PV modules by a pyrolysis synthesis method with an annual capacity of 20 000 tonnes, and a laboratory of dismantling PV modules by a chemical method.

**Fig. 2.2-9 Mechanical method PV module recycling pilot line**

RESOLAR Energy Technology (Shanghai) Co., Ltd. has independently developed the "GST (Green Swelling Technology) Green Separation Method"—a high-efficiency, environmentally friendly, low-cost, industrialized joint separation method—and can complete the production of 6N (99.9999%) grade silicon material. The recycled silicon material has significant advantages in terms of carbon emissions and cost and realizes the full cycle of silicon material and metal from EOL PV modules to new PV modules. The company has built and mass-produced a 10 000-tonne PV recycling line in Fengyang, Anhui Province (Fig. 2.2-10), which produces recycled glass, aluminium, 6N-grade silicon, silver ingots, soldering tapes, and junction box cables with significant economic benefits. The company cooperated with Trina Solar to produce the world's first fully recycled PV module in 2024.


**Fig. 2.2-10 Anhui Fengyang 10 000-tonnes PV module recycling plant**

DAS SOLAR was established in August 2018. As a national high-tech enterprise, the company deeply integrates the R&D, manufacturing, and sales of high-efficiency PV cells, photovoltaic modules, and system applications, while seamlessly connecting power station investment, construction, and operations.

Currently, DAS SOLAR is focusing on developing photovoltaic module recycling equipment, with a core emphasis on mechanical separation methods. Therefore, DAS SOLAR established in 2024 an independent subsidiary, DAS Intelligent Eco. The company is building a mechanical disassembly production line that integrates adaptive frame removal, thermal delamination, ultra-fine crushing, induced airflow, multi-stage component sorting, and comprehensive dust removal technologies. This technology enables the complete disassembly and reuse of photovoltaic glass and achieves high-efficiency separation of copper, silicon powder, and silver powder, reducing the energy required for purification. The equipment is fully automated, intelligent, and visualized, with a small footprint and high efficiency, making it suitable for the global PV module recycling industry. The production line is expected to be officially launched in 2025, contributing to the sustainable development of the global photovoltaic industry.

### (4) Outlook

As mentioned, China's cumulative EOL PV module volume is projected to reach 1 million tonnes in 2030, 12 million tonnes in 2040, and 55 million tonnes in 2050 under the regular loss scenario. Under the early loss scenario, these figures are expected to increase to 4 million tonnes, 23 million tonnes, and 66 million tonnes, respectively.

To treat such an amount of PV module waste, various activities are ongoing. In addition, by collecting the technical, industrial, and policy research projects on PV recycling performed by national, provincial, and ministries as well as various organizations from 2023 to 2024, the development of the PV recycling market has moved from scientific research to the industrial scale.

[Key Technologies and Equipment R&D for Circular Economy]

The Ministry of Science and Technology has organized and implemented the application for the key special project “Key Technologies and Equipment for Circular Economy” within the 2023 National Key Research and Development Program [137], designating the PV industry as one of the focal areas. This project aims to conduct significant scientific research on critical issues such as the reduction and mitigation of resource-based solid waste at the source ecodesign, green process control, and high-quality recycling to promote the establishment of an innovative technological system for a circular economy that facilitates the efficient and comprehensive use of resources. The primary aim of this project is to address national strategic priorities by tackling critical scientific and technological challenges in areas such as source waste reduction, harm minimization, clean production methodologies, and high-quality recycling. This endeavor encompasses the creation of a suite of essential common technologies, including digital ecological design for products, clean processes to minimize solid waste at the source, waste-free clean medium conversion, collaborative treatment of multisource organic solid waste, intelligent disassembly and repurposing of waste materials, environmental health risk management of chemicals, and the establishment of industrial circular linkages. Moreover, the project will formulate a comprehensive set of technical standards and specifications, leading to the development of an innovative technological framework for a circular economy that is applicable across various industries and contexts, comprising between 10 to 15 distinct sets. In addition, the initiative aspires to spearhead the establishment of a pivotal product circular industrial chain and a strategic regional low-carbon circular integration demonstration that serves as an international benchmark—significantly bolstering the circular supply capacity of secondary strategic resources and providing robust support for pollution reduction, carbon mitigation, and sustainable development within both industrial and regional contexts.

In the area of integration and demonstration of circular economy systems in key regions, the project “Integrated Technology & Demonstration of Efficient Circular for Recycling of EOL PV Laminated Parts (Application Demonstration Category)” was set up. The research content of the project focuses on solving the problem of efficient dissociation and clean remanufacture of EOL crystalline silicon PV laminates and is committed to the R&D of a complete set of chemical technology solutions.

[Public Service Platform for Intelligent PV Module Recycling Technology Standards, Carbon Footprint Accounting Validation, and Industrialization of Achievements for Intelligent PV]

The Ministry of Industry and Information Technology of the People’s Republic of China has implemented the project “Public Service Platform for Module Recycling Technology Standards, Carbon Footprint Accounting Validation, and Industrialization of Achievements for Intelligent PV” [138], which aims to research and formulate relevant standards and policy recommendations on PV module recycling and PV products’ carbon footprints. The project will build a carbon emission database and carbon footprint accounting system for the PV industry that is adapted to the characteristics of China’s resources and energy as well as develop and demonstrate the application of PV module recycling technology and equipment to promote both the scaled-up and standardized development of the PV module recycling industry and the green and low-carbon development of China’s PV industry.

[ECOPV PV Recycle Industry Development Center activities]

ECOPV PV Recycle Industry Development Center focuses on the PV recycling industry and comprehensively promotes PV recycling-related work by bringing together all parties, integrating resources, and collaborating and interacting. Since its establishment in 2022, the Center has been performing key research activities on common, fundamental, and urgent issues of the industry each year. Until now, it has successfully conducted in-depth research on six activities in the areas of retired PV market forecast, full life cycle assessment, economic analysis, and recyclability design.

The specific activities include Activity 1, "Forecasting the Chinese EOL PV Module Recycling Market," which aims to predict future market trends; Activity 2, "Research and Recommendations on Standards and Norms for Responsibility PV Recycling Enterprises," which investigates and proposes standard guidelines for responsibility enterprises; Activity 3, "Carbon Footprint and Life Cycle Assessment (LCA) Analysis of PV Modules Lifecycle," which analyses the carbon footprint from production to recycling; Activity 4, "Technical and Economic Feasibility Analysis of Recycling and Circular Utilization of EOL PV Modules," which evaluates the technical and economic viability of recycling and circulation; Activity 5, "Recommendations Guidelines on the DfR PV Modules," which proposes guidelines for recyclability in DfR design; and Activity 6, "Market Analysis and Technical Demonstration of Circulation of EOL PV Modules," which not only analyses the circular utilization technology market but also showcases the first demonstration remanufacturing PV module with 100% recycling and DfR materials, providing a case reference for the ecodesign of green PV modules.

### *2.2.4 Australia*

#### (1) Relevant regulations and schemes for EOL management of PV modules

Currently, there is no PV waste legislation or stewardship program in the national phase of Australia. In 2016, the Australian federal government added PV systems to the priority list for product stewardship action [139]. Because of insufficient progress with the industry-led scheme, the government committed to developing a mandatory product stewardship program to address PV system waste. The Australian Department of Climate Change, Energy, the Environment, and Water (DCCEEW) released a proposal for this regulatory scheme, titled “Regulation for Small Electrical Products and Solar Photovoltaic Systems”, for public consultation in June 2023. Although the scheme has not yet been finalized, it is expected to be implemented by 2025 [140][141]. However, limited progress has been made to date, and it is highly likely the implementation will be delayed.

This proposed scheme targets three key categories: material recovery, PV waste collection, and consumer awareness.

- Material recovery: Setting standards for the proportion of materials from recycled products that must be recovered for remanufacture.
- PV waste collection: Establishing a free PV waste disposal network appropriate for the collection of Australia’s installed PV capacity.
- Consumer awareness: Educating and increasing awareness among consumers about the sustainability of PV products.

The proposed structure is illustrated in Fig. 2.2-11, with stakeholders and responsibilities summarized in Table 2.2-9.

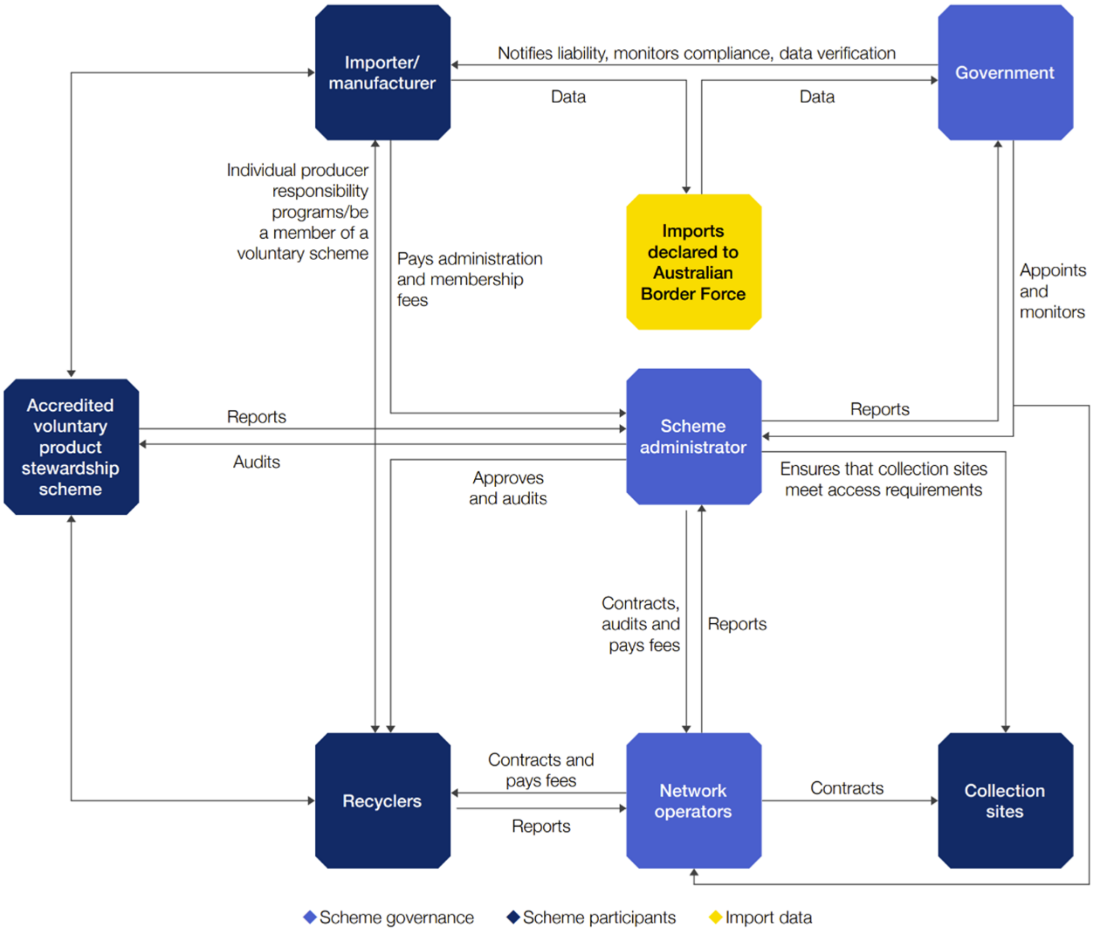



Fig. 2.2-11 Structure of proposed regulatory scheme [140]

**Table 2.2-9 Proposed stakeholders and responsibilities for the Australian e-Stewardship Scheme for PV [140]**

| Stakeholder | Responsibilities |
|---|---|
| **Scheme Administrator** | Ensure the scheme meets its outcomes.<br>Manage risk, perform audits of recyclers and recycling network operators, and ensure appropriate and equitable public access to the scheme.<br>Report to the government on the scheme's performance.<br>Contract network operators to undertake collection and recycling. |
| **Network Operators** | Establish and manage collection, transportation, and recycling services for a designated geographic area.<br>Manage contracts with approved recyclers to ensure recycling occurs (recycling network operators can also be recyclers if they can meet the obligations for both roles under the scheme).<br>Pay recycling fees.<br>Report recycling outcomes to the scheme administrator. |
| **Liable Parties** | Register with the scheme administrator.<br>Manage their obligations under the scheme by paying scheme administrator fees or implement their own program to manage collection and recycling of their products. Programs will need to be registered with the scheme administrator and meet auditing and reporting obligations. |
| **Recyclers** | Register with the scheme administrator as an approved recycler.<br>Contract to network operators to conduct recycling consistent with the standards required by the scheme. |
| **Australian Government** | Manage the compliance of liable parties.<br>Appoint scheme administrator and network operators.<br>Provide oversight and undertake regular compliance activities to ensure scheme obligations are upheld. |

Regarding the state-level regulations on the management of PV waste, Victoria stands as the only Australian state and territory that has legally banned all e-waste, including PV modules, from landfill disposal [139][142]. This regulation has been in effect since 1 July 2019 under the *Victoria Environmental Protection Act 1970* [143]. The Queensland government has also drafted an *E-Products Action Plan*, proposing a long-term (5–10 years) goal to ban the disposal of electrical and electronic equipment, including PV modules, from landfills [144]. Meanwhile, Western Australia's latest *E-Waste to Landfill Ban* consultation paper [145] outlines future phases that will include PV module waste in landfill restrictions.

### (2) Treatment and amount of EOL PV modules

An Australian PV waste projection study estimated the volume of EOL PV modules through 2050 [146]. The results from this study can be used to estimate the amount of PV waste expected within this decade. As shown in Fig. 2.2-12, it was estimated PV module waste was nearly 40 000 tonnes in 2023, increasing each year to reach nearly 100 000 tonnes in 2030. Cumulative volume will exceed 2 million tonnes by 2050. As shown in Fig. 2.2-12, more than 80% of cumulative PV module waste currently comes from small-scale PV systems (<100 kW), which is attributed to the early development of Australia's residential PV market. The volume of PV module waste from large-scale PV systems is expected to grow significantly after 2030 [139].

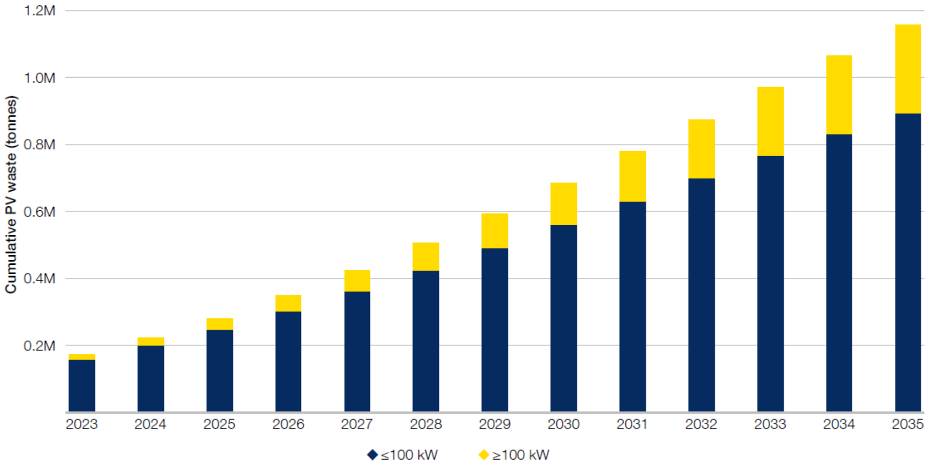



**Fig. 2.2-12 Projected cumulative PV module waste in tonnes in Australia [139]**

However, the actual amount of PV module waste, the percentage that was recycled or reused rather than sent to landfill, and the reasons for decommissioning all remain unknown because there is no official statistical information on wasted PV modules.

### (3) Companies treating EOL PV modules for recycling

PV module recycling companies have emerged in Australia since 2022. Validated information confirms seven companies shown in Table 2.2-10 are now operating PV module recycling facilities, whereas others remain in the storage or development stage.

**Table 2.2-10 PV module recycling companies in Australia**

| Company | Location | Modules collected 2023–2024 | Modules recycled 2023–2024 |
|---|---|---|---|
| PV Industries | Melbourne, VIC<br>Sydney, NSW | ~10 000 modules | ~10 000 modules |
| Elecsome | Melbourne, VIC<br>Kilmany, VIC | ~75 000 modules | ~5 000 modules |
| Sircel | Parkes, NSW<br>Dandenong, VIC<br>Yatala, QLD | 10 tonnes | 10 tonnes |
| Solar Renew | Wagga Wagga, NSW | N/A | 0 |
| Solar Recovery Corporation | Melbourne, VIC<br>Biloela, QLD | ~80 000 modules | 0 |
| Pan Pacific Recycling | Crestmead, QLD | N/A | N/A |
| Lotus Energy Recycling | Melbourne, VIC | N/A | N/A |

Without a mandatory recycling scheme, the industry operates on a voluntary basis, with each company responsible for developing its own collection network. Collection methods include direct contracts with EPC companies for broken modules during large solar farm construction, commercial and industrial (C&I) decommissioning projects, household module removal, and collaborations with councils to establish drop-off points. Recycling companies typically charge a recycling fee of 3–15 AUD per module, significantly reduced from 10–30 AUD just a few years ago. In addition, a collection fee is charged based on the distance and size of the pickup.

PV inverters and batteries, by comparison, are recycled by established e-waste recyclers alongside other electronic waste streams because this market is more mature than PV module recycling.

The following information was gathered through an Australian PV recycler survey conducted between June and October 2024, focusing on companies with significant development and operations in PV recycling. Other companies—at the early development stage or only at the collection and storage stage—are excluded from this year's update.

**PV Industries**

PV Industries [147] operates recycling facilities in Sydney and Melbourne, processing approximately 10 000 modules to date using proprietary mechanical recycling technologies developed in house. These facilities recover high-value materials such as glass, copper, and aluminium, with partial recovery of plastics. In 2024, PV Industries successfully extracted silver from PV cell waste, though this remains in the development stage. The company also received EPA approval for the use of its recycled glass in certain industrial applications and supplied glass for use in an infrastructure project.

PV Industries' recycling process includes (1) arrange collection or drop-off, (2) transport to PV module recycling facilities, (3) frame, junction box, and cable separation, (4) glass separation (patented), (5) previous metal recovery, and (6) materials sent for reuse in local manufacturing.

PV Industries has developed an algorithm and application that quickly identifies and analyses defects in luminescence and IR images to assess whether modules are suitable for reuse. This innovation helps ensure the quality of reused modules, building confidence in their reliability.

**Elecsome**

Elecsome [148] operates a PV module recycling plant with a robust mechanical processing capacity of 1 million modules a year (5 t/h) in Kilmany, Victoria. Between 2022 and 2024, the company has collected 75 000 modules, with 5 000 modules recycled and 500 modules reused. Elecsome's advanced mechanical treatment technology (Fig. 2.2-13) enables the recovery of high-value materials, including glass, silicon, silver, copper, plastics, aluminium frames, and junction boxes, with ~97% average recycling rate.

Elecsome also produces SolarCrete, a nano-engineered blend made from PV module glass fines, which serves as a sustainable alternative to sand. The company is collaborating with universities to develop methods for recovering silicon and silver, achieving purity levels of 98% for silicon and 99.9% for silver. The recovered materials, typically in powder form, have recovery rates ranging from 75% to 95%. Elecsome is working to refine these methods and plans to implement them on a large scale in the near future.

The company collects PV module waste through decommissioned modules at solar farms and local tip sites, with 99% volume collected from large solar farms.

**Fig. 2.2-13 Pictures of Elecsome PV recycling operation and products during recycling**

### Sircel Solar

Sircel Solar [149] began operations in 2024 with three facilities across Australia, each with an annual recycling capacity of 2 000 tonnes. The Parkes, NSW facility uses deframing and NPC's Hot Knife glass separation technology (Fig. 2.2-14); the Dandenong, VIC facility employs shredding and sorting technology; and the Yatala, QLD facility focuses on deframing as of the end of 2024. For reuse, Sircel operates facilities in Parkes and Yatala, each capable of inspecting and testing up to 100 tonnes of modules annually.

In its first year, Sircel processed 10 tonnes of PV module waste and aims to handle modules of all conditions while maintaining high recovery rates. The current technology recovers aluminium, glass, silver, copper, and plastics, with ongoing efforts to develop solutions for silicon recovery. Sircel also processes inverters, solar batteries, and cables as part of its broader electronic waste recycling operations. Modules are collected through council drop-off points and directly from solar farms.

**Fig. 2.2-14 Sircel's delamination equipment in Parkes, NSW**

### Solar Renew

Solar Renew [150], a partnership between Solar Professionals and Kurrajong Recycling, operates a pilot PV module recycling plant in Wagga Wagga, New South Wales. The recycling pilot plant employs semi-automated recycling technology. The system works by delaminating the modules into the main components of glass, aluminium, copper, silicon, and silver, with the process enabling each of the separated materials to be returned or sold into various commodity markets. Fig. 2.2-15 shows an overview of Solar Renew's PV module delamination process. The recycling process begins with mechanical dismantling to separate aluminium frames and junction boxes without damage to the glass. Modules then pass across a heated stage prior to removal of the polymer backsheet, which exposes the wafer and copper tabbing—which is still bonded to the glass. The final separation stage involves the pyrolytic removal of the encapsulant, allowing clean separation of the wafer and tabbing from the glass sheet. A secondary process to mechanically abrade the wafer and tabbing off the glass is being commissioned.

This unique process results in discrete component recovery with no cross-contamination and retains the glass as a whole sheet. As such, this approach maximizes both the recovery rate and value of each component for use in a range of markets such as low-iron float glass for reuse in greenhouses (Fig. 2.2-16) and potentially the manufacture of new PV modules.

With new funding, the company is advancing second-generation commercial recycling technology, aiming for a processing speed of one module per minute, and developing novel environmentally friendly beneficiation processing of the wafer material with the University of Newcastle to recover high-purity silver as well as silicon. Initial results have yielded a silver recovery rate of greater than 90%. Similar results for high-purity silicon recovery are also expected based on early testing, along with the potential to separately recover other components such as copper.


**Fig. 2.2-15 Overview of Solar Renew's PV module delamination process**

**Fig. 2.2-16 Solar Renew's agricultural greenhouse made from recycled PV module glass**

**Lotus Energy Recycling**

Lotus Energy Recycling established Australia's first PV module recycling facility in Melbourne in 2020. Using mechanical crushing and milling, the facility separates materials such as glass, silicon, and metals for repurposing into alternative applications (Fig. 2.2-17).

**Fig. 2.2-17 Lotus Energy Recycling's crushing and milling technology; recovered products on the right**

**Solar Recovery Corporation**

SRC [151] has collected 80 000 PV modules to date, currently stored intact with their aluminium frames still attached. By May 2025, the company plans to establish mechanical recycling facilities in Melbourne (VIC), and Biloela (QLD), each with an annual capacity of 4 600 tonnes. SRC uses patented technology to achieve more than 99% recovery of valuable materials such as silicon, aluminium, copper, and glass. The modules will be processed as part of SRC's sustainable recycling approach, ensuring responsible material recovery and reuse. Removing the aluminium frames will transition the modules to "active waste," which will be managed following proper handling protocols.

**Pan Pacific Recycling**

Pan Pacific Recycling [152], based in Crestmead, Queensland, operates a mechanical PV module recycling facility with capacity up to 240 000 modules annually. The collected modules are sorted based on their type, size, and technology. Different types of PV modules may require slightly different recycling methods.

**Smart Energy Council**

In 2024, the Smart Energy Council (SEC) launched a product stewardship pilot program in Queensland [153], funded by the Queensland Government, to explore the feasibility of collecting, reusing, and recycling PV modules from households and solar farms. The pilot aims to collect 30 000 modules and gather data to inform policies for a nationwide solution.

Six drop-off points have been established across Queensland, allowing PV installers to dispose of PV module waste free of charge. SEC collaborates with Pan Pacific Recycling to handle module recycling and the Blue Tribe Company to test modules for reuse.

Through an online search, other companies in Australia claiming to accept old PV modules include ACE Recycling Group, MDB Solar, Widoph Green, and Solarec.

### (4) Outlook

Fast growing: PV modules have been widely installed across Australia since the 1990s. According to IEA, annual PV installations in Australia reached approximately 4 235 MW by 2023, achieving a world-leading rate of more than 1.33 kW of PV power per person. By the end of 2023, the cumulative installed PV capacity was approximately 34 631 MW, with projections to grow to 50 GW by 2030 and 138 GW by 2050 [139][154]. PV waste generation is also set to increase significantly, with volumes expected to reach 1 GW per year by 2030—primarily from upgrades of distributed rooftop PV systems. Large-scale decommissioning is anticipated to begin post-2030. Across states and territories of Australia, New South Wales (NSW), Victoria (VIC), and Queensland (QLD) are expected to experience the largest annual waste generation. Photovoltaic waste generation is expected to be highly concentrated in densely populated areas, particularly in the cities of Sydney, Melbourne, and Brisbane. The volume of waste is anticipated to grow rapidly, highlighting the urgent need for immediate action by the PV recycling industry [139].

End market and local PV manufacturing: A major challenge for the Australian PV end-of-life industry is finding end markets willing to pay for recycled high-quality materials beyond aluminium frames and copper cables. The lack of a domestic PV module supply chain makes it difficult to identify markets for materials such as glass and silicon. Some businesses are making progress, such as PV Industries, which sold 6 tonnes of glass for reuse in a construction project. However, without consistent demand for these materials, sustaining the recycling industry remains a challenge—limiting the ability to close the loop and achieve a circular economy. One notable government incentive is the Solar Sunshot program, launched in March 2024, which will provide up to 1 billion AUD in funding to build Australia's PV manufacturing capabilities [155]. It is proposed that the program will support the entire PV supply chain, starting with Round 1 on module manufacturing, then Round 2 on other stages of the supply chain—including the end-of-life treatment of PV modules and other components [10]. The promotion of domestic manufacturing could also create opportunities to use materials recovered from PV recycling for new module production, if technologies capable of achieving the required recycling rates and purities are developed. A recent report highlights that enhancing mid-stream processing capabilities will be crucial in integrating recycled materials into domestic manufacturing, reducing reliance on global supply chains [156].

Silver recovery: Silver is the most valuable material in PV modules, particularly in older models with high silver content. Several companies are actively researching less hazardous methods to recover high-purity silver, but these efforts are still in the R&D phase. Over the next 3 years, the commercialization of silver recovery processes is expected to emerge, though challenges in scalability and efficiency persist.

Competition between recycling and offshore reuse: One of the greatest challenges for Australia's recycling industry is competition from the export of end-of-life modules to developing countries for reuse, often without proper testing. The offshore reuse groups typically pay for these modules, whereas domestic recycling companies must charge fees for their services, creating a significant cost disparity. This makes it difficult for recyclers to secure enough volume, which drives up the cost of recycling and limits industry growth.

Funding and industry growth: Between 2021 and 2024, substantial funding has been directed toward advancing PV module recycling and reuse in Australia. This includes 7.2 million AUD for four CRCP projects, 10 million AUD from the NSW Government's Circular Solar program, 10 million AUD from the Queensland Government for PV system recycling solutions, and 5 million AUD ARC Research Hub on PV recycling. These initiatives have also leveraged private funding to support commercialization and implement high-volume processing solutions. The industry is poised to commercialize innovative, integrated solutions and achieve significant growth in the next 3 years.

**Future Outlook**

The outlook for the PV recycling and reuse industry in Australia is highly promising, driven by anticipated government policies, technological advancements, and increasing environmental awareness among consumers and businesses. Financial incentives and industrial collaboration will help establish a strong recycling ecosystem, enabling higher-volume processing solutions and fostering innovation.

## 2.3 North America: United States of America

### (1) Relevant regulations and schemes for EOL management of PV modules

In the United States, PV project owners are often legally responsible for managing end-of-life PV modules under waste management regulations. Similar to any other solid waste, PV modules are managed under the U.S. Resource Conservation and Recovery Act (RCRA). The Toxicity Characteristic Leaching Procedure (TCLP) is EPA's defined test methodology that may be used to determine whether solid waste such as PV modules should be regulated and managed as hazardous waste.

There are no federal regulations specific to PV module recycling, but EPA initiated a rulemaking effort in October 2023 in which PV modules would be added to universal waste regulations, i.e. hazardous wastes that are determined to pose less risk to people and the environmental than other hazardous wastes. [157]. This designation would allow for less-stringent collection restrictions and management requirements compared to fully regulated hazardous waste. Several federal exclusions or exemptions may apply to PV module recycling and may lessen requirements mandated by law. Currently, PV modules classified as hazardous waste may be recycled using the transfer-based exclusion (40 CFR 261.4(a)(24)) in states that have adopted the exclusion and follow the requirements in either the 2015 [158] or 2018 [159] Definition of Solid Waste (DSW) Rule [160][161].[1]

Three states have adopted regulations specific to PV module EOL management. Effective in 2021 in California (SB 489) [162] and in 2025 in Hawaii (HAR 11-273.1) [163], PV modules are designated as universal waste to encourage proper management of hazardous PV modules, which may be either recycled or landfilled by designated universal waste facilities. In 2017, Washington State passed ESSB 5939, requiring PV manufacturers to offer free take-back of end-of-life modules and reuse or recycle 85% by weight [164]. In response to implementation hurdles and industry resistance, SB 5175 was enacted in April 2025 to delay enforcement: manufacturers must now submit stewardship plans by 2030, and starting in 2031, may only sell modules in the state with an approved plan covering free collection and reuse/recycling targets. Several other states have completed or are developing policies and/or studying the issue, for example, North Carolina [165] and New Jersey [166].

Several industry initiatives are emerging to promote recycling or study potential regulatory, policy, and standards options to advance PV circularity. Some module manufacturers offer customer recycling programs, such as First Solar's global PV module recycling program [167]. The Solar Energy Industries Association (SEIA) offers a National PV Recycling Program that connects PV system owners with a vetted network of PV recycling and refurbishment providers [168]. SEIA is also developing three standards related to PV EOL management through the American National Standards Institute (ANSI) [169]. Stakeholder groups are encouraging consumers to use their collective purchasing power to advance circular business practices for clean energy. For example, EPRI's Circular Economies for Energy Technologies Interest Group is exploring the use of environmental product declarations and other product assessment tools in the electric power sector. The Clean Energy Buyers Alliance's (CEBA) Principles for Purpose-Driven Energy Procurement and the Clean Energy Buyers Institute's (CEBI) Beyond the Megawatt Toolkit address waste and EOL management [170].

A recent circular economy roadmap for PV identified several opportunities for PV value chain stakeholders to adopt circular strategies, including: design for recyclability; voluntary labelling of composition; manufacturer take-back and recycling programs; investment in dedicated PV recycling equipment and infrastructure; R&D to improve recycling efficiency, yield, and purity; enhanced end markets for recovered material; workforce development; policies and regulations to simplify recycling logistics; and customer demand signals to promote responsible management [171]. A working group on End-of-Life Decision Making and PV Module Management as part of a National Science Foundation-

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[1] EPA encourages adoption of the 2018 DSW rule; however, it considers the revised transfer-based exclusion in 40 CFR sections 261.4(a)(24) and (25) to be less stringent than the 2015 DSW rule. Therefore, EPA currently does not require states that have adopted the 2015 version to revise their programs. Roughly one-third of states have adopted the entire 2018 DSW rule. More details about state adoption can be found in [161].

supported (NSF) project, **S**ecuring critical material supply chains by enabling ph**O**tovoltaic circu**LAR**ity (SOLAR), discussed the role of voluntary sustainability and environmental quality standards and the need for recommendations on effectiveness in promoting recycling [172]. Two voluntary standards now include criteria specifically for PV:

- The Electronic Product Environmental Assessment Tool (EPEAT) Ecolabel for PV Modules and Inverters is a voluntary industry standard that establishes a framework and standardized sustainability criteria for manufacturers and provides information to consumers [173]. It is primarily a procurement standard but also includes criteria around recycled content, product take-back, and responsible recycling.
- The Sustainable Electronics Recycling International (SERI) Responsible Recycling (R2) standard provides a framework and standardized criteria to aid electronic recyclers in sustainable business practices. It was revised to make the existing standard applicable to PV module materials and recycling processes [174]. The R2 standard creates a label allowing qualified recyclers to be easily identified in the market as providing recycling services meeting a high global standard for data, health, safety, and environmental stewardship.

### (2) Treatment and amount of EOL PV modules

Although the United States does not collect publicly accessible empirical data on EOL PV module volumes, the National Renewable Energy Laboratory's (NREL) PV in the Circular Economy (PV ICE) model estimates about 760 MW of crystalline silicon (c-Si) PV modules were expected to reach EOL in 2022, increasing to more than 1 GW annually by 2030 [175], which translates to nearly 5 million modules per year in 2030 (44 500 t/y), based on PV ICE assumptions for module characteristics and annual deployment (see Fig. 2.3-1) [176]. By 2050, decommissioned c-Si module quantities are estimated to grow roughly an order of magnitude higher to 10.8 GW/y (more than 44 million modules/y; 820 000 t/y). The PV ICE estimates are based on modelled data using information on technology deployment, lifetime, and reliability. It is possible the current volume of EOL modules is higher or lower than modelled predictions. Reasons for PV ICE estimates to underestimate true EOL modules are extreme weather events and economic-driven decisions to retire modules before failure or the end of warranty periods are not modelled.

It is informative to consider the projected EOL amount relative to the capacity to recycle. In 2023, EPRI surveyed 12 recyclers, of which seven c-Si module recyclers and one cadmium telluride (CdTe) module recycler provided capacity and throughput data for their operations [177]. The data are plotted alongside the modelled PV ICE EOL c-Si module projections in Fig. 2.3-1. One preliminary observation is the more than 1 700 MW-equivalent (67 000 t) of existing facility capacity for the seven c-Si module recyclers is sufficient to support the simulated supply of 1 200 MW (44 500 t) of EOL c-Si modules in 2030. However, this comparison may not be accurate for several reasons, two stated here and others in the bulleted list below. First, some of the existing capacity may currently be used to recycle other products and thus may not be available to support future EOL PV module streams. Secondly and conversely, capacity for recyclers that did not participate in the EPRI study—and capacity for new recyclers that enter the market in the coming years—could increase the estimate of available capacity by 2030.

The capacity and throughput data for a subset of U.S. recyclers provide useful insights into the scale of current recycling operations in the United States. Of the seven recyclers that were interviewed as part of the EPRI study, all reported they are actively preparing for growing future demand. Some are adding capacity through construction of new facilities or additional processing lines in existing facilities; some are investing in new equipment and process improvements; several are exploring new PV recycling technologies and separation methods; and efforts are underway to expand business partnerships with material processing companies and upcycling partners. Further data collection and tracking efforts, along with long-term policy and regulation certainty, are needed to improve the accuracy of modeled projections of EOL PV modules. Greater confidence in future demand would support recycler capacity expansion planning efforts and evaluations of circular economy pathways.

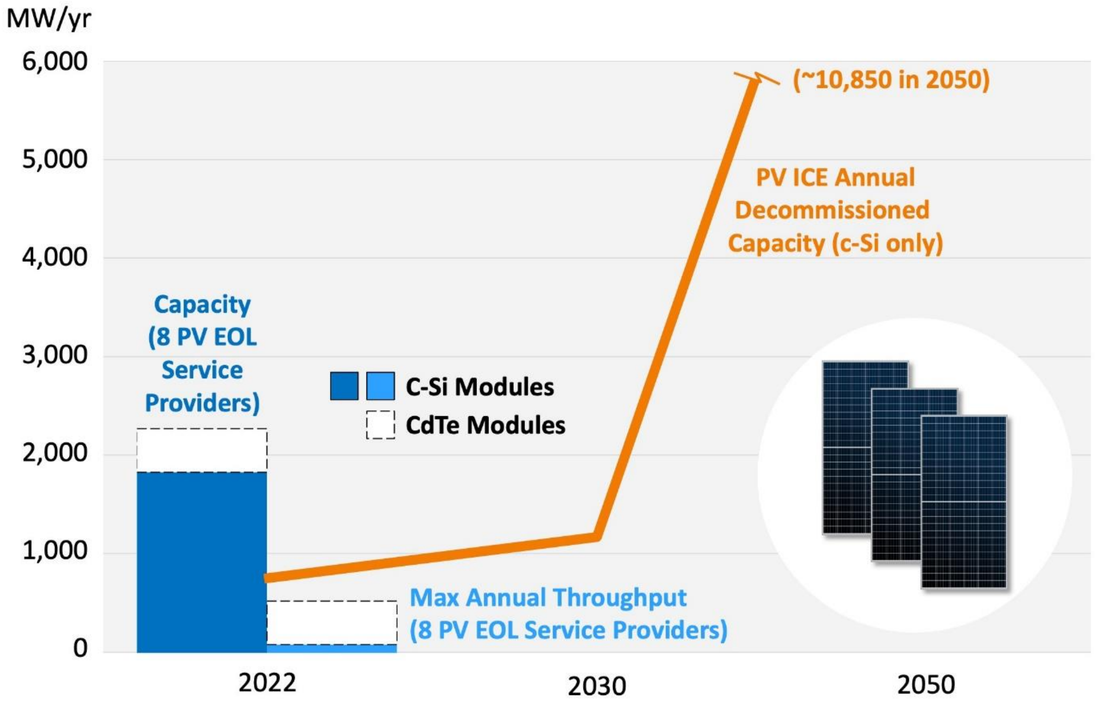



**Fig. 2.3-1 Estimated annual EOL PV modules through 2050 (orange line) and current recycler capacity and throughput by module technology type [177]**

### (3) Companies treating EOL PV modules for recycling

Table 2.3-1 shows a list of 43 companies that the authors of this section understand to accept PV modules or materials for recycling in the United States [20]. This list is based on internet research, selected direct communication, and the professional network of the authors of this section; it is possible some firms recycling PV modules or materials are missing or some included in Table 2.3-1 do not in fact provide these services (e.g., they are recycling facilitators who ship to others for processing).

The 43 identified U.S. recyclers are geographically diverse with facilities in 27 states (Fig. 2.3-2). Several states have multiple facilities operated by various EOL service providers.

**Table 2.3-1 Examples of U.S. companies that accept PV modules or materials for recycling [20]**

| Name | Location | Name | Location |
|---|---|---|---|
| Cleanlites Recycling | OH, SC, MI, MN | PC Recycler, Inc. dba Securis | VA |
| COM2 | IL, WI | Purewafer | CA |
| Commercial Metals Company (CMC) Recycling | TX | PV Solar Recycling | MI |
| Commercial Solar Panel Recycling | NJ | PVRecycling | (no location named on website) |
| Dynamic Lifecycle Innovations | TN, WI | Recycle1234 | CA |
| Echo Environmental | TX | Revive PV | FL |
| Electronic Recycling & IT Asset Disposition Services | CA, CO, IN, MA, NJ, NC, TX, WA | Silicon Specialists | CA |
| EcoRecycle | GA | Silrec Corporation | KY |
| EcoTech Recycling | WA | Solar Recycling | CA |
| Elgin Recycling | IL | Solar Technology and Recovery | TX |
| Everlights | IL, MO | SOLARCYCLE | AZ, TX |
| EVTERRA Recycling | GA, NV, IL, TX | solarpanelrecycling.com | GA, NC, TX |
| Fabtech Enterprises, Inc. | Recycling partners located in AZ, CA, CO, IL, GA, MA, NC, OH, UT, TX | Solarsilicon Recycling Services (SRS) | CA |
| First Solar | AL, LA, OH | Strategic Solar Recycling | (no location named on website) |
| Green Century Electronics Recycling | OR | Surplus Service | CA |
| Green Clean Solar | GA | Sycamore | PA |
| Interco Trading Company | IL | TBF Computing Inc. | GA |
| Metal & Catalyst Resources | TX | The Retrofit Companies | MN |
| METech | CA, CO, MA, NC, UT | United Electronic Recycling | TX |
| Okon Metals | TX | United Scrap Metal | IL |
| Ontility | TN | We Recycle Solar | AZ |
| One Planet | FL | | |

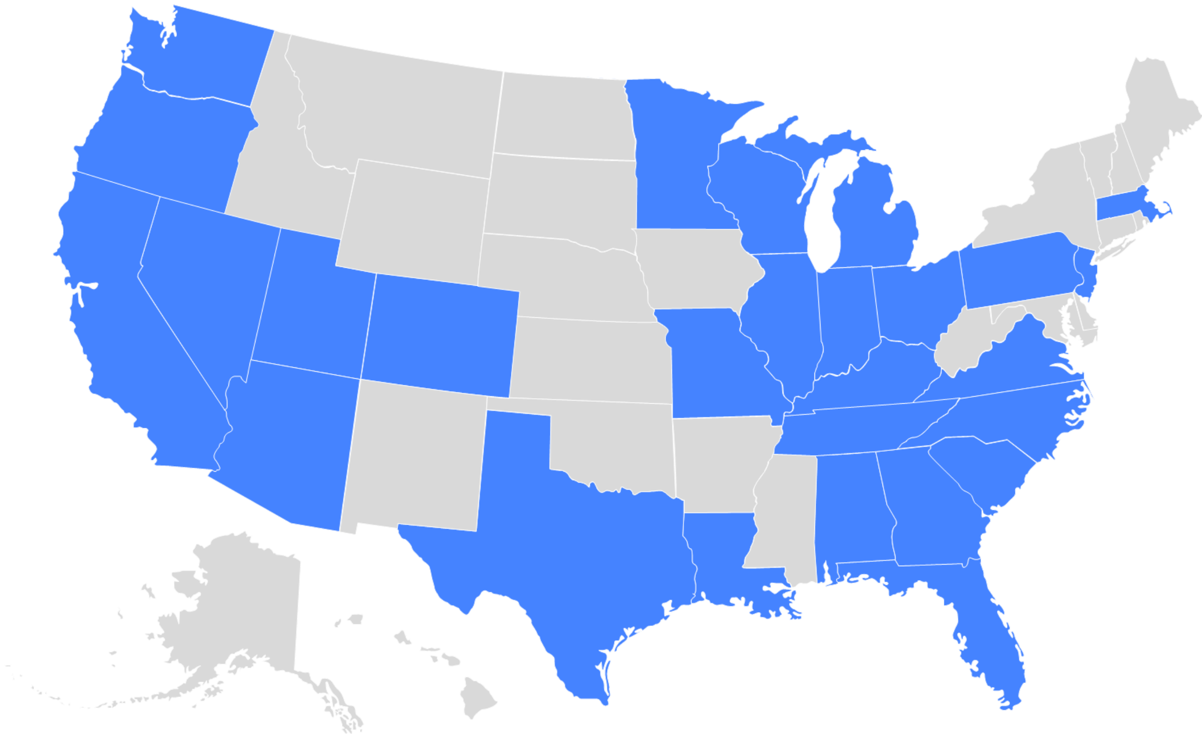


**Fig. 2.3-2 Map showing 27 states where 43 U.S. PV module recycling facilities are located**

**PV module recycling facility operated by SOLARCYCLE**

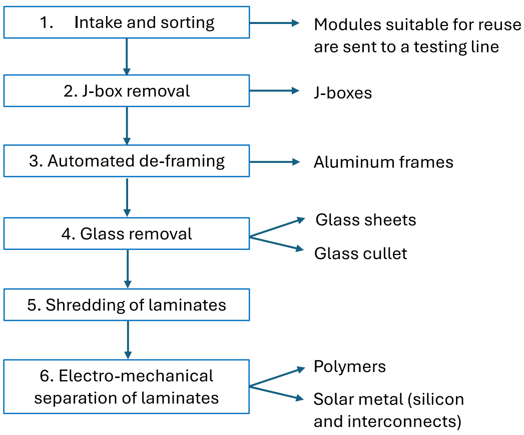
Facility: PV recycling facility owned by SOLARCYCLE, Inc.

Locations: Odessa, Texas; Mesa, Arizona; Cedartown, Georgia

SOLARCYCLE is an advanced recycler of PV modules that was founded in 2022 and currently has three facilities: an Odessa, Texas facility focused on the recycling and reuse of crystalline-silicon (c-Si) modules; a facility in Mesa, Arizona that includes corporate headquarters, an R&D facility, and a thin film recycling line; and a Cedartown, Georgia facility, which is under construction and will include advanced recycling facilities for all types of solar.

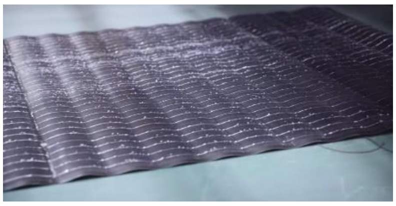
The Odessa, Texas facility has been online since January 2023 and in 2024 processed 500 000 modules. The facility is mostly powered by a 500-kW second-life solar farm comprising a mix of reused commercial and residential modules. This facility is expected to have the capacity to recycle 1 million c-Si modules per year in 2025.

Treatment process:




The Texas facility recycles c-Si modules using a proprietary mechanical process with electro-mechanical separation of secondary materials. As shown, the process begins with intake and sorting of the modules. Those that are suitable for reuse are sent to a testing line, and those that are suitable for recycling have their J-boxes removed and are then sent to an automated tool that removes the frames. Depending on the condition of the module, the glass is removed using different mechanical processes that create either a full sheet or glass cullet. The remaining laminate (composed of encapsulant, cells, interconnects, and backsheet) is shredded, and the materials are separated using an electro-mechanical process that separates the polymers from the solar metal (a mix of silicon, copper, silver, and other metals).


***@Courtesy of SOLARCYCLE***



Of the 12 U.S. recyclers that participated in the 2023 EPRI study, 9 offer in-house recycling services for PV modules, including the laminate, and 3 companies are recycling facilitators that partner with third-party in-house recyclers for some or all recycling steps [177]. Currently, 4 of the 12 participating recyclers have processes that can separate silicon from the other laminate materials, and 2 recyclers recover copper. Of the two companies that recover copper, one reported that sometimes silver can also be recovered; the other reported that trace amounts of aluminium and other trace metals (elements not specified) are recovered. One CdTe module recycler can recover the CdTe semiconductor for use in manufacturing new PV modules. Although process details were mostly not disclosed, four recyclers reported the use of mechanical methods, such as shredders and hammermills, and one also uses chemical separation. A fifth recycler indicated custom machinery is used to cleanly separate glass. Across the 12 participating recyclers, experience processing PV modules ranges from 1 to 20 years, with an average of about 4 years and a median of 2 years. Ten of the recyclers also sell modules for reuse, and six offer repair or remanufacturing services.

The 2022 U.S. Inflation Reduction Act (IRA) included appropriations to support recycling infrastructure authorized under the 2021 Infrastructure, Investment and Jobs Act (IIJA) [178]. The legislation also provided R&D funding to advance PV circularity. In 2023, the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) awarded 10 million USD [179] and announced another 20 million USD in IIJA funding to drive PV technology reuse and recycling, including an 8 million USD award in 2024 to strengthen the U.S. circular economy for PV [180][181]. DOE is also funding two prizes that provide funding to winning teams proposing novel concepts for the following:

1. Promoting registration of inverters and modules with Ecolabel (PRIME) [182]: The prize incentivizes the registration of PV module and inverter products through the EPEAT PV module and inverter ecolabel [173], which references an ANSI Sustainability Leadership Standard for PV Modules and PV Inverters [183]. The ANSI standard includes criteria on end-of-life management supportive of the development of recycling infrastructure and manufacturer take-back programs.
2. Re-X Before Recycling [184]: The prize supports innovations to unlock new or expanded supply chains that can reintegrate end-of-use products into the economy via reuse, repair, refurbishment, remanufacturing, and/or repurposing (“Re-X”) before recycling, including for PV modules and components.

### (4) Outlook

Current estimates for EOL c-Si PV modules in the United States are 87 000 t/y and 820 000 t/y by 2030 and 2050, respectively [175]. The United States has a large and growing number of recyclers that accept PV modules [177]. U.S. recyclers are investing in dedicated PV recycling equipment and processes customized for PV modules, and at least a few companies have developed solutions that recover high-value materials such as silicon, silver, and copper. In addition to recycling, there is growing availability of repair and resale services for EOL PV modules in the United States. Knowledge of available services and capabilities enables informed decision making that can advance the PV circular economy.

The cost of recycling compared to landfill disposal is a significant barrier in the U.S. market. Recycling prices as of 2023 are 14 USD per module or higher [177][185], whereas landfill tipping fees may be as low as 1–5 USD [186]. To improve the value proposition for recycling, high-value recycling technologies must be successfully scaled for commercial application, and material upcycling markets must be established. Uncertainty in current and future regulations and policies for PV recycling and a lack of EOL PV module data (mass, composition, dispositioning plans, and so on) are additional barriers that may be mitigating additional investment in PV recycling programs and infrastructure. Greater certainty in future EOL PV module volumes and management requirements can provide confidence to investors and attract upcycling partners.

# 3 TECHNOLOGY R&D FOR PHOTOVOLTAIC MODULE RECYCLING

PV deployment has accelerated more quickly than expected in the 2010s. This means, in the coming decades, EOL PV module volumes will increase faster than anticipated. To meet and optimize the EOL management of PV module, regulatory and technological approaches—including supporting technology R&D—should be well integrated, and their potential options should be adapted to the conditions of each country or region.

Examining the treatment of EOL PV modules in the market, regardless of whether there are specific waste regulations for PV recycling such as WEEE in the EU, several companies are treating PV module waste for proper EOL management and recycling. However, the current low volumes, recycling technologies, logistics challenges, and undeveloped markets for recovered materials result in high-cost, low-revenue scenarios of PV module recycling. Further improvement in PV EOL processing is therefore needed to meet future demand and to realize high-value and low-cost recycling.

New technologies to improve process efficiency, recovery and recycling rates, cost effectiveness, and environmental performance have been developed by several R&D projects. Most of such R&D projects have been publicly funded.

In this chapter, technology R&D projects for PV module recycling, implemented by public/government funding (including EU funding) in the IEA PVPS Task 12 participating countries, are overviewed.

## 3.1 Trends in technology R&D for PV module recycling

If the numbers of PV module waste are not excessive, the current technological situation will be able to cover the needs for proper EOL management. However, recycling technologies for PV modules need to be further developed and scaled for the mass treatment of PV module waste.

Technology R&D for PV module recycling has been implemented for more than 20 years. Objectives or motivations for such R&D are changing along with changes in PV technology and the market situation, as shown in Table 3.1-1.

Initially, the recycling of c-Si focused on recovering Si cells/wafers to reduce production costs. Subsequently, the recovery of high-value and hazardous materials came to the fore. In the case of thin-film compounds such as CdTe and CIGS, the major focus has been to mitigate environmental impacts by recovering hazardous and valuable materials with consistency and high yield.

Over the past decade, growing concerns over the efficient use of resources and increases in recovery and recycling rates for glass were recognized as economic enablers, as was the recovery of valuable and hazardous materials. The WEEE Directive in Europe accelerated this trend. Since then, recovery of high-weight components at lower costs has been the focus of technical innovations. Recently, recovery of low-weight valuable materials for increasing recovery and recycling rates has been an additional focus. In addition, improving the quality of recovered materials to improve their secondary use is an issue to be addressed.

The scope of PV module recycling technology is also expanding from delamination to metal recovery and will be likely to explore the valuable use of recovered material. Using recovered materials in new PV cell and module manufacturing would be an ultimate target of PV module recycling, whereas impurities and additives are issues to be solved.

Although this report does not explore that topic because of its very early stage of development, fundamental research into perovskite PV cell/module recycling is also beginning.

**Table 3.1-1 Changes in objectives and motivations for PV module recycling**

<table>
<tr><th colspan="2"></th><th>c-Si</th><th>Thin-film compound (CdTe and CIGS)</th></tr>
<tr><td colspan="2">1990s</td><td>Recovery of Si wafers without breakage because the module cost was very high and was dominated by the cost of the Si cell.</td><td>Recovering hazardous materials such as Cd and Se because of environmental issues and recovering rare metals such as Te and In because of the potential resource constraint issue.</td></tr>
<tr><td rowspan="2">2000s</td><td>First half</td><td>In addition to Si wafers, recovering Ag because of high value, and recovering Pb because of environmental issues.</td><td>Recovering semiconductor metals/layers is a major objective, with the issue of resource constraint being less of a concern.</td></tr>
<tr><td>Second half</td><td colspan="2">Recovery of glass is also a major concern to increase the efficiency of resource utilization and to increase the recovery/recycling rate (weight %).</td></tr>
<tr><td colspan="2">2010s</td><td>Recovery of high-weight components, such as glass, at a lower cost is a major aim. However, low-weight valuable components can be recovered if economically justified. Recovering metals at a lower cost is likely to be a major concern.</td><td>Recovery of both high-weight components such as glass and low-weight semiconductor metals/layers at a lower cost is an innovation driver. In addition to increasing the recovery/recycling rates, the quality of the materials recovered is also an issue.</td></tr>
<tr><td colspan="2">2020s</td><td colspan="2">Recovering materials with high purity and high yield and circulating such materials as valuable resources are targets of recycling. Recycling shall be introduced as a part of the PV supply chain and be shifting towards enabling recycling of high-value metals rather than high-weight alone.</td></tr>
</table>

## 3.2 Overview of technology R&D projects for PV module recycling

In this chapter, technology R&D projects for PV module recycling in Europe and other countries are overviewed.

### *3.2.1 Examples of PV recycling R&D projects in Europe*

#### (1) EU funded projects

In 2019, the European Commission (EC) unveiled the European Green Deal, a comprehensive plan to address climate change through specific targeted actions. The goal is for Europe to achieve net-zero greenhouse gas emissions by 2050 [187]. In addition, the plan aims to decouple economic growth from resource consumption. This ambitious project will impact millions of people, and all critical European institutions will be dedicated to its implementation for years. If successful, Europe will become the first continent to achieve climate neutrality [188]. Within the European decarbonization strategy, photovoltaics hold a pivotal position. Challenges include the use of potentially hazardous materials in manufacturing, the energy and resources required for installation, and the proper disposal or recycling of components at the end-of-life.

The European Union has taken significant steps by creating policies and instructions for managing PV modules at the EOL. Extended producer responsibility, introduced by the WEEE Directive, has obliged producers and importers in each European member state to organize the collection, transport, recycling, and financing of these operations for their PV equipment since 2014 [189].

Within this framework, the European Union has also made significant strides in recovering and recycling PV modules, investing in many projects over the past few decades. The Horizon 2020 Work Programme (WP) from 2014 to 2020, as detailed in the previous status report published by the European Commission, included 140 PV projects with an allocation of 455 million EUR. The successor to Horizon 2020, Horizon Europe (2021–2027), is expected to build on this progress and further enhance PV's innovation and demonstration activities [190].

Under these frameworks, some R&D projects have been implemented in Europe, for example, as follows:

- PHOTORAMA
- EVERPV
- RETRIEVE
- FORESi
- RESILEX
- ICARUS
- QUASAR
- APOLLO

Among these, PHOTORAMA, EVERPV, RETRIEVE, and APOLLO are focusing on delaminating PV modules, recovering component materials including cell metals separately, and recycling and purifying such recovered materials for next products such as PV modules. Other projects are focusing on resilient enhancement of silicon supply and industry in Europe. FORESi's target is the recovery of highly pure Si and recycling for wafers, cells, and modules. RESiLEX is targeting sustainable silicon production, Si recycling with high purity, and developing Si usage such as battery anodes in addition to PV cells rather than delaminating technology. ICARUS is targeting recycling various waste through PV manufacturing such as kerf-loss silicon, silica crucible waste, and graphite furnace waste. Such an approach will be effective for developing intended end use of Si recovered from EOL PV modules. Further, QUASAR is focusing on the systematic collection and management of EOL PV modules for reuse/repair/recycling by integrating various technologies and methodologies.

In addition to these technology R&D approaches, Recyclability Index for PV modules has been discussed under the Ecodesign standard.

In this chapter, outlines of these projects are summarized. In addition, some details of R&D projects are shown in the appendix.

**[PHOTORAMA]**

PHOTORAMA (PHOtovoltaic waste management – advanced Technologies for recOvery & recycling of secondary RAw MAterials from end-of-life modules) is a project from May 2021 to April 2025. CEA, France is leading this project and coordinating a consortium of 12 organizations [23].

PHOTORAMA is aiming to i) develop trailblazing technologies to implement a strong and reliable PV recycling scheme, ii) demonstrate innovative recycling solutions with a pilot line that is at TRL 7, iii) demonstrate full circularity by re-injecting the secondary rare materials into cross-sectoral value chains, iv) drive market adoption of technologies as sustainable solutions, and v) strengthen sustainable waste management actions under the European Innovation Partnership (EIP) framework.

Targeted PV modules and targeted recovered materials are as follows:

- Crystalline Si : Aluminium frame, junction boxes, glass and cell metals (Cu, Al, Ag, Si, In (from HJT))
- CI(G)S: Aluminium frame, junction boxes, glass and cell metals (In, Ga).

Recycling technology developed will have following steps (Fig. 3.2-1):

1. Mechanical automated disassembling (frame, junction box)
2. Mechanical delamination using diamond wire cutting (c-Si, especially bi-glass), mechanical delamination using water jet (c-Si), optical delamination using flashlight (CI(G)S)
3. Metal recovery by using leaching process combined with electrowinning (EW).

Key points of this technology R&D are as follows:

- Multi-step pilot line demonstration for full management of c-Si and CIGS, from EOL PV modules to the production of secondary raw materials
- Scale-up of the technologies from TRL 4–5 to TRL 7 operating in an industrial environment
- Demonstration of the reintegration of the secondary raw materials for industrial manufacturing (PV products or other sectors).

Expected nominal capacity of the pilot line will be 1 200 t/y, and targeted recovery rate will be as follows:

- Global recovery rate: 98% including energy fuel from polymer residues
- Metal recovery rate: 95%–98%.

In 2024, PHOTORAMA won the Innovation Awards 2024 at EU Sustainable Energy Week 2024 (European Commission) that “recognise outstanding individuals and projects for their innovation and efforts in the field of energy efficiency and renewables” [191].

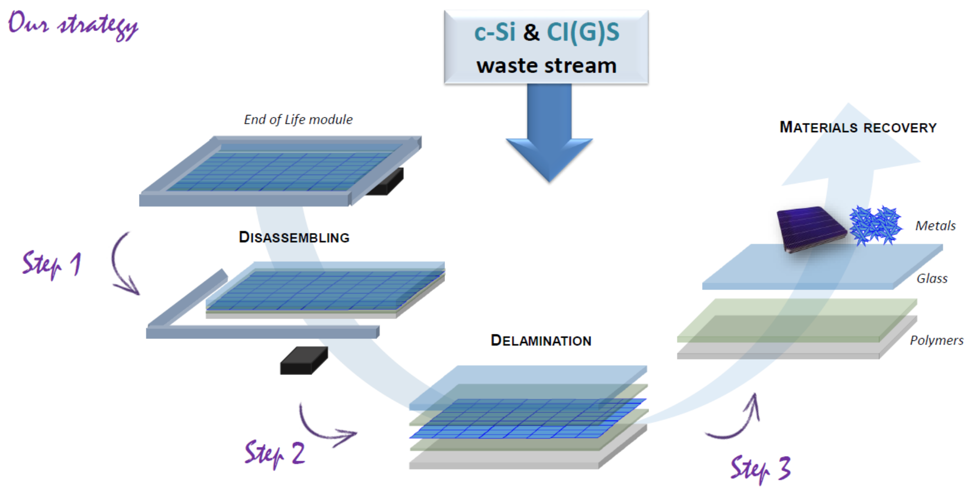



**Fig. 3.2-1 Strategy of PHOTORAMA project [192]**

**[EVERPV]**

EVERPV focuses on highly efficient delamination technologies to recover and reuse metals, glass, and polymers from end-of-life PV modules. This project started in September 2023; CEA, France is leading this project and coordinating a consortium of 16 organizations [193].

Fig. 3.2-2 shows objective and structure of EVERPV project. The objectives of EVERPV are to i) provide Europe with efficient and sustainable technologies for the recovery of end-of-life PV modules, which are high-purity and high-integrity materials, and ii) focus on the delamination step (consisting of separating the various layers of the PV module) because it is a crucial technology at the beginning of the recycling process to achieve high-purity and high-integrity recovery of metals, glass, and polymers.

The crystalline Si module is targeted and several delamination technologies are used and compared, e.g., mechanical by CEA, optical/thermal by ENEA, and mechanical and thermal by 9-Tech. After delamination, metals and polymers are recovered by chemical separation and leaching.

Targeted materials recovered and recovery rates are as follows:

- Glass: recovery rate 100%, recycling rate 100%, 99% purity on 30 kg; scale-up to 30 tonnes
- EVA: 100 kg recovered, 95% purity
- PET: 100 kg recovered, 99% purity
- Fluoropolymers: by-product of PET recycling, recovery and reuse in different applications or back to PV
- Ag: 1 kg recovered, 99% purity
- Cu: by-product – not quantified
- Si: by-product – not quantified.

Two pilot lines are installed during the project: one in France, one in Italy.

- In France: One piece of equipment removes the backsheet from the modules mechanically; another piece of equipment removes cells+EVA mechanically. Backsheet powders generated are treated to produce recycled PET, and fluoride residues are treated and used for other applications. Cells+EVA powders are treated to produce recycled EVA and recycled Ag and silicon. Glass is fully recycled in the flat glass industry.
- In Italy: One piece of equipment removes the backsheet using IR lamps; the rest of the module is pyrolyzed to recover glass and metals. Cu ribbons are recovered and recycled. Ag is recycled, and silicon is a by-product. Glass is recycled in the flat glass industry.

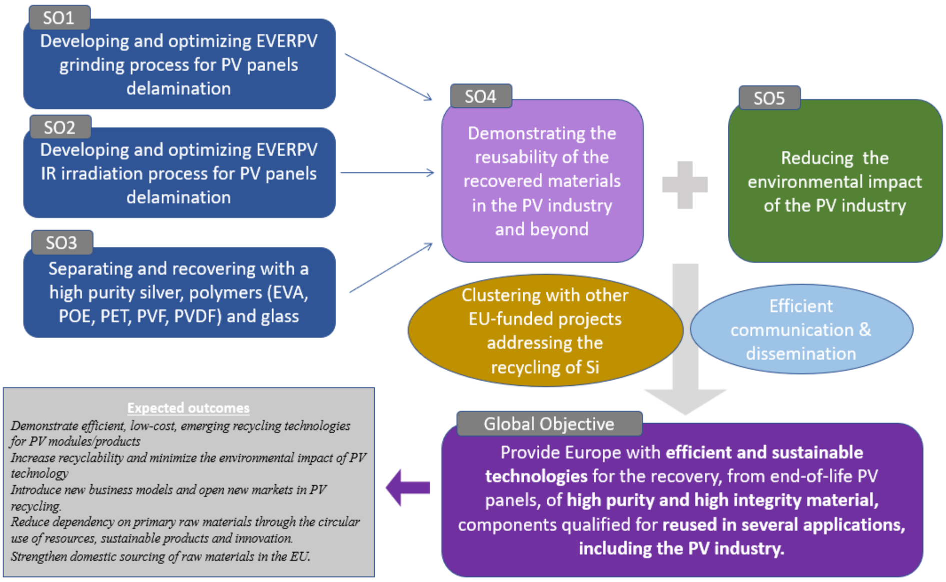



**Fig. 3.2-2 Objective and structure of EVERPV project [194]**

**[RETRIEVE]**

RETRIEVE started in 2023; Institutt for Energiteknikk (IFE), Norway is leading and coordinating this project.

The project aims to i) develop a set of novel and cost-effective technologies for the recovery and upcycling of various material fractions from recycled EOL PV modules, setting innovative pathways to loop glass, silicon, and metal components back into the manufacture of new PV modules, and ii) realize closed-loop recycling of recovered glass from EOL PV modules (Fig. 3.2-3).

Although a delamination (dismantling PV module) process is still not clear, the expected capacity of a pilot plant will be 1 760 t/y, and targeted recovery rates will be as follows:

- Glass: more than 99%; upcycle it back to photovoltaic quality
- Silicon: more than 98%; upcycle it back to photovoltaic quality
- Silver: more than 99%.

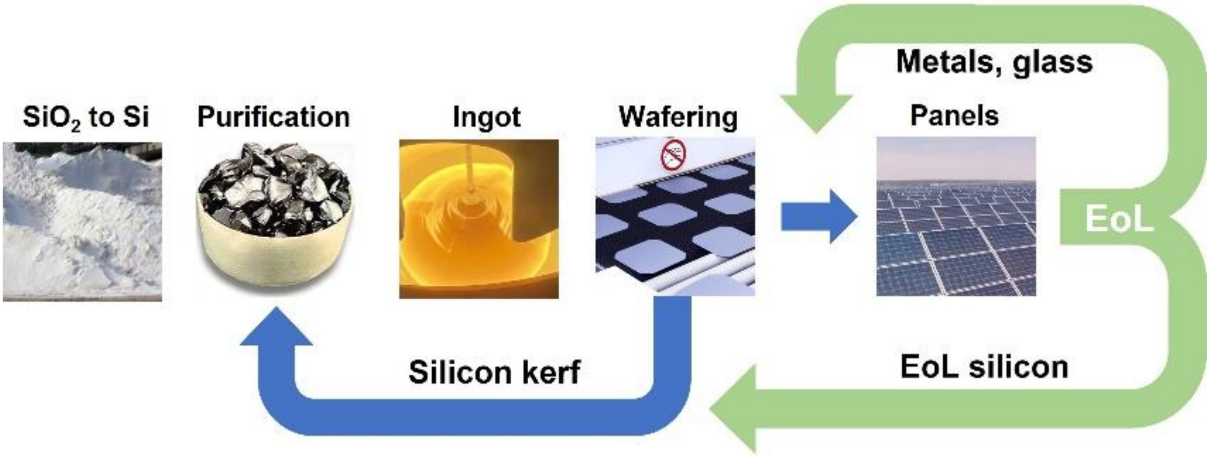



**Fig. 3.2-3 From quartz to EoL modules: Value chains for existing kerf recycling along with materials recycling of EOL PV modules [195]**

**[FORESi]**

FORESi is a 3-year EU-funded project that started in January 2024, led by SiPow AS, Norway, and aims at FOstering a Recycled European Silicon Supply through the world's first industrial demonstration of a cradle-to-cradle silicon value chain.

To contribute to sustainable energy sovereignty for Europe, FORESi will demonstrate a circular recycling process from end-of-life PV modules to new PV and electric vehicle (EV) battery applications. The project will demonstrate the technical, economic, and environmental viability of the entire recycling process and deliver the design of an optimized turnkey recycling factory for end-of-life PV modules, paving the way for European industrial mass production of recycled silicon.

FORESi will also develop an integrated online platform for the collection of PV modules and provide a PV testing methodology for the reuse and repair of EOL PV modules.

Targeting Si recovery from mono- and multi-crystalline Si PV modules, quantitative targets are as follows:

- Demonstrate a fully automated dismantling machine and a novel sustainable process for the recycling of end-of-life PV modules with a target recovery rate of at least 95%.
- Demonstrate the circularity potential of the PV value chain by producing new PV cells with up to 15% upcycled silicon from end-of-life PV modules.

Expected technical innovations are shown in Fig. 3.2-4 and divided into four steps, and a combination chemical and mechanical approach is envisioned to dismantle/delaminate PV modules:

- Step 1, Collection and Logistics: PV Collection Logistics platform (Innovation 1) and PV Testing Process to Reuse and Repair EOL PV modules (Innovation 2)
- Step 2, Recycling: Fully Automatised Dismantling Technology for EOL modules (Innovation 3) and Chemical separation technology for Glass/Si laminate (Innovation 4)
- Step 3, Purification: The Industrial Purification process from different EOL waste scraps to Highly Pure Silicon (Innovation 5)
- Step 4, Production of New Wafers and Modules: Circular PV cells and modules with 15% recycled Silicon from end-of-life PV modules (Innovation 6).


**Fig. 3.2-4 Expected innovations under the FORESi project [196]**

**[RESiLEX]**

RESiLEX (Resilient Enhancement for the Silicon Industry Leveraging the European matrix) is a project starting June 2022. RESiLEX covers the full value chain of the Silicon and Iberian Sustainable Mining Cluster (ISMC); Spain is leading this project [197].

The general objective of Project RESiLEX is to demonstrate innovative, industry-driven technological and business solutions covering the full silicon value chain to improve the resilience and sustainability of this critical raw material value chain in Europe.

Under the objective, RESiLEX will develop technological solutions for reusing silicon, recycling PV modules, and designing new products in the fields of mining, solar, and batteries.

Among technical WPs, e.g., WP2–6, main key points are shown in Fig. 3.2-5:

- Critical raw materials from waste:
  - ➢ Mining activities, mining waste and acid waste waters, recovery of critical raw materials
- PV modules from recycled silicon:
  - ➢ End-of-life PV modules or kerf, recycling treatment and purification, ingots from recycled silicon, wafers and PV cells
- Anodes for batteries:
  - ➢ End-of-life PV modules, recycling treatment and purification, silicon-based anodes.

Regarding WP5, to substitute primary silicon source in major applications such as silicon wafers or anodic materials, a target recovery rate of a highly efficient silicon recycling process from EOL PV modules is up to 97%.

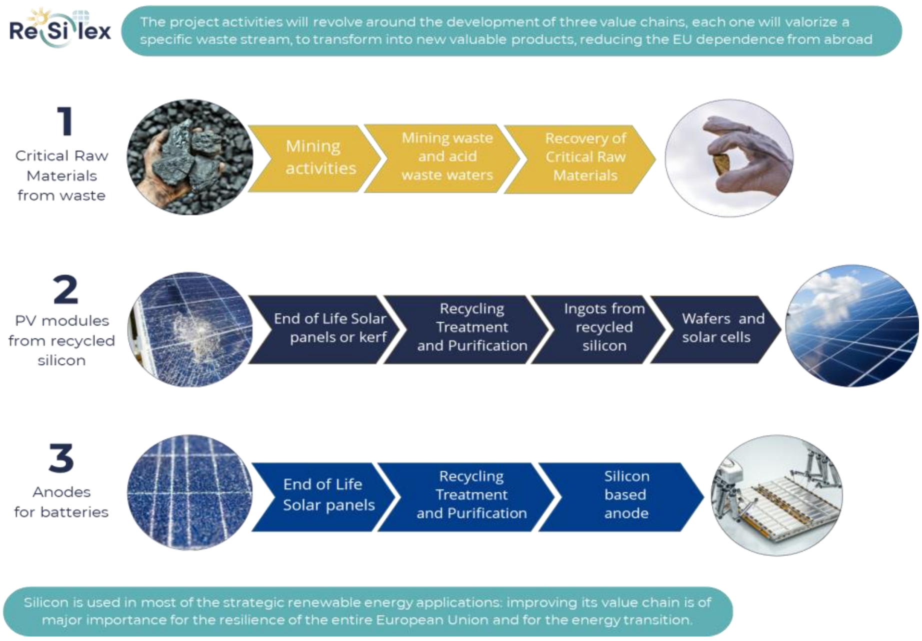



**Fig. 3.2-5 Main key points of RESiLEX project [source: provided by the project coordinator]**

**[ICARUS]**

ICARUS focuses on innovative eco-efficient processing and refining routes for secondary raw materials from silicon ingot and wafer manufacturing for accelerated use in high-end markets. This project started in June 2021; SINTEF, Norway is leading this project [198].

Because the production of photovoltaic modules generates significant resource flows—much of which becomes waste, including kerf-loss silicon, graphite, and silica from ingot production−ICARUS aims to turn this waste into valuable secondary raw materials:

- Enable the recovery of >95% of high-value material from ingot and wafer manufacturing
- Scale-up modular solutions to process, recycle, and refine and transform Si-kerf into valuable raw materials
- Develop industrial symbiosis by providing processed and refined material to further high-end applications
- Ensure the implementation of the project's outcomes in the real world.

Regarding recycling PV manufacturing waste from silicon ingot and wafer manufacturing: Kerf-loss silicon, silica crucible waste, and graphite furnace waste, quantitative targets are as follows:

- Recovery rate >95% for silicon, silica, and graphite
- Refined silicon achieving solar-grade purity 6–9N

To achieve these targets, four industrial pilots are demonstrated, as shown in Fig. 3.2-6:

- Industrial pilot A: Make the ingots manufacturing industry waste-free: Collection, sorting, purification, and pretreatment of kerf-loss silicon, silica, and graphite waste products delivering various intermediate products for further processing.
- Industrial pilot B: Integrating closed-loop value chain in a solar silicon route: Agglomeration of silica and kerf-loss silicon into briquettes, with subsequent carbothermic reduction of briquettes in a submerged arc furnace producing metallurgical grade silicon. Thermal and chemical refining of metallurgical grade silicon to solar grade silicon.
- Industrial pilot C: Enabling industrial uptake—controlled conditioning of silicon: Thermal treatment of kerf-loss silicon for impurity removal based on kerf-loss silicon powder feeding, melting, solidification, and granulation targeting solar-grade-purity silicon.
- Industrial pilot D: Si-waste-to-material: Chemical conversion of kerf-loss silicon into green hydrogen and silicate (water glass).

By reusing these recycled materials, the project helps prevent waste generation and promotes resource efficiency. In addition, ICARUS enhances the raw materials knowledge base by creating a comprehensive waste inventory for silicon kerf, graphite, and silica, supporting future advancements in recycling technologies.

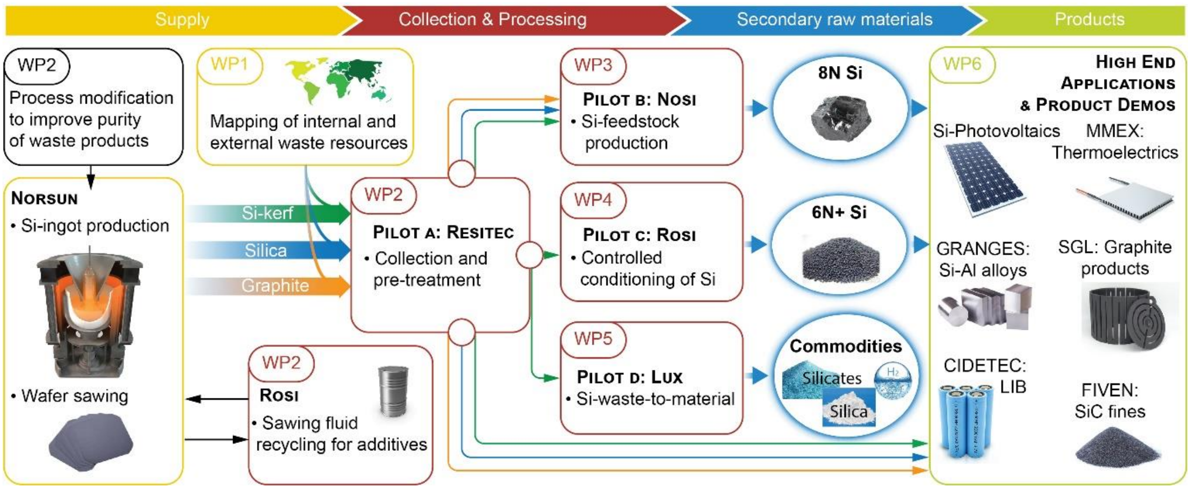



**Fig. 3.2-6 Overview and structure of ICARUS project [provided by the project coordinator]**

**[QUASAR]**

QUASAR is aiming to develop and implement solutions for the systematic collection and management of EOL PV modules, integrating various technologies and methodologies, as shown in Fig. 3.2-7 [199]. This project started in September 2023; SINTEF, Norway is leading this project.

- Involving all stakeholders across the EOL supply chain

- Incorporating concepts of reverse logistics technologies, AI/machine learning, and product lifecycle information management (PLIM) using digital twins
- Implementing best practices for sorting, warehouse operations, testing, and repair/reuse.

QUASAR will foster:

- EOL decision support: assessing PV condition for reuse/repair/recycling
- Repair technology solutions: diverting 50% of the PV waste from the recycling path
- Recycling technologies: enabling high purity of raw material for reuse in various industries
- Closed-loop systems: facilitating a circular economy for the PV industry.

QUASAR will up-scale and demonstrate emerging recycling technologies such as the following:

- Pyrolysis and chemical treatment
- Waterjet delamination

Expected recycling treatment capacity will be 17 500 t/y. Recycling rates are ≥90% for Si, ≥90% for Ag, ≥90% for polymers, and ≥80% for glass cullet suitable for PV and float glass manufacturing and ≥95% for intact glass panes for direct reuse, resulting in expected revenue from recycled materials of 400–650 EUR/t.

In addition, as other indicators, reduction of decommission costs: 20%, PV module inspection cost: <5 EUR per module, and module repair costs: <7.5 EUR per module are targeted.

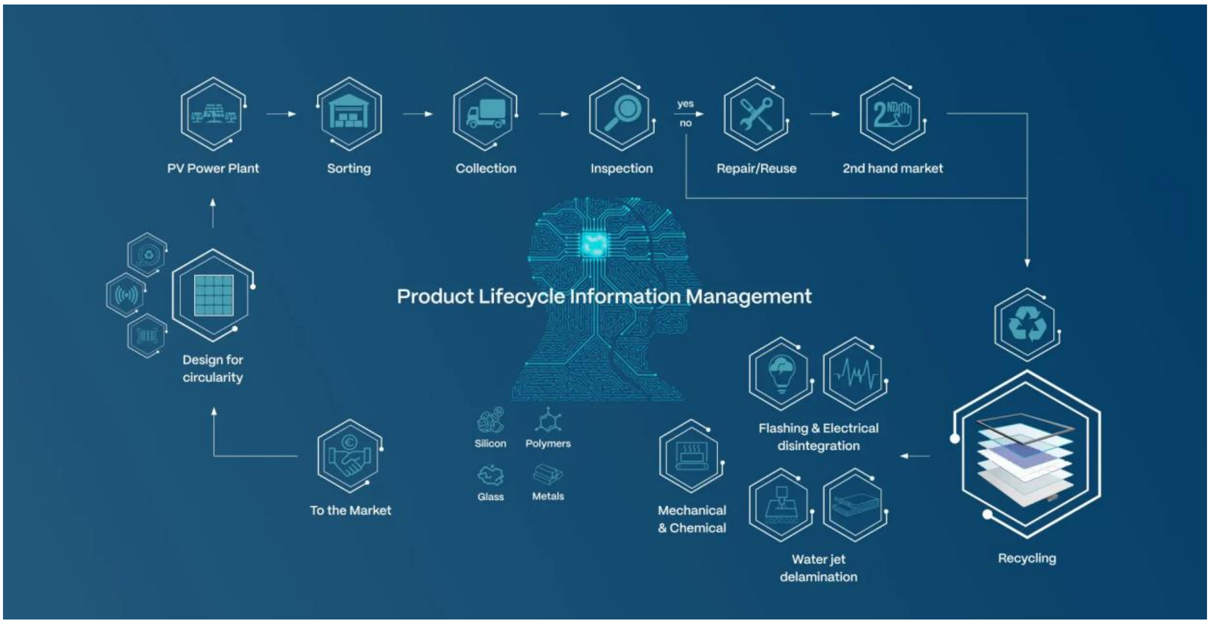



**Fig. 3.2-7 Product lifecycle information management proposed by QUASAR project [199]**

[**APOLLO**]

APOLLO is a three-year project running from 2024 to 2026, coordinated by Fraunhofer Gesellschaft (Germany), with a consortium of 18 partners from nine countries [200]. The project aims to establish a pilot line at APOLLO Micro Factory to process 40 tonnes of EOL crystalline silicon PV waste, recovering enough material to produce 1 tonne of remanufactured solar-grade silicon. From recovered material, project partners will remanufacture 30 new demonstration PERC c-Si and tandem Si–perovskite modules. APOLLO targets an increase in overall material recovery from 18% to 93% (by weight).

APOLLO’s key goals are to:

- Establish a circular PV-waste value chain
- Prove a continuous ultrasonic “sonification” hydrometallurgy that quickly separates Si, Ag and Cu,

- Refine Si to ≥ 99.999 9 % purity for new c-Si and perovskite/Si tandem devices
- Produce recycled glass cullet from EOL PV modules to use in flat glass manufacturing
- Trace every fraction of recovered content via a block-chain Digital Product Passport

APOLLO integrates a suite of innovative technologies, including:

- Optical and mechanical sorting to categorize materials by glass composition
- Crushing, ultrasonication, froth flotation, and electrostatic separation for efficient delamination and silicon/metal recovery
- Acid leaching and gas-phase purification to upgrade recovered silicon to ≥99.999 9% purity
- Ingot casting and PV remanufacturing using recycled materials
- Blockchain-based DPP

The project will also generate quantitative data for life-cycle assessment, techno-economic analysis, and tear-down analysis to inform future regulatory and design-for-recycling standards.

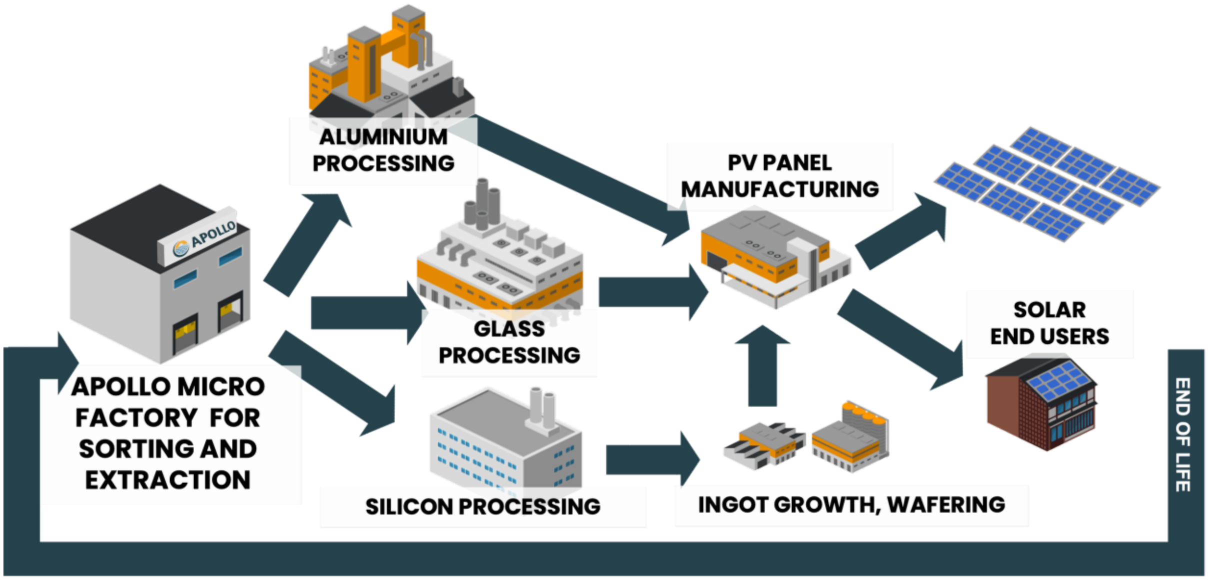



**Fig. 3.2-8 A schematic of the APOLLO Micro Factory from the APOLLO project [200]**

**[Recyclability Index]**

The European Climate, Infrastructure, and Environment Executive Agency (CINEA) has commissioned a study for the development of recyclability indexes for photovoltaic products (PV modules and inverters).

This study is developed in a comprehensive European policy context to reduce the generation of waste, the consumption of resources, and the associated environmental impacts of electric and electronic products, including PV modules and inverters:

- The Waste Electric and Electronic Equipment Directive (WEEE) 2012/19/EU
- The Circular Economy Action Plans (December 2015 and March 2020) (CEAP)
- The Ecodesign Directive (2009/125/EC) (ED) and the new Ecodesign for Sustainable Products Regulation (ESPR)
- The Energy Labelling Framework Regulation ((EU) 2017/1369) (EL)

Moreover, relevant standardization activities in this field have been performed by standardization committee "CEN/CLC/TC 10 - Energy-related products - Material Efficiency Aspects for Ecodesign" with the publication of EN 45555:2020 - General methods for assessing the recyclability and recoverability of energy-related products.

Potential policy application for these recyclability indexes for PV modules and inverters could include a compulsory disclosure of the indexes for each PV module model/inverter model placed on the EU market, as an effect of ecodesign and/or energy labelling measures.

The study has the following objectives:

- The analysis and development of scoring systems (indexes) for the recyclability of PV modules and inverters (the systems for each of the two products can differ)
- Calibration and validation of the scoring systems on real products.

The proposed methodology aims to create a recyclability index for PV modules and inverters, reflecting a significant stride toward enhancing sustainability in the photovoltaic industry.

The methodology will encompass the identification of priority parts based on material relevance and recyclability, the determination of key parameters for recycling, the establishment of a scoring criteria, the definition of recyclability score classes for photovoltaic modules and inverters, and the calibration and validation of the method.

### (2) Projects in European countries

In addition to the EU funded projects above, several R&D projects have been conducted in each country. In this section, examples of projects implemented in the following countries are overviewed:

- Italy
- Spain
- Austria
- Sweden

**[R&D project in Italy]**

Italy is a part of the multilateral initiative "Mission Innovation" at an international level. This initiative aims to advance technological innovation to support the shift to clean energy by increasing public funding for cleantech research. Consistent with this initiative, the IEMAP (Italian Energy Materials Acceleration Platform) project aims to establish an experimental and computational infrastructure to rapidly design and select advanced materials for energy purposes.

A key focus of this project is to develop new and sustainable methods for recycling PV modules. Targeting glass-covered c-Si PV modules, delamination treatment based on thermo-mechanical (IR) technology, and recovery of PV cell metals by hydrometallurgical approach are experimented and optimized. In addition to glass, recovery of polyester from sheet, and Ag as AgBr and Cu as $CuC_2O_4$ from PV cells are targeted. A prototype for processing has been developed based on an ENEA Beta-Tech Srl patent. This process, known as "light thermal," aims to minimize destruction and maximize recovery, including the EVA and the backsheet. With this patent, the goal is to recover 100% of the main components of the modules while minimizing energy consumption and gaseous emissions.

Fig. 3.2-9 show an expected flow chart regarding PV module recycling in this project.

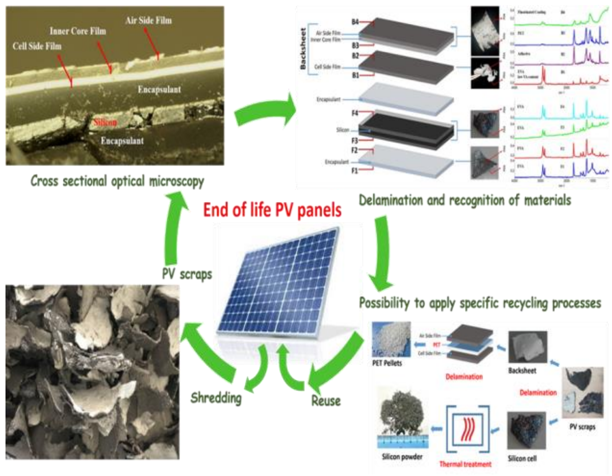



**Fig. 3.2-9 Flow chart of the activities regarding recycling PV of project IEMAP (program Mission Innovation) [201]**

In addition, under EIT RawMaterials, which is initiated and funded by the EIT (European Institute of Innovation and Technology) and is the largest consortium in the raw materials sector worldwide, the EIT Regional Innovation Scheme (RIS) was founded to meet the diverse innovation needs of eligible countries, integrate potential new partners and participants from the local innovation ecosystem in EIT Community activities, and promote a new economic point of view: the circular economy.

In this framework, The PARSIVAL (PAnels Recycling to create SIlicon VALue chain) project is a direct result of the RIS because it addresses the challenge of PV module waste and promotes the creation of a circular PV value chain in Apulia (Italy) and Extremadura (Spain). This project could transform the current situation and pave the way for a more sustainable future.

During the project, innovative technologies are developed for the reuse of low-efficiency PV modules after reconditioning and the recycling of end-of-life PV modules. The proposed technology focuses on recycling all valuable materials in PV modules (aluminium, glass, copper, silver, and silicon PV cells) as shown in Fig. 3.2-10; the project also aims to study the end market to reuse and value the recovered materials. Three applications are analysed: batteries, ferroalloys, and PV cells. Finally, the project has assessed the feasibility of constructing a PV module reconditioning and recycling plant in the areas under consideration and contributes to creating a network of professionals in the sector.

Recycling processes comprise removal of the aluminium frame and terminal box, heat treatment for combusting EVA, mechanical separation of Cu ribbon and Si cells from glass, and hydrometallurgical treatment of Si cells using ultrasound to recover Ag. Target indicators for R&D are recovery rate: 87%; energy consumption: 100 kWh/t; and cost for industrial plant: 180 EUR/t.

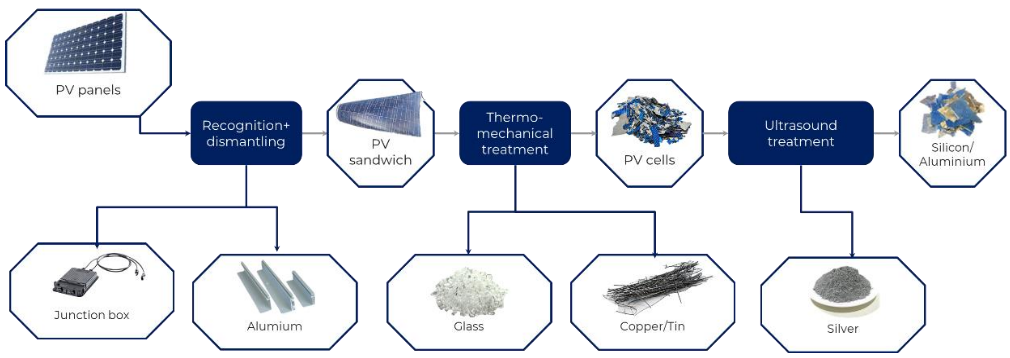



**Fig. 3.2-10 Treatment processes proposed of PARSIVAL project [202]**

**[R&D project in Spain]**

In Spain, there are two nationally funded projects regarding EOL PV modules.

Circularity of Photovoltaic systems by Recycling, Repairing and Reusing photovoltaic modules (FOTOVOL3R) aims to contribute to the circularity of PV systems through the analysis of Recycling, Reparation, and Reutilization of PV modules, considering the life cycle analysis and public perception. From a viewpoint of technical R&D, repairing modules by using mechanical methods and characterization of selected repaired PV modules in the laboratory and real installations are main focuses, rather than concrete recycling technology development.

Fig. 3.2-11 shows an image summarizing FOTOVOL3R project.

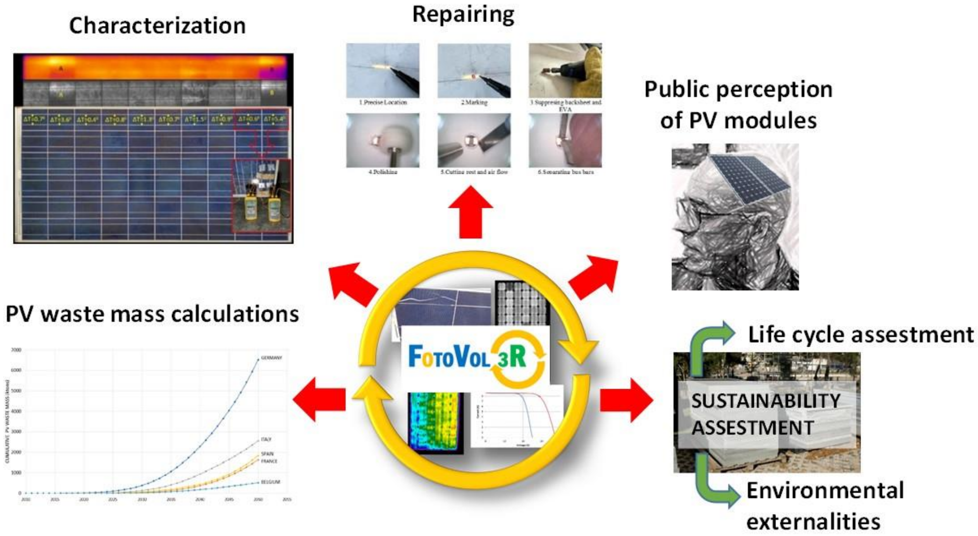



**Fig. 3.2-11 Image summarizing FOTOVOL3R project [203]**

Recycling of silicon for new solar generation (RESILIENS) aims to develop a PV cell recycling process that allows the recovery of Si and metals from discarded PV devices and reuse them in the manufacturing of new PV cells with a minimum number of intermediate steps, energy, and material consumption in the process. A chemical route for the recovery of metals and Cz crystallization for the recovery of the silicon are targeted. Alkaline treatments are optimized following a careful design-of-experiments process, allowing for complementary removal and recovery of metals from front and rear contacts without damaging the quality of the demetallized substrates. Monocrystalline wafers are grown from silicon fragments of old multicrystalline wafers showing improvements in lifetime values after a phosphorus diffusion gettering conditioning process, rendering them compatible with high-efficiency PV cell architectures.

**[R&D project in Austria]**

To improve the treatment of PV module waste, the PVReValue - Holistic recycling of PV modules project is implemented. Targeting crystalline Si modules comprising both glass-backsheet and glass-glass modules, the overarching intention of PVReValue is to develop a holistic processing and recycling process for PV modules with the following steps - i) input characterization, ii) composite separation, iii) processing, iv) output characterization, and v) recycling of the output fractions—to achieve a recycling rate of more than 95% by weight.

Fig. 3.2-12 shows an overview of PVReValue project. As part of fundamental research, various methods for delamination such as water jet, milling, thermal treatment, dielectric heating, and laser are tested. In addition, combinations of further mechanical and chemical methods for recovery of high-quality recyclable secondary materials are examined.

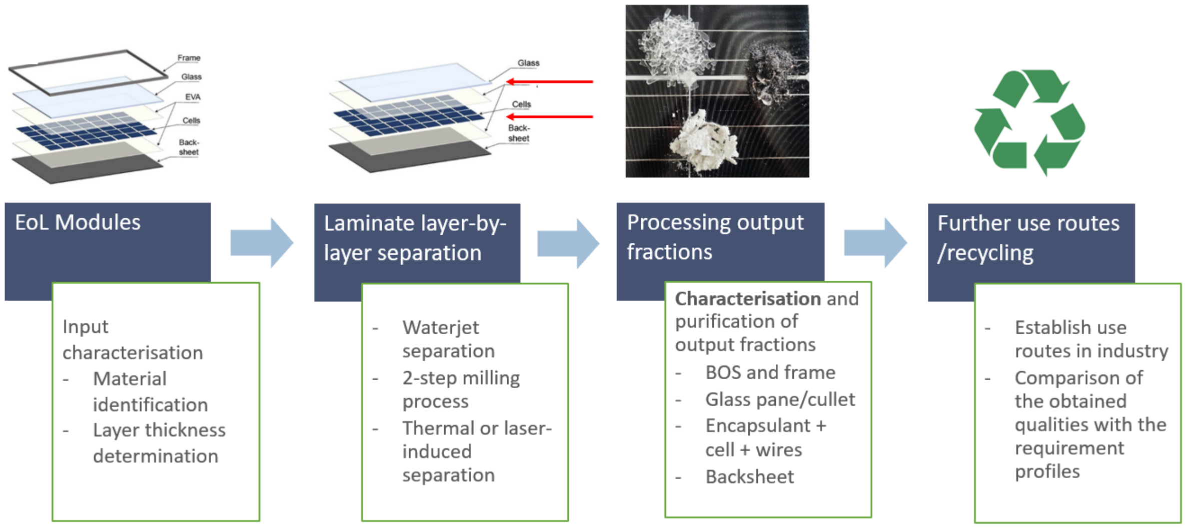



**Fig. 3.2-12 Overview of the workflow of PVReValue [204]**

**[R&D project in Sweden]**

One project implemented in Sweden is focusing on recovering valuable metals from PV cells—e.g., Ag from c-Si module—and Ag, In, Ga, and Mo from CIGS cells. The project covers thermal, mechanical, and supercritical fluid treatment for delamination, hydrometallurgical treatment for metal recovery.

In addition, although it seems to not be concrete technology R&D, two projects for circular PV module management (CircSolar) and developing circular management of PV modules and wind turbine blades (SolVind) are conducted. The CircSolar project aims to develop a proposal for the circular management of PV modules, primarily using thermal/mechanical treatment of mono-crystalline Si modules.

### *3.2.2 Examples of PV recycling R&D projects in Asia and the Pacific*

#### (1) Japan

In Japan, to realize high-value recycling, R&D projects to find solutions are conducted under the NEDO project, funded by the Ministry of Economy, Trading and Industry (METI) [119].

National technology R&D for PV module recycling started in 2010 in Japan. Since then, some projects were carried out and several technologies have been operated commercially (Fig. 3.2-13).

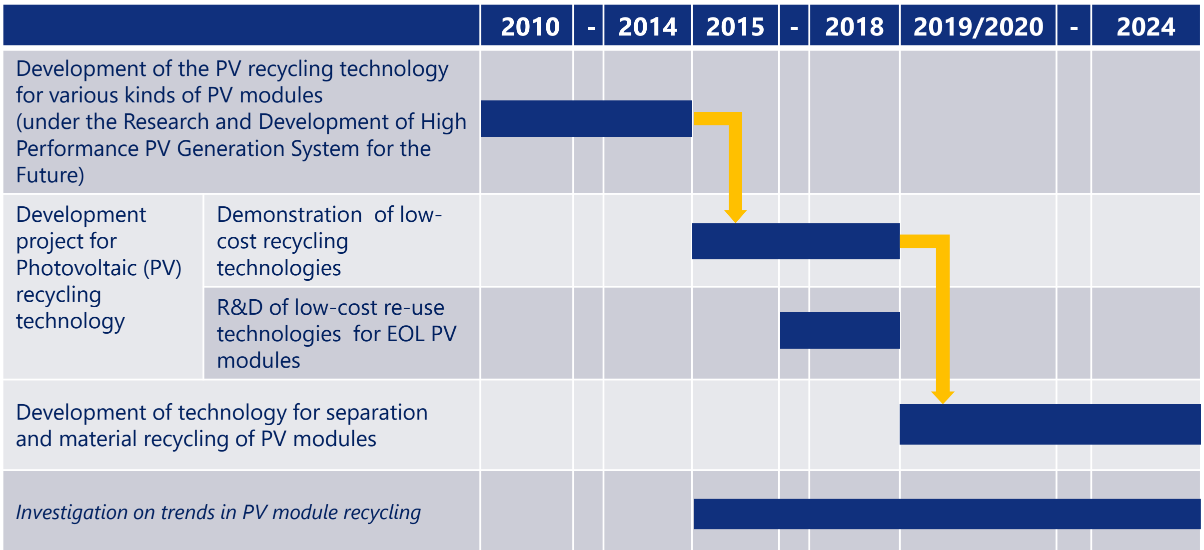



**Fig. 3.2-13 History of PV recycling R&D by NEDO, Japan**

To further improve current technologies, two projects have been implemented since 2020.

One is implemented by Solar Frontier K.K. The "Separator," e.g., mechanical method, is used to delaminate the PV module structure. This technology is available for both CIGS and crystalline Si PV modules. After separating glass as full size (unbroken), PV cell metals and polymers are recovered using a chemical method.

The other project is pyrolysis technology for crystalline Si PV modules, implemented by Tokuyama Corporation. Tokuyama is attempting low-temperature pyrolysis using special catalyst. Full-size glass recovered by the pyrolysis can be recycled for float glass manufacturing [121].

Under the project plan by NEDO, these two projects have the same targets regarding material recovery rate and net-treatment cost:

- Material recovery rate: >80%
- Net-treatment cost: <3 JPY/W, supposing 200 MW/year treatment, corresponding to 15 000–16 000 tonnes.

#### (2) China

Under the National Key R&D Programme, "Key Technologies and Equipment R&D for Circular Economy," as a Key Special Project in 2023, the project "Integrated Technology & Demonstration of Efficient Circular for Recycling of EOL PV Laminated Parts (Application Demonstration Category)" was set up.

The research portion of the project focuses on solving the problem of efficient dissociation and clean remanufacture of EOL crystalline silicon PV laminates and is committed to the R&D of a complete set of chemical technology solutions.

- Researching and developing standards and policy recommendations of PV module recycling and PV product carbon footprint.
- Building a PV industry carbon emission database and carbon footprint accounting system.

- Researching and developing PV module recycling technology and equipment and demonstrating the application of PV module recycling.
- Promoting the PV module recycling on an industry scale, standardized development, and helping China's PV industry with green and low-carbon development.

This project was initiated at the end of 2022, formally launched at the beginning of 2023, and is currently in the research stage. However, research progress and results related to the project have not yet been made public.

### (3) Australia

In Australia, a political approach to regulate PV module EOL treatment is likely to be enforced in several years. Although a few companies for PV module recycling are already operating, to prepare for upcoming mass treatment, high-efficiency and high-value recycling technologies are expected.

Currently, the University of New South Wales (UNSW) is leading three technology R&D projects.

The first project is to develop a delamination technology combining thermal (pyrolysis), mechanical, and chemical methods. The project, granted by the Australian Renewable Energy Agency (ARENA) (2020/RND015 1.36 million AUD, plus 0.55 million AUD industry cash contribution), aims to develop a highly efficient, low-cost, closed-loop recycling system to recover valuable metals and silicon from EOL PV modules, leveraging interdisciplinary expertise in pyrolysis and hydrometallurgy, PV, and off-gas/wastewater treatment, in collaboration with industries in Australia and overseas. Target materials and indicators are i) recovery rate: >95% of Ag, Cu, and Si from crystalline Si PV cells and ii) energy consumption: <25 kWh/kW.

In addition, UNSW is trying to develop a mobile equipment fitting into transportable containers together with other universities, under granting by New South Wales Environmental Protection Authority (NSW EPA) (2021/CSEO00010 1.0 million AUD, plus 0.41 million AUD industry cash contribution) [205]. Thermal, mechanical, and chemical methods are adopted, and the project targets more than 95% silver, copper, silicon, and glass recovery; energy consumption at less than 30 kWh/kilowatt-peak (kWp); and a stable run greater than 8 hours. After lab-scale fundamental studies, the reactors will be scaled-up to pilot and then virtually trialed through simulations to industry scale for fitting into transportable containers with an optimized layout.

Recently, UNSW received another major R&D initiative on PV recycling funded by the Australian Research Council - ARC Research Hub for Photovoltaic Solar Panel Recycling and Sustainability (PVRS) (IH240100012), which is the world-first research hub on PV recycling, funded by Australian Research Council (ARC) in July 2024 with 5 million AUD cash contribution and worldwide participation organisations of Industries, Universities and Institutions with 8.6 million AUD cash contribution. The Hub aims to transform Australia's photovoltaic solar panel recycling industry by developing advanced technologies of green PV recycling and materials reuse, redesigning PV panels for recycling and reliability and advancing policy informing by leveraging interdisciplinary expertise and collaborations across the value chain. It directly addresses Australia's National Net-Zero Plan and Waste Action Plan. Outcomes expected are industry translations of scalable PV recycling solutions and new panel designs, new supply chains, and Australia's R&D critical mass and workforce training, with environmental and economic benefits of PV waste reduction, new jobs and markets of onshore recycling chain and sustainable energy security in Australia.

Swinburne University of Technology is working to provide a novel technology solution that contributes to the production of solar-grade silicon (99.9999%) from secondary silicon raw materials, under ARENA's grant. Fig. 3.2-14 shows a recycling process proposed. The pyrometallurgical process to be investigated involves the application of external electricity through electrodes placed across molten silicon and slag phases. This technology could remove impurities (such as B and P) at faster rates and higher amounts compared to the regular refining or current Si production process and promote the recovery of high-value precious metals (including Ag paste) from EOL PV, making the overall recycling process economically attractive. Target materials are Si and Ag, and quantitative targets are impurities removal (>90%) such as phosphorus and boron, and Ag recovery in Si (>90%). Equilibrium and kinetic experiments will be conducted at laboratory scale, and a pilot-scale reactor will be designed, constructed, and tested.

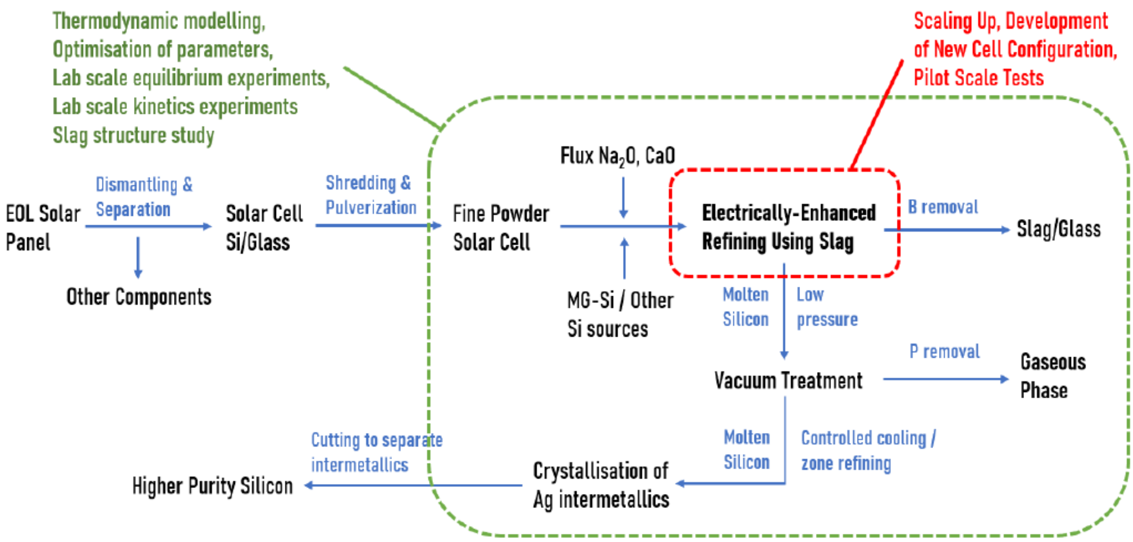



**Fig. 3.2-14 Recycling process proposed by Swinburne University of Technology**

The NSW EPA's 10 million AUD Circular Solar Grant Funding Program significantly boosted the state's solar recycling capacity by 10 000 t/y, supporting the construction of three new recycling facilities (in Greater Sydney and regional NSW), a reuse project, and an R&D project. Key projects include PV Industries (scaling to 8 000 t/y), Sircel (2 000 t/y, >90% material recovery), and Blue Tribe (diverting 10 000 reusable panels by 2030). Innovations emerged, such as UNSW's mobile recycling technology, Blue Tribe's portable testing for reusable panels, and Sircel's advanced global recycling solution. The program also fostered secondary markets (e.g., glass repurposed for construction) and cost-effective logistics networks, while creating jobs and partnerships across the supply chain. Collectively, these efforts aim to divert 12 000–20 000 tonnes of solar panels and 800 tonnes of batteries annually from landfills.

Another 7.2 million AUD was funded by Department of Industry, Science and Resources to support three industry-lead CRCP research projects to commercialise new solar panel recycling technologies at industrial scale. Lead recipients include PVIndutries, Elecsome, and Solar Renew.

# 4 SUMMARY AND CONCLUSIONS

The amount of PV module waste is gradually increasing worldwide, regulations have become or are likely to be implemented in several regions, and new facilities and equipment for PV module recycling—mainly for delamination—are being operated. In addition, several R&D projects for high-value recycling and circulating materials have been implemented.

This report provides an overview and update of the status of PV module recycling in two main chapters, based on contributions by IEA PVPS Task 12 members. First, regulatory schemes, information on PV module waste and relevant companies, and the outlook of each region and/or country are surveyed. Second, recent R&D projects on PV module recycling technologies supported by national and/or regional public funding are summarized.

## 4.1 Status of PV module recycling

***Europe***

In Europe, PV module recycling has been mandated since 2012 through the WEEE Directive 2012/19/EU. All EU member states have adopted 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, 48 395 tonnes of PV module waste were collected in 18 countries in 2022, the latest data available.

In Germany, the amount of collected PV modules was 16 430 tonnes in 2022; 16 017 tonnes were recovered, from which 15 195 tonnes were recycled or prepared for reuse. In practice, recycling of Si-based modules uses schemes that are partially adapted from other industries, mainly based on mechanical process schemes from flat glass recycling. The Reiling company group is the most relevant player for the treatment and recycling of Si-based PV modules in Germany. For non-Si-based thin-film modules, the only existing commercial/industrial-scale recycling plant is First Solar's recycling plant in Frankfurt Oder, which specializes in recycling cadmium telluride (CdTe) modules. In addition to currently operating PV module recycling plants, further developments and activities could extend the available recycling technologies and infrastructure in Germany, such as LuxChemtech, ImpulsTec, FLAXRES, and Solar Materials. According to the IRENA/PVPS Task 12 report on EOL PV modules published in 2016, the waste projection range in Germany is between 400 000 tonnes and 1 million tonnes in 2030 and increases up to 4.3 million tonnes in 2050. In view of the current situation of the waste management system and recycling infrastructure in Germany, there is still a clear need for improvement throughout the treatment chain—especially in anticipation of the growing volume of end-of-life module flows. German experience and lessons learned in managing larger volumes of EOL PV modules will be valuable for other countries preparing for similar challenges.

In France, the amount of PV modules treated in 2024 was 7 143 tonnes, from which 86.81% were recycled, 5.07% recovered, and 8.12% disposed. Soren, the nonprofit eco-organization approved by ministerial decree, manages both the collection and recycling by operating private tendering procedures that enable the centralization of PV waste management in France. The collected PV module waste should be redirected to one of three treatment facilities currently mandated: Gallo France in the North and ENVIE 2E Midi Pyrénées and ENVIE 2E Aquitaine, both in southwestern France. PV module waste identified as part of the CdTe waste stream is sent to the recycling facility of First Solar in Germany. PV module waste collected in the North may be redirected to Comet and Recma in Belgium, whereas ROSI Solar in Rhône Alpes operates output fractions from ENVIE 2E Aquitaine. (Note that Soren will launch a new tender process in 2025 to select the recycling operators for the next 5 years.) The projections of the amount of PV module waste expected in France by Soren show more than 43 000 tonnes are expected by 2030 and 118 000 tonnes by 2040.

In Italy, the amount of collected PV modules in 2022 was 21 493 tonnes, consisting of 628 tonnes from households and 21 315 tonnes from other sources, which was rapidly increased compared to 2021—the largest amount in the EU countries in 2022. Dedicated PV recycling facilities have not been developed in Italy to-date because EOL module volumes haven’t become large until 2022. However, preparing for coming decades, companies such as 9-Tech and EcoWeTech have started up a pilot plant and demonstration. According to the IRENA/IEA PVPS Task 12 report on EOL PV modules published in 2016, 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 tonnes for the year 2030 and is expected to increase to 2.2 million tonnes in 2050.

In Spain, the amount of collected PV modules was 2 603 tonnes in 2022; 2 284 tonnes were recovered, and 2 279 tonnes were put to recycling and prepared for reuse. Several recycling facilities are authorized for the treatment of PV modules, such as Solar Recycling, Reciclajes Pozo Cañada SL (Pozocañada, Castilla la Mancha), FCC ÁMBITO S.A., La Hormiga Verde**,** Medenasa, CERFO, and ROSI Solar (planned in 2025). The amount of PV module waste in Spain is small but will increase in the short to medium term because of the EOL of the first PV plants installed.

In Belgium, 1 855 tonnes of PV module waste were collected and treated in 2022, with 70% recovered for recycling, and no reuse reported. In Belgium, PV CYCLE was officially recognized as the compliance scheme for PV modules. PV CYCLE is a nonprofit organization established in the framework of the environmental policy agreement on PV modules. Other companies such as Comet Group, Maltha, Out of Use, and Recma are involved in the collection and recycling of PV modules. The expected increase in solar energy installations suggests that the country may face challenges related to the growing volume of PV module waste in the coming decades. Regulatory pressures will play a significant role in driving the growth of PV module waste management in Belgium.

In the Netherlands, PV module waste collected in 2023 was 1 381 tonnes. Stichting Open (OPEN Foundation), which is a nonprofit organization for producer responsibility of e-waste including PV modules, implements the legal responsibility of e-waste producers on behalf of all producers of electrical appliances. PV module waste is not treated on a large scale within the Netherlands but is mainly transported to Belgian facilities. However, Stichting Open has started selecting partners to handle PV module recycling and has initiated a tendering procedure. Under the partner selection process, volumes are forecasted to be 2 000 tonnes in 2026, growing to 22 000 tonnes by 2032 for reliable recycling technologies and 400 tonnes in 2026, increasing to 4 400 tonnes by 2032 for emerging technologies. Considering various reports regarding PV module waste in the future, the expected amount of PV module waste will be more than 10 000 t/y around 2030 and will reach more than 100 000 t/y around 2050.

In Austria, PV module waste collected in 2023 was 62 tonnes. Because of the low waste volumes, there are no specific recycling plants treating only PV modules in Austria. Several electronic waste recycling facilities can treat silicon-based modules on a pilot-scale level. Currently, modules are stored until they reach a sufficient volume before undergoing treatment. Waste projections made for Austria in 2020, according to the methodology developed by the IRENA/IEA PVPS Task 12 report on EOL PV modules published in 2016, suggests the expected amount of PV module waste in 2050 will be close to around 20 000 t/y.

In Sweden, cumulative installed PV capacity is unimportant in volume. Considering the PV modules’ service life, the current waste stream is negligible - a significant volume of PV module waste is not expected to enter the waste management system until after 2040. Current levels of PV module waste generated remain insufficient to sustain an industrial-scale recycling process. However, several companies express interest in and accept PV module waste for recycling.

In Switzerland, PV module waste collected in 2023 was about 750 tonnes. The central scheme for the recycling of PV modules is managed by SENS eRecycling, a foundation dedicated to the collection and recycling of electronic waste. Currently, there are no recycling facilities for PV modules available or under development in Switzerland. KWB Planreal AG is the sole company commissioned by SENS eRecycling for the collection of PV module waste in Switzerland; it collects and stores the PV module waste before transporting them to Germany. It is projected the annual amount of PV module waste will reach more than 5 000 tonnes around 2032, 10 000 tonnes in 2039, and more than 20 000 tonnes before 2050.

## ***Asia-Pacific and U.S.A.***

In Japan, PV module waste must be treated under the general regulatory framework for waste management. More recently, the Ministry of Economy, Trade, and Industry (METI) and the Ministry of Environment (MOE) have jointly assessed how to handle EOL PV modules and a concept of regulation for promoting the proper treatment of EOL PV modules such as recycling was drafted. This concept proposes to mandate the recycling of EOL PV modules, to establish a payment scheme, and to manage the scheme through an independent/third-party organization. Although there is no official statistical information on PV module waste, according to MOE, it was estimated PV module waste collected was 2 079 tonnes in 2022, of which 1 638 tonnes were recycled and 441 tonnes were reused. More than 40 companies treat PV module waste for recycling, and it seems more than half use specific equipment for PV module recycling. The major approach is a mechanical method, whereas some companies use a thermal method such as pyrolysis. It is forecasted the amount of PV module waste will increase to 220 000–340 000 t/y by the mid-2030s. A challenge to achieving a high-value recycling business is to find high-value products for the glass and metals recovered from EOL PV modules. R&D projects to find solutions for high-value recycling are conducted by NEDO.

In South Korea, EPR regulation—including PV module waste—has been enforced since January 2023. Collection and recycling of PV module waste are being conducted by E-Cycle Governance, which is a nonprofit organization authorized as the exclusive operating body for PV module waste EPR by the Ministry of Environment. Companies that perform collection and recycling register as members of E-Cycle Governance, carrying out operations and receiving subsidies based on their processing performance. In 2023—the first year of EPR implementation—688 tonnes of PV module waste were recycled. Currently, a network of specialized PV recycling companies has been established across five regional centers with a nationwide recycling capacity of 14 725 t/y in total: Won Kwang S&T, Yoonjin Tech, Chungbuk Technopark, Seokchung Korea, and JRC. According to predictions updated by the Korea Environment Institute in 2020, the amount of annual module waste is predicted to reach 1 000 tonnes in 2024, consistently increasing to 20 935 tonnes in 2030 and 112 564 tonnes in 2040.

In China, from 2023 to 2024, the PV recycling and circulation industry continued to improve because of the successive release of national incentive policies, the continuous improvement of the technology, and the large increase in the number of recycling enterprises. ECOPV PV Recycle Industry Development Center, established in 2022, focuses on the PV recycling industry and comprehensively promotes PV recycling-related work by bringing together all parties, integrating resources, and collaborating and interacting. Regarding the amount of PV module waste, there is no released official figure available. It seems some large-scale centralized PV power plants in the West will store them in a centralized manner, whereas the other part of the PV module waste will be dismantled and recycled by a PV module recycle company. China's PV recycling industry is developing fast, and several key enterprises have constructed PV module recycling lines such as State Power Investment Group, JinkoSolar, Yingli Energy, Changzhou Ruisai Environmental Technology, and RESOLAR Energy Technology. According to the ECOPV PV Recycle Industry Development Center, cumulative EOL PV module volume is projected to reach 1 million tonnes in 2030, 12 million tonnes in 2040, and 55 million tonnes in 2050 under the regular loss scenario, by referring a definition of the IRENA/Task12 report. Under the early loss scenario, these figures are expected to increase to 4 million tonnes, 23 million tonnes, and 66 million tonnes, respectively.

In Australia, there is no PV waste legislation or stewardship program on a national scale. However, the Australian Department of Climate Change, Energy, the Environment, and Water released a proposal for a national regulatory scheme, titled "Regulation for Small Electrical Products and Solar Photovoltaic Systems," for public consultation in June 2023. Although the scheme has not yet been finalized, it is expected to be implemented in 2025. This proposed scheme targets three key categories: material recovery, PV waste collection, and consumer awareness. Although there is no official statistical information on wasted PV modules (it is estimated as still small), PV module recycling companies have emerged in Australia since 2022—such as PV Industries, Elecsome, Sircel, Solar Renew, Solar Recovery Corporation, Pan Pacific Recycling, and Lotus Energy Recycling. Without a mandatory recycling scheme, the industry operates on a voluntary basis, with each company responsible for developing its own collection network. An Australian

PV waste projection study estimated a cumulative volume of PV module waste would exceed 2 million tonnes by 2050, growing significantly after 2030.

In the United States, there are no federal regulations specific to PV module recycling, but EPA initiated a rulemaking effort in October 2023 in which PV modules would be added to universal hazardous waste regulations. This designation would allow for less-stringent collection restrictions and management requirements compared to fully regulated hazardous waste. Several regulatory federal exclusions or exemptions may apply to EOL PV module management and may lessen requirements mandated by law. Three states—California, Hawaii, and Washington state—have adopted regulations specific to PV module EOL management, and several other states have completed or are developing policies and/or studying the issue. In addition, several industry initiatives are emerging to promote recycling or study potential regulatory, policy, and standards options to advance PV circularity, including Solar Energy Industries Association (SEIA) and Global Electronics Council. Although the United States does not collect publicly accessible empirical data on EOL PV module volumes, the National Renewable Energy Laboratory's (NREL) PV in the Circular Economy (PV ICE) model estimates approximately 760 MW of crystalline silicon (c-Si) PV modules were expected to reach EOL in 2022, increasing to more than 1 GW annually by 2030. It seems at least 43 companies will accept PV modules or materials for recycling in the United States. These companies are geographically diverse with facilities in 27 states. Current estimates for EOL c-Si PV modules in the United States are 87 000 t/y and 820 000 t/y by 2030 and 2050, respectively. U.S. recyclers are investing in dedicated PV recycling equipment and processes customized for PV modules. In addition to recycling, there is growing availability of repair and resale services for EOL PV modules in the United States. Knowledge of available services and capabilities enables informed decision making that can advance the PV circular economy.

## 4.2 Technology R&D for PV module recycling

Along with the increase of PV module waste and stakeholder concern to PV circularity, several R&D projects for high-value recycling and circulating materials have been implemented around the world. Focusing on glass-based crystalline Si PV module, the treatment steps developed by such R&D projects are 1) delamination, 2) metal recovery, and 3) usage of materials.

- Delamination: removal of glass from PV module by breaking its structure
- Metal recovery: separation and recovery of metals used in Si PV cells
- Usage of materials: identification of how to recycle/use materials recovered as well as preparation for the usage.

Fig 4.2-1 shows R&D projects summarized in Chapter 3 with the target steps of each project.

| Region | Project / Organisation | Delamination | Metal recovery | Usage of materials |
|---|---|---|---|---|
| Europe | PHOTORAMA | Waterjet/Diamond wire | DES leaching → Electrowinning | Exploring end-usage |
| | EVERPV | Grinding/IR ramp → Recovery of glass, cell metals and polymers | | Exploring end-usage |
| | RETRIEVE | Recovery of glass, cell metals and polymers | | Exploring end-usage |
| | FORESi | Mechanical | Chemical | Si recycling |
| | ReSiLeX | | | Si recycling |
| | ICARUS | | | Si recycling |
| | QUASAR | Waterjet/Pyrolysis → chemical | | Exploring end-usage |
| | APOLLO | Optical/Mechanical/Sonification/chemical | | Exploring end-usage |
| Italy | IEMAP | Separator | | Exploring end-usage |
| | Parsival | Thermal-mechanical-chemical | Hydrometallurgical with ultrasounds | |
| Spain | RESILIENS | | Chemical | Si recycling |
| Austria | PVReValue | Waterjet/Mechanical/Thermal → Chemical | | Exploring end-usage |
| Japan | Solar Frontier (NEDO) | Separator | Chemical | Exploring end-usage |
| | Tokuyama (NEDO) | Pyrolysis | | Exploring end-usage |
| Australia | UNSW | Pyrolysis | Chemical | |
| | Swinburne Univ. | | Pyrometallurgy | Si recycling |

**Fig. 4.2-1 Target steps of R&D projects for PV module recycling**

All projects focusing on “delamination” cover “metal recovery,” and some of them further focus on “usage of materials”—whereas most projects implemented previously (until a few years ago) focused on only “delamination”; “metal recovery” was an additional option or independent topic. In addition to projects covering “delamination” to “materials usage,” some projects target “material usage” only. Until a few years ago, projects for “material usage” were rare.

Examining the delamination technologies, there are several approaches. It seems existing approaches such as pyrolysis and shredding are further improved for higher treatment efficiency. In addition, new mechanical approaches such as diamond wire, separator, and hot/heated blade are used, and a water jet and an IR lamp are adopted to PV module recycling (= delamination).

Metal recovery is realized using a chemical approach. A common chemical approach investigated is use of acid. However, considering impact to the environment, environmentally friendly solvents are also being explored, for example, DES leaching and electrowinning in the PHOTORAMA project.

Regarding material usage, recycling of Si recovered from PV cells is a focus. In addition to raw materials of Si ingot, wafer and cells for PV, other industrial products such as anode material of lithium ion battery and liquid glass are proposed as targets of Si recycling.

Table 4.2-1 shows targets of recovered materials and expected use application of recovered materials of each project.

**Table 4.2-1 Target of recovered materials and expected use application of recovered materials**

| Region | Project / Organisation | Expected materials recovery | Target of recovery | Expected use application |
|---|---|---|---|---|
| Europe | PHOTORAMA | Glass, Al, Cu, Si, Ag, In (from HJT), polymer | Recovery rate<br>: 98% (whole), 95% metal | n.a. |
| | EVERPV | Glass, Al, Cu, Si, Ag, EVA, PET/PVF | Glass: 100% (recovery rate)<br>Ag: 99% (purity), EVA/PET: 95% (purity) | Glass: flat glass<br>Polymer: to be explored |
| | RETRIEVE | Glass, Al, Cu, Si, Ag, polymer | Recovery rate<br>: glass 99%, Si 98%, Ag 99% | Glass: PV glass,<br>Al, Cu, Ag: non-ferrous metal, Polymer: synthesis gas |
| | FORESi | n.a. | Recovery rate: 95% (whole) | Si; SOG-Si (>15%) |
| | ReSiLeX | Si | n.a. | Si: SOG-SI, LiB anode material<br>Recycling of 97% of recovered Si |
| | ICARUS | Si (plus silica & graphite from manufacturing waste) | Recovery rate: 95% (whole) | SI: SOG-Si, liquid glass |
| | QUASAR | Glass, Al, Cu, Si, Ag, polymer | Recovery rate: Si 90%, Ag: 90%, polymer 90% | Glass: flat glass (float glass), Metals: PV cell/module |
| | APOLLO | Glass, Al, Cu, Si, Ag, polymer | Recovery rate: 93% (whole), Si purity: 6N | Glass: PV glass, Si: SOG-Si |
| Italy | IEMAP | Glass, Cu, Ag, polymer | n.a. | Ag: AgBr, Cu: $CuC_2O_4$ |
| | Parsival | Glass, Al, Cu, Si, Ag | Recovery rate: 87% (whole) | - |
| Spain | RESILIENS | Si, other metals from Si cell | n.a. | Si: SOG-Si |
| Austria | PVReValue | Glass, Si, metals, polymer | Recovery rate: 95% (whole) | n.a. |
| Japan | Solar Frontier (NEDO) | Glass. Al, Cu, Si, Ag, polymer | Recovery rate: 80% (whole) | n.a. |
| | Tokuyama (NEDO) | Glass, Al, Cu, Si cell | Recovery rate: 80% (whole) | n.a. |
| Australia | UNSW | Glass, Al, Cu, Si, Ag | Recovery rate: 95% (whole) | n.a. |
| | Swinburne Univ. | Si, Ag | Si: 6N (purity), Ag: 90% (recovery rate) | Si: SOG-Si |

Expected materials recovered are almost all materials including polymer. Looking at the target, recovery rate and/or degree of purity of specific materials such as Si, Ag, glass, and polymer are set, depending on the project. Regarding the expected use application of recovered materials, glass is most commonly investigated for use in new PV glass and Si for reuse in new PV as well as an anode material for lithium-ion batteries (RESILIENCE) and liquid waterglass (ICARUS). In addition, in the EVERPV, RETRIEVE and PVReValue projects, recycling of polymer is targeted.

## 4.3 Changes and progress compared to previous reports

This report updated and expanded upon a prior Task 12 reports on these subjects: 1) regulatory schemes, information on expected PV module waste, recycling companies, and the outlook of each region and/or country, published in 2022 [6], and 2) recent R&D projects on PV module recycling technologies supported by national and/or regional public funding, published in 2018 [206].

Table 4.3-1 shows a comparison between this report and previous report, published in 2022, regarding 'Collected EOL PV modules', 'No. of recyclers identified', and 'Specific Regulation/legislation for PV EOL treatment'.

Results show that the amount of collected EOL PV modules have been growing by several fold in the time between the two reports, except for Japan. In case of Japan, the amount of decommissioned PV modules in 2020 was larger than in 2022 because of natural disasters like typhoon. Corresponding to the increase of EOL PV modules, PV module recycling companies identified in the report are increasing, even for Japan. Although the WEEE Directive in Europe has come into force in the market since 2010s, country-specific regulation for PV were not yet introduced in all European countries in 2022. Now, in South Korea, a PV EPR regulation has been enforced starting in 2023, and political deliberation is taking place in Japan, Australia, and the United States.

**Table 4.3-1a Comparison between this report and previous one [6]: Europe**

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Collected EOL PV modules [t/y] (by EUROSTAT)</th><th colspan="2">No. of recyclers identified</th><th colspan="2">Regulation/legislation</th></tr>
<tr><th>2018</th><th>2022</th><th>2021/2022</th><th>2024/2025</th><th>2021/2022</th><th>2024/2025</th></tr>
<tr><td colspan="2">Europe</td><td>13 951</td><td>48 395</td><td>-</td><td>-</td><td colspan="2" rowspan="10">WEEE Directive</td></tr>
<tr><td></td><td>Germany</td><td>7 865</td><td>16 430</td><td>2</td><td>6</td></tr>
<tr><td></td><td>France</td><td>1 555</td><td>3 582</td><td>3</td><td>3 + 1</td></tr>
<tr><td></td><td>Italy</td><td>1 350</td><td>21 493</td><td>0</td><td>2</td></tr>
<tr><td></td><td>Spain</td><td>462</td><td>2 603</td><td>0</td><td>7</td></tr>
<tr><td></td><td>Belgium</td><td>168</td><td>1 855</td><td rowspan="6">No survey</td><td>3</td></tr>
<tr><td></td><td>Netherlands</td><td>131</td><td>1 035</td><td>2</td></tr>
<tr><td></td><td>Austria</td><td>8</td><td>12</td><td>4</td></tr>
<tr><td></td><td>Sweden</td><td>-</td><td>-</td><td>3</td></tr>
<tr><td></td><td>Switzerland</td><td>-</td><td>-</td><td>0</td><td>No survey</td><td></td></tr>
</table>

**Table 4.3-1b Comparison between this report and previous one [6]: Asia-Pacific & U.S.A.**

<table>
<tr><th rowspan="2"></th><th colspan="2">Collected EOL PV modules [t/y]</th><th colspan="2">No. of recyclers identified</th><th colspan="2">Specific regulation/legislation for PV EOL treatment (national level)</th></tr>
<tr><th>Previous</th><th>This time</th><th>2021/2022</th><th>2024/2025</th><th>2021/2022</th><th>2024/2025</th></tr>
<tr><td>Japan</td><td>6 300<br>(in 2020)</td><td>2 079<br>(in 2022)</td><td>29</td><td>42</td><td>No</td><td>Under discussion</td></tr>
<tr><td>South Korea</td><td>279<br>(in 2020)</td><td>688<br>(in 2023)</td><td>3</td><td>5</td><td>Under discussion</td><td>EPR since 2023</td></tr>
<tr><td>China</td><td>No data</td><td>No data</td><td>7</td><td>10</td><td>No</td><td>No</td></tr>
<tr><td>Australia</td><td>No data</td><td>No data</td><td>7</td><td>7</td><td>Under discussion</td><td>Expected in 2025</td></tr>
<tr><td>United States</td><td>No data</td><td>760 [MW]*<br>(in 2022)</td><td>8</td><td>39</td><td>No</td><td>Under discussion</td></tr>
</table>

* Value shown is an NREL-modeled estimate of EOL crystalline-silicon modules. Collected EOL PV modules are not tracked in the U.S.

As for c-Si module recycling R&D projects, comparing the results from this report to the prior one [204], recovering high-weight components of modules like glass at lower cost was the focus of technical innovations. Recently, several R&D projects for high value recycling and material recovery have been implemented in the world. The treatment steps developed by such R&D projects are delamination, metal recovery, and preparation of materials for markets. The focus has been on increasing recovery of low-weight valuable materials, and increasing the quality of recovered materials to improve their secondary use. As for material preparation for markets, recovery rate and purity targets for specific materials such as Si, Ag, glass and polymer are being set.

## 4.4 Conclusions

PV deployment accelerated more quickly than expected in the 2010s. This means, in the coming decades, PV modules reaching end-of-life will increase faster than previously anticipated. To meet and optimize the EOL management of PV waste, regulatory and technological approaches—including supportive technology R&D—should be well integrated, and options should be adapted to the conditions of each country or region.

Regarding the status of PV recycling, the EU has adopted PV-specific waste regulations. In other parts of the world, legislative and regulatory frameworks for PV module waste are installed or in preparation. Regardless of whether there are PV-specific waste regulations, many companies are treating PV module waste for proper EOL management and recycling, a number which has increased since the last time IEA PVPS Task 12 surveyed three years ago.

The current low volumes, limited recycling technologies, logistics challenges, and underdeveloped markets for recovered materials result in a high-cost, low-revenue scenario for PV module recycling today. Further improvement in the PV recycling capacity and technology is needed to meet future increased demand and to realize the goal of high-value, low-cost recycling. To improve economic aspects of PV module recycling, considering values of recovered materials such as critical minerals would be also necessary.

PV module recycling technology is expanding from delamination to metal recovery as well as exploring more valuable markets for recovered materials. Enabling the use of recovered materials in new PV cells/modules and other high-value markets are ultimate targets, whereas impurities and additives remain issues to be solved. Recycled materials from PV module waste could play a significant role in material supply for future PV module production and other industries.

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# APPENDIX – EXAMPLES OF R&D PROJECTS ON PV MODULE RECYCLING

| Country /region | Project title | Targeted PV module |
|---|---|---|
| Europe | PHOTORAMA: PHOtovoltaic waste management – advanced Technologies for recOvery & recycling of secondary RAw MAterials from end-of-life modules | crystalline Si and CI(G)S |
| | EVERPV: Highly efficient delamination technologies to recover and reuse metals, glass, and polymers from end-of-life PV panels | crystalline Si |
| | RETRIEVE: Reintegration of photovoltaic panel waste back into manufacturing as high value products | crystalline Si |
| | FORESi: FOstering a Recycled European Silicon supply | crystalline Si |
| | RESiLEX: Resilient Enhancement for the Silicon Industry Leveraging the European matrix | crystalline Si |
| | ICARUS: Innovative eco-efficient processing and refining routes for secondary raw materials from silicon ingot and wafer manufacturing for accelerated utilisation in high-end markets | crystalline Si |
| | QUASAR | crystalline Si |
| | Development of a recyclability index for PV modules and PV inverters | all types |
| | APOLLO: A Proactive Approach to the Recovery and Recycling of Photovoltaic Modules | crystalline Si and Perovskite/Si tandems |
| Italy | IEMAP: Italian Energy Materials Acceleration Platform | crystalline Si |
| | PARSIVAL Project | crystalline Si |
| Spain | Circularity of Photovoltaic systems by Recycling, Repairing, and Reusing photovoltaic modules (FOTOVOL3R) | crystalline Si |
| | Recycling of silicon for new solar generation (RESILIENS) | crystalline Si |
| Austria | PVReValue - Holistic recycling of PV modules | crystalline Si |
| Sweden | Crucial metal recycling from waste solar cells and reuse in manufacturing for the sustainable solar energy industry | crystalline Si and CI(G)S |
| | CircSolar: Paneling the Path to Circular Sunpower | crystalline Si |
| | SolVind Policy Innovation Lab | - |
| Japan | Demonstration of environmentally friendly material recycling technology for crystalline Si and CIGS PV modules | crystalline Si and CI(G)S |
| | Technology development for PV module recycling using a low-temperature pyrolysis method | crystalline Si |
| China | Integrated Technology & Demonstration of Efficient Circular for Recycling of EOL PV Laminated Parts (Application Demonstration Category) | crystalline Si |
| Australia | End-of-life, highly efficient, low-cost, and eco-friendly recycling technology for silicon photovoltaic panels | crystalline Si |
| | Highly efficient, mobile, and flexible recycling technology for PV panels | crystalline Si |

| | | |
|---|---|---|
| | Electrically Enhanced Recycling Process for EOL Si PV Cells | crystalline Si |
| | Establish an advanced solar panel recycling facility | all types |

| | |
|---|---|
| Project title | PHOTORAMA: PHOtovoltaic waste management – advanced Technologies for recOvery & recycling of secondary RAw MAterials from end-of-life modules |
| Granting agency | European Union's Horizon 2020 research and innovation programme under grant agreement No. 958223 |
| Implementing organization | Consortium of 12 organizations:<br>CEA (France), SINTEF (Norway), Maltha (Belgium), LuxChemtech (Germany), Bifa (Germany), RHP (Austria), ZSI (Austria), ENEL Green Power (Italy), ENEA (Italy), Idener R&D (Spain), Mondragon Assembly (Spain, France), Soren (France)<br>Coordinator: CEA |
| Project period | May 2021–April 2025 |
| Project objective and target | To develop trailblazing technologies to implement a strong and reliable PV recycling scheme<br>To demonstrate innovative recycling solutions with a pilot line that is at TRL 7<br>To demonstrate full circularity by re-injecting the secondary rare materials into cross-sectoral value chains,<br>To drive market adoption of PHOTORAMA technologies as sustainable solutions<br>To strengthen sustainable waste management actions under the EIP framework |
| Project structure | WP1: PHOTORAMA Pilot Line – Waste collection, module disassembling, pilot line qualification<br>WP2: Delamination – Enabling high added value from module layer separation<br>WP3: Metal recovery – Enabling high added value from metal extraction<br>WP4: Make PV industry circular – Reuse of recycled materials as new products<br>WP5: Techno-economic, environmental, and social assessments<br>WP6: Social awareness, dissemination, and clustering<br>WP7: Business plan and exploitation<br>WP8: Project management |
| Targeted PV module | Crystalline-Silicon and CI(G)S |
| Recycling technology type | Mechanical automated disassembling (frame, junction box)<br>Mechanical delamination using diamond wire cutting (c-Si, especially bi-glass), mechanical delamination using water jet (c-Si), optical delamination using flashlight (CI(G)S)<br>Metal recovery using leaching process combined to electrowinning |
| Targeted and recovered materials | Aluminium (frame sent to refinery), junction boxes (sent to small domestic appliance WEEE directive stream), glass<br>Metals from c-Si: Cu, Al, Ag, Si, In (from HJT)<br>Metals from CIGS: In, Ga |

| | |
|---|---|
| Quantitative target | Full nominal capacity of the pilot line at 1 200 t/y<br><br>Global recovery rate: 98% including fuel from polymer residues<br><br>Metal recovery rate: 95%–98% |
| Description of technology | Pilot line designed as a combination of several technologies, including successively:<br>1. Disassembling external components of any kind of PV types designed with two stations (frame removal using hydraulic cylinder, JB removal using a tearing blade system).<br>2. c-Si delamination by water jet precisely de-layering cells and polymers until reaching hard glass sheet, delamination using diamond wire to cut through the interface glass frontsheet/cells or cells/backsheet, usually used for bi-glass module structure.<br>3. CI(G)S delamination by flashlight to weaken the polymer/semiconductor layer and then mechanically unstick front- and backsheets.<br>4. Metal recovery: leaching using ionometallurgy approach with deep eutectic solvent (silver) and leaching using methane sulfonic acid combined to an oxidizing agent (silver, indium, gallium) depending on the technology (c-Si including HJT, CI(G)S), both renewable systems. Electrowinning processes have been optimized to extract the metal. |
| Key points of technology R&D | • Multi-step pilot line demonstration for full management of c-Si and CIGS, from EOL modules to the production of secondary raw materials<br>• Scale-up of the technologies from TRL 4–5 to TRL 7 operating in industrial environment<br>• Demonstration of the re-integration of the secondary raw materials for industrial manufacturing (PV products or other sectors) |
| Website information | https://www.photorama-project.eu/<br><br>https://cordis.europa.eu/project/id/958223 |
| Other remarks | PHOTORAMA won the Innovation Awards 2024 at EU Sustainable Energy Week 2024 (European Commission) that “recognise outstanding individuals and projects for their innovation and efforts in the field of energy efficiency and renewables.” (https://sustainable-energy-week.ec.europa.eu/awards/eusew-2024-awards-winners_en) |

[Diamond wire pilot unit (CEA, Mondragon Assembly)]

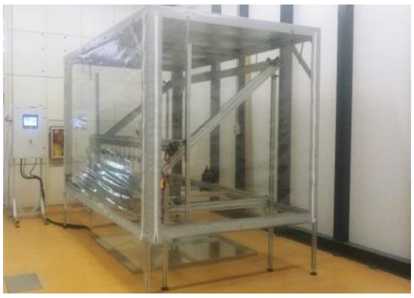
[Optical delamination pilot unit with extraction system (LuxChemtech)]


[Glass samples from PHOTORAMA processed in the industrial line at Maltha]

| | |
|---|---|
| Project title | EVERPV: Highly efficient delamination technologies to recover and reuse metals, glass, and polymers from end-of-life photovoltaic panels |
| Granting agency | European Union's Horizon Europe research and innovation programme under grant agreement No. 101122208 |
| Implementing organization | Consortium of 16 organizations:<br><br>CEA (France), ENEA (Italy), TECNALIA (Spain), ENVIE (France), UAB Valoe (Lithuania), Saint Gobain (France and Germany), 9-Tech (Italy), UNITAR (Switzerland), ERION (Italy), SOREN (France), CSEM (Switzerland), JBR (UK), and Mylar (UK)<br><br>Coordinator: CEA |
| Project period | Sep. 2023–Oct. 2026 |
| Project objective and target | EVERPV's global objective is to provide Europe with efficient and sustainable technologies for the recovery of end-of-life PV modules, which are high-purity and high-integrity materials. These components will be qualified for reuse in several applications, including the PV industry (closed-loop recycling).<br><br>More specifically, EVERPV will focus on the delamination step (consisting of separating the various layers of the PV module) because it is crucial at the beginning of the recycling process to achieve high-purity and high-integrity recovery of metals, glass, and polymers. The most efficient route will be implemented at TRL 7, using the technology in two PV recycling lines in France and Italy (at ENVIE and 9-Tech's premises, respectively), to ensure immediate benefits for the European recycling industry. |
| Project structure | WP1: Demonstration of delamination technologies for high-purity and high-integrity materials recovery<br>WP2: Benchmark of the best delamination technologies for PV recycling<br>WP3: Purification and characterization of recovered materials (glass, backsheet)<br>WP4: Purification and characterization of recovered materials (silver, encapsulant)<br>WP5: Demonstration of reuse potential of high-value recycled materials<br>WP6: Drivers and requirements to deploy a circular and sustainable PV industry<br>WP7 and 8: Management and coordination<br>WP9 and 10: Communication, dissemination, and exploitation |
| Targeted PV module | Crystalline silicon (glass/backsheet structure) |
| Recycling technology type | Delamination<br><br>- Mechanical by CEA<br>- Optical/thermal by ENEA<br>- Mechanical and thermal by 9-Tech<br><br>Metals and polymers recovery by chemical separation and leaching |
| Targeted and recovered materials | Glass, EVA, PET, fluoropolymers, Ag, Cu, Si |

| | |
|---|---|
| Quantitative target | Glass: recovery rate 100%, recycling rate 100%, 99% purity on 30 kg; scale-up to 30 tonnes<br>EVA: 100 kg recovered, 95% purity<br>PET: 100 kg recovered, 99% purity<br>Fluoropolymers: by-product of PET recycling, recovery, and reuse in different applications or back to PV<br>Ag: 1 kg recovered, 99% purity<br>Cu: by-product – not quantified<br>Si: by-product – not quantified |
| Description of technology | Two pilot lines installed during the project: one in France, one in Italy.<br>In France: One piece of equipment removes the backsheet from the modules mechanically; another piece of equipment removes cells+EVA mechanically. Backsheet powders generated are treated to produce recycled PET, and fluoride residues are treated and used for other applications. Cells+EVA powders are treated to produce recycled EVA and recycled Ag and silicon. Glass is fully recycled in the flat glass industry.<br>In Italy: One piece of equipment removes the backsheet using IR lamps; the rest of the module is pyrolyzed to recover glass and metals. Cu ribbons are recovered and recycled. Ag is recycled, and silicon is a by-product. Glass is recycled in the flat glass industry. |
| Key points of technology R&D | • Removal of backsheet from PV module using IR lamps; removes potential fluoride materials prior to pyrolysis.<br>• Ag, Si, Cu, and glass can be extracted/recycled.<br>• Sanding of backsheet to recover powders from which PET can be recycled.<br>• Sanding or cells and EVA to recover powders from which Ag, Si, Cu, and EVA can be extracted.<br>• Unbroken glass can be recycled.<br>• Combination of IR lamps and sanding possible. |
| Website information | https://everpv.eu/<br>https://cordis.europa.eu/project/id/101122208 |

[Backsheet removal equipment from ENEA]



[Sanding equipment from CEA]

| | |
|---|---|
| Project title | RETRIEVE: Reintegration of photovoltaic panel waste back into manufacturing as high value products |
| Granting agency | European Union's Horizon Europe research and innovation programme under grant agreement No. 101122332 |
| Implementing organization | Consortium of 19 organizations:<br><br>Institutt for Energiteknikk (IFE) (Norway), IFE Invest AS IFEI (Norway), Fraunhofer CSP (Germany), ELKEM SOLAR AS (REC Solar AS) (Norway), NORSUN (Norway), Iberdrola SA (Spain), Agency for Business Competitiveness (ACCIÓ) (Spain), King Danylo University (KDU) (Ukraine), Solar Energy Association of Ukraine (ASEU) (Ukraine), T. Şişe ve Cam Fabrikaları (ŞİŞECAM) (Turkey), Valoe Cells (Lithuania), Flemish institute for technological research (VITO) (Belgium), Soli Tek R&D AS (SOLITEK) (Lithuania), Bern University of Applied Sciences (BFH) (Switzerland), Barna Steel AS (CELSA) (Spain), Ferimet SL (Spain), TotalEnergies (France), Forschungszentrum Jülich/Helmholtz Institute Erlangen-Nürnberg (HI ERN) (Germany), Romanian Photovoltaic Industry Association (Romania)<br><br>Coordinator: IFE |
| Project period | Oct. 2023–Mar. 2027 |
| Project objective and target | RETRIEVE will develop a set of novel and cost-effective technologies for the recovery and upcycling of various material fractions from recycled EOL PV modules, setting innovative pathways to loop glass, silicon, and metal components back into the manufacture of new PV modules.<br><br>RETRIEVE aims for closed-loop recycling of recovered glass from EOL PV modules. |
| Project structure | WP1: Coordination and management<br><br>WP2: Circular PV market development<br><br>WP3: Recycling in circular PV production, development, and demonstration<br><br>WP4: Demonstration of reuse potential of the upcycled materials<br><br>WP5: Exploitation, commercialization, and business case development<br><br>WP6: Assessment of resource efficiency, circularity, and environmental impact assessment of the recycling technology<br><br>WP7: Communication, dissemination, and capacity building |
| Targeted PV module | Crystalline silicon (c-Si) technologies |
| Recycling technology type | RETRIEVE proposes an innovative cleaning technology that can be simulated via thermodynamic modelling to reveal the necessary process chemicals and their necessary amounts based on the impurity content of the various batches. To achieve this, analytical methods will be adapted or designed for in-line monitoring of glass purity. In this way, independent of the composition of the received glass or the type of module recovered, the cleaning procedure will be easily modulated and operated.<br><br>RETRIEVE also offers hydrometallurgical processing where the used process chemicals will be recovered and reused.<br><br>RETRIEVE will improve the metallurgical purification process for silicon sawdust to meet current and future requirements from the PV industry. |

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| Targeted and recovered materials | Glass, silicon, silver |
| Quantitative target | Develop a pilot plant for the advanced dismantling of PV modules capable of processing 400 modules/batch equivalent to 8 t/batch and with a yearly capacity greater than 1 760 tonnes.<br>Recover more than 99% of glass and upcycle it back to photovoltaic quality.<br>Recover more than 98% of silicon and upcycle it back to photovoltaic quality.<br>Recover more than 99% of silver from end-of-life modules. |
| Website information | https://www.retrieveproject.eu/<br>https://cordis.europa.eu/project/id/101122332 |

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| Project title | FORESi: FOstering a Recycled European Silicon supply |
| Granting agency | European Union's Horizon Programme under grant agreement No. 101138503 |
| Implementing organization | Consortium of 11 organizations:<br><br>SiPow AS (Norway), Recma (France), Latvijas Tehnologiskais Centrs Nodibinajums – LTC (Latvia), Bay Zoltan Alkalmazott Kutatasi Kozhasznu Nonprofit KFT – BZN (Hungary), Boralex (France), Applied Materials Italia SRL (Italy), Mondragon Assembly SA – MASSO (Spain), Commissariat à l'Énergie Atomique et aux Énergies Alternatives – CEA (France), Hespul Association (France), Carbon (France), Slovenská Technická Univerzita v Bratislave – STUBA (Slovakia)<br><br>Coordinator: SiPow AS |
| Project period | Jan. 2024–Jan. 2027 |
| Project objective and target | Develop and demonstrate new PV logistics collection, reuse, and repair processes at the EU level.<br><br>Demonstrate a fully automated dismantling machine and a novel sustainable process for the recycling of end-of-life PV modules with a target recovery rate of at least 95%.<br><br>Demonstrate at industrial scale a new process for purifying silicon from various wasted materials to produce highly pure monocrystalline silicon.<br><br>Demonstrate the circularity potential of the PV value chain by producing new PV cells with up to 15% upcycled silicon from end-of-life PV modules.<br><br>Evaluate and define the optimal parameters to achieve the highest economic, technical, social, and environmental impact along the recycling value chain.<br><br>Provide a design for a turnkey PV recycling factory together with EU policy recommendations to increase the sustainability and future resilience of the European silicon PV value chain.<br><br>Ensure the long-term scale-up of FORESi innovations through realistic exploitation strategies, inter-cluster collaboration, and stakeholder engagement. |
| Project structure | WP1: Project management<br><br>WP2: Specifications and design for a PV recycling turnkey factory<br><br>WP3: Building and operating the units for a PV recycling turnkey factory<br><br>WP4: Multifaceted impact assessment<br><br>WP5: Business and exploitation plans for replication<br><br>WP6: Dissemination, communication, and clustering activities |
| Targeted PV module | Mono- and polycrystalline Si |
| Recycling technology type | Chemical, mechanical |
| Targeted and recovered materials | Silicon |

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| Quantitative target | Demonstrate a fully automated dismantling machine and a novel sustainable process for the recycling of end-of-life PV modules with a target recovery rate of at least 95%.<br><br>Demonstrate the circularity potential of the PV value chain by producing new PV cells with up to 15% upcycled silicon from end-of-life PV modules. |
| Description of technology | The six technology innovations are allocated in the various steps as follows:<br>- Step 1, Collection and Logistics: PV collection logistics platform (Innovation 1) and PV testing process to reuse and repair EOL PV modules (Innovation 2)<br>- Step 2, Recycling: Fully automated dismantling technology for EOL modules (Innovation 3) and chemical separation technology for glass/Si laminate (Innovation 4)<br>- Step 3, Purification: Industrial purification process from various EOL wasted scraps to highly pure silicon (Innovation 5)<br>- Step 4, Production of new wafers and modules: Circular PV cells and modules with 15% recycled silicon from end-of-life PV modules (Innovation 6). |
| Key points of technology R&D | Recycling – recycling solar energy – recovery raw materials – silicon – pure silicon – WEEE photovoltaic treatment processes – renewable energy – environmental engineering – photovoltaic chemical sciences |
| Website information | https://www.foresi.eu/en/<br><br>https://cordis.europa.eu/project/id/101138503 |

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| Project title | RESiLEX: Resilient Enhancement for the Silicon Industry Leveraging the European matrix |
| Granting agency | European Union's Horizon Europe research and innovation programme under grant agreement No. 101058583 |
| Implementing organization | Consortium of 23 organizations:<br><br>Iberian Sustainable Mining Cluster (ISMC) (Spain), ETA Florence Renewable Energies (Italy, communications and dissemination), NanoPow (Norway), SolarPower Europe (Belgium), Groupe Comet (Belgium), CEA (France), Cleancarb (France), Tharsis Mining (Spain), Envie (France), Université de Liège (Belgium), CETAQUA Water Technology Centre (Spain), CNRS (France), Recma Groupe (France), NTNU (Norway), Tenerrdis (France), Ghent University (Belgium), CSEM (Switzerland), Imperial College London (UK), ICAMCYL (Spain), Leonore Development (France), Grenoble INP (France), Gesminle (Spain), Pasek Minerales (Spain)<br><br>Coordinator: ISMC |
| Project period | Jun. 2022–May 2026 |
| Project objective and target | The general objective of Project RESiLEX is to demonstrate industry-driven technological and business innovative solutions covering the full silicon value chain to contribute to improving the resilience and sustainability of this critical raw material value chain in Europe.<br><br>RESiLEX will develop technological solutions for reusing silicon, recycling PV modules, and designing new products in the fields of mining, solar, and batteries and assess the economic, social, and environmental impact of these solutions, identify a roadmap, and provide open-source policy-making recommendations to accelerate the replication of those with the highest potential while addressing transversal challenges from the European mining industry. |
| Project structure | WP1: Project management<br><br>WP2: Recovery of valuable and critical raw materials in the mining industry<br><br>WP3: Sustainable silicon production<br><br>WP4: Sustainable, eco-designed PV cells and modules<br><br>WP5: Si recycling from PV modules<br><br>WP6: Development of high-efficiency Si composite for Li-ion batteries<br><br>WP7: Multifaceted impact assessment and EU policy recommendations<br><br>WP8: Dissemination, exploitation, scale-up, and replication |
| Targeted PV module | Targeted PV module for development: SHJ PV cells, ECA interconnection or BB0, various BOM and module structure (glass/glass – glass/backsheet – lightweight module) |
| Recycling technology type | Froth flotation and electrostatism for silicon separation in EOL PV modules |

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| Target and description of technology | Each activity has a dedicated demonstration pilot, reaching TRL 6–7.<br><br>Recovery of valuable and critical raw materials in the mining industry:<br>- This activity focuses on the mineral extraction industry to develop and validate innovative solutions focused on the recovery of critical raw materials from waste generated within this field, such as cobalt or antimony.<br><br>Sustainable silicon production:<br>- Focusing on the first steps of the silicon value chain, the activity's main objective is the demonstration and development of a carbon-free sustainable process for producing silicon and silicon alloys suitable for PV applications.<br>- Develop and demonstrate a carbon-free, sustainable, and more efficient process (by 13%) for production of Si and Si alloys compatible with c-Si ingot production for PV applications. (Target: 80% $CO_2$ reduction and 13% improvement of the process yield.)<br><br>Sustainable, eco-designed PV cells and modules:<br>- Improving the eco-design and sustainability of silicon-based PV cells and modules, developing and demonstrating several aspects, such as CRM-free PV cells and silicon wafers from revalorized silicon waste.<br>- Develop more efficient, sustainable, eco-designed, and cost-competitive photovoltaic PV cells and modules (target: 25% cost reduction for PV cells with an efficiency still higher than 25%).<br><br>Silicon recycling from PV modules:<br>- Development of innovative methods for recycling end-of-life PV modules by extracting and reusing silicon and other materials used for their construction. Here, the main aim is to reduce the EU's demand for primary materials and hence lessen its reliance on imported CRM.<br>- Demonstrate a highly efficient silicon recycling process from end-of-life PV modules to substitute primary silicon source in major applications such as silicon wafers or anodic materials. (Target: up to 97% recovery rate.)<br><br>Development of high-efficiency Si composite for Li-ion batteries:<br>- Recovered silicon obtained during the previous activity will be used to replace the graphene anode in Li-ion batteries with high-energy-density silicon-carbon composite anodes.<br>- Demonstrate high-energy-density 2 Ah Li-ion battery cells with Si composite from recycled PV modules. (Target: high-energy-density battery cells >10% compared to the SOA, from secondary raw silicon).<br><br>Multifaceted impact assessment and EU policy recommendations:<br>- Assessing the improvements reached in the silicon value chain and integrating the developed solutions in a wider context. Based on this analysis, RESiLEX will provide EU policy recommendations through an open-source platform. |

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| Key points of technology R&D | Critical raw materials from waste: mining activities, mining waste and acid waste waters, recovery of critical raw materials<br><br>PV modules from recycled silicon: end-of-life PV modules or kerf, recycling treatment and purification, ingots from recycled silicon, wafers and PV cells<br><br>Anodes for batteries: end-of-life PV modules, recycling treatment and purification, silicon-based anodes |
| Website information | www.resilex-project.eu<br><br>https://cordis.europa.eu/project/id/101058583 |

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| Project title | ICARUS: Innovative eco-efficient processing and refining routes for secondary raw materials from silicon ingot and wafer manufacturing for accelerated use in high-end markets |
| Granting agency | European Union's Horizon 2020 research and innovation programme under grant agreement No. 958365 |
| Implementing organization | Consortium of 17 organizations:<br><br>SINTEF AS (Norway), Northern Silicon (NOSI) (Norway), ReSiTec (Norway), NORSUN (Norway), ROSI (France), Institut Polytechnique de Grenoble – IPG (France), CEA (France), LuxChemtech (Germany), bifa Umweltinstitut (Germany), CIDETEC (Spain), University of Cyprus (Cyprus), Magneti Marelli (Italy), Gränges (Sweden), SGL Carbon (Germany), ChemConserve (Netherlands), Benkei (France), Fiven (Norway)<br><br>Coordinator: SINTEF AS |
| Project period | Jun. 2021–31 May 2025 |
| Project objective and target | The production of photovoltaic modules generates significant resource flows, much of which currently becomes waste - including kerf-loss silicon, graphite, and silica from ingot production. The ICARUS project aims to turn this waste into valuable secondary raw materials. By 2027, it could unlock 3.5 million tonnes of silicon, 700 000 tonnes of silica, and 480 000 tonnes of graphite.<br><br><u>Objective 1:</u> Enable the recovery of >95% of high-value material from ingot and wafer manufacturing<br><br><u>Objective 2:</u> Scale-up modular solutions to process, recycle, and refine Si-kerf and alternatively transform Si-kerf into valuable raw materials<br><br><u>Objective 3:</u> Develop industrial symbiosis by providing processed and refined material to further high-end applications<br><br><u>Objective 4:</u> Ensure the implementation of the project's outcomes in the real world |
| Project structure | The ICARUS project focuses on developing and scaling up four key industrial pilot technologies, aiming to reach a TRL of 7 by the project's end. These technologies target the recovery and refining of silicon kerf, graphite, and silica waste, transforming them into high-value secondary raw materials that can be used in various final products. The upscaling and demonstration of these industrial pilot technologies are divided across four distinct work packages, each focusing on different aspects of the waste recovery process. A separate work package is dedicated to integrating the recovered secondary raw materials into final products, with six tasks corresponding to the targeted end products. Supporting work packages focus on creating a waste inventory, conducting techno-economic assessments, and performing life cycle analyses. |
| Targeted PV module | PV manufacturing waste from silicon ingot and wafer manufacturing: kerf-loss silicon, silica crucible waste, and graphite furnace waste. |
| Recycling technology type | Mechanical, thermal, and chemical. |

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| Targeted and recovered materials | Silicon, silica (in the form of high-purity quartz), and isostatic graphite from the furnace parts. |
| Quantitative target | Recovery rate >95% for silicon, silica, and graphite<br><br>Refined silicon achieving solar-grade purity 6–9N |
| Description of technology | Industrial pilot A - Make the ingot manufacturing industry waste-free: Collection, sorting, purification, and pretreatment of kerf-loss silicon, silica, and graphite waste products delivering different intermediate products for further processing.<br><br>Industrial pilot B - Integrating closed-loop value chain in the solar silicon route: Agglomeration of silica and kerf-loss silicon into briquettes, with subsequent carbothermic reduction of briquettes in a submerged arc furnace producing metallurgical grade silicon. Thermal and chemical refining of metallurgical grade silicon to solar grade silicon.<br><br>Industrial pilot C - Enabling industrial uptake—controlled conditioning of silicon: Thermal treatment of kerf-loss silicon for impurity removal based on kerf-loss silicon powder feeding, melting, solidification, and granulation targeting solar-grade-purity silicon.<br><br>Industrial pilot D - Si-waste-to-material: Chemical conversion of kerf-loss silicon into green hydrogen and silicate (water glass). |
| Key points of technology R&D | ICARUS contributes through four industrial pilots focused on recycling and processing silicon, silica, and graphite, offering a sustainable alternative to using primary raw materials in industrial applications. By reusing these recycled materials, the project helps prevent waste generation and promotes resource efficiency. In addition, ICARUS enhances the raw materials knowledge base by creating a comprehensive waste inventory for silicon kerf, graphite, and silica, supporting future advancements in recycling technologies. |
| Website information | https://www.icarus.eu.com/<br><br>https://cordis.europa.eu/project/id/958365 |

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| Project title | QUASAR: >70% eco-efficiency gains in the PV EOL supply chain by closed-loop systems with enhanced recycling rates, systematic collection, and management using digital twins |
| Granting agency | European Union's Horizon Europe research and innovation programme under grant agreement No. 101122298 |
| Implementing organization | Consortium of 19 organizations (including partners):<br><br>SINTEF (Norway), Scatec (Norway), Scatec Africa (South Africa), 2nd Life Solar (Germany), Soren (France), ROSI (France), Norway Solar Energy Cluster (Norway), Equinor Energy (Norway), LuxChemtech GmbH (Germany), Elkem (Norway), SoliTek (Lithuania), Hochschule Offenburg (Germany), Bifa Umweltinstitut GmbH (Germany), EPRI Europe (Ireland), EPRI (USA), Institute Photovoltaique d'Ile de France (IPVF) (France), DOW Silicones (Belgium), DOW Chemicals Iberila (Spain), Norner Research (Norway)<br><br>Coordinator: SINTEF AS |
| Project period | Sep. 2023–Aug. 2027 |
| Project objective and target | QUASAR will develop and implement solutions for a systematic collection and management methodology and decision tools for EOL PV modules based on a holistic approach between all parts and actors across the EOL supply chain including concepts of reverse logistic technologies, AI/machine learning, PLIM based on digital twins, and best practices for sorting, warehouse operations, testing, and repair/reuse.<br><br>EOL decision making will be supported through the delivery of a digital product passport thanks to smart sensor tags as well as rapid, nondestructive testing methods for assessing EOL PV condition for reuse/repair/recycling in the field and at waste treatment facilities. Repair technology solutions will be provided along with guidelines for second-life warranty, quality thresholds, product reliability, labeling, and tracking.<br><br>Material closed-loop systems will be implemented to enable a circular economy for the PV industry. |
| Project structure | QUASAR is divided into 14 synergistic interdisciplinary work packages:<br><br>WP1 From EOL-PV to Secondary Raw Materials<br>WP2-3 Waste Stream/EOL-Management/Digitalisation<br>WP4 Industrial Pilot-A: Thermal/Chemical Delamination & Upscaling<br>WP5-7 Industrial Pilot-B: Water-Jet Delamination<br>WP8 Products: From Technological Value to the Market<br>WP9 Design & Methods for Improved Circularity<br>WP10 Business Models & Replication Strategy<br>WP11-12 Process Assessment: TEA, LCA, Social Acceptance, Circular Economy<br>WP13 Communication, Dissemination, Outreach Activities<br>WP14 Project Management |
| Targeted PV module | Crystalline Si |

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| Recycling technology type | QUASAR will up-scale and demonstrate two emerging recycling technologies based on delamination through the following:<br>[pilot A] pyrolysis and chemical treatment (ROSI Solar)<br>[pilot B] waterjet delamination (LuxChemtech) |
| Targeted and recovered materials | Silicon, metals, glass, and polymers |
| Quantitative target | Reduction of decommission costs: 20%<br>PV module inspection cost: <5 EUR per module<br>Module repair costs: <7.5 EUR per module<br>Recycling treatment capacity: 17 500 t/y<br>EOL PV recycling rates: ≥90% for silicon, ≥90% for silver, ≥90% for polymers, ≥80% for glass cullet suitable for PV and float glass manufacturing and ≥95% for intact glass panes for direct reuse, resulting in expected revenue from recycled materials of 400–650 EUR/t. |
| Website information | https://quasar-project.eu/<br>https://cordis.europa.eu/project/id/101122298 |

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| Project title APOLLO | APOLLO: A Proactive Approach to the Recovery and Recycling of Photovoltaic Modules |
| Granting agency | Co-funded by:<br><br>European Union's Horizon 2020 research and innovation programme under grant agreement No 101122277<br>The Swiss State Secretariat for Education<br>Research and Innovation (SERI)<br>UK Research and Innovation (UKRI) |
| Implementing organization | Consortium of 18 organizations:<br><br>Fraunhofer Gesellschaft (Germany), Kalyon PV (Türkiye), Metran Rohstoff-Aufbereitungs (Germany), Minespider (Germany), EDP NEW (Portugal), Instituto Pedro Nunes (Portugal), Solaveni (Germany), SINTEF (Norway), ODTÜ-GÜNAM (Türkiye), Saule Technologies (Poland), Bittner Umwelttechnik (Germany), University of Glasgow (UK), Pilkington NSG Group (Japan), Norwegian University of Science and Technology (Norway), FENIX TNT (Czech Republic), Swansea University (UK), EPFL (Switzerland), University of Leicester (UK)<br><br>Coordinator: Fraunhofer Gesellschaft |
| Project period | Jan. 2024 – Dec. 2026 |
| Project objective and target | APOLLO project will establish a circular approach, efficiently recovering all constituents for reuse in new PVs. Innovative techniques increase weight recovery. Recycled silicon will be used for new ingots, cells and modules. These modules will incorporate new designs, materials and manufacturing methods, and will be designed for disassembly and recycling. Incoming modules will be streamed by glass composition, enabling batch recovery of high-quality glass, to be used for new solar-grade glass. A novel continuous ‘sonification’ technique, (ultrasonically excited etchant) will rapidly separate silicon, silver, copper and other metals in a sequence along a pipe-based process. Used liquid etchants will be recycled in a closed loop resulting in low waste, small footprint. Further, recovered silicon will be refined to a purity suitable for new PV-grade ingot growth. |
| Project structure | Objectives:<br><br>- Pre-recycling analysis and classification of PV modules by glass composition<br>- Pilot processing line to extract all of the material fractions of legacy and future PVs<br>- Refinement of reclaimed PV Si to facilitate ingot growth for new PV<br>- Specify and build future PV modules (standard c-Si and tandem Per/Si) with improved recyclability incorporating APOLLO innovations<br>- Develop and implement a PV-centred Digital Product Passport (DPP) facilitating an online marketplace<br>- Develop, quantify and promote a new circular business model for waste PV |
| Targeted PV module | Crystalline Si and Perovskite/Si tandems |

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| Recycling technology type | Optical and mechanical sorting, crushing, ultrasonication, froth flotation, electrostatic separation, acid leaching, gas-phase purification, ingot casting, blockchain-based digital product passport |
| Targeted and recovered materials | High-purity solar glass, elemental silicon (≥ 99.9999 %), silver, copper, aluminium frame and separable polymer fractions |
| Quantitative target | - Create a pilot line to process 40 tonnes of PV waste, producing materials for 1 tonne of remanufactured silicon and 30 exemplar PV modules: 20 PERC-based modules, 10 Tandem modules and 30sqm of single junction perovskite cells<br>- Deliver purified silicon with a minimum purity of 99.9999%<br>- Boost material recovery rates from 18% to 93% |
| Description of technology | 1. Sorting: Waste categorised by glass composition enabling batch processing for high-quality glass recovery for PV.<br>2. Extraction: 93% wt of all material types recovered through novel mechanical and sonification processes.<br>3. Refining: Recovered Si returned to ingots for re-manufacture into new PV cells.<br>4. Reusing: Si, glass, and tech-critical metals will be recovered and demonstrated in new PV modules.<br>5. Tracing & Circularity: Secure PV-centred blockchain digital Product Passport and a PV marketplace implemented. |
| Key points of technology R&D | - Si lab scale purification proven<br>- TCM extraction optimised<br>- Si ingot creation from recovered materials<br>- PV passport and marketplace implemented<br>- Pilot line complete and assessed (TRL 7) |
| Website information | https://www.apolloproject.eu<br>https://cordis.europa.eu/project/id/101122277 |

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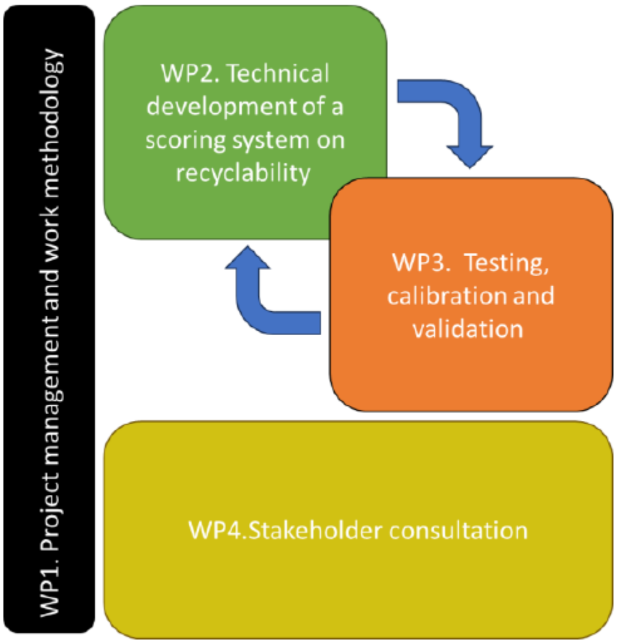
| Project title | Development of a recyclability index for PV modules and PV inverters |
| Granting agency | CINEA – European Climate, Infrastructure and Environment Executive Agency |
| Implementing organization | Viegand Maagøe (Denmark), Universidad de Murcia (Spain), and National Renewable Energy Center (CENER) (Spain) |
| Project period | Dec. 2023–May 2025 |
| Project objective and target | Analysis and development of scoring systems (indexes) for the recyclability of PV modules and inverters (the systems for each of the two products can differ).<br>Calibration and validation of the scoring systems on real products. |
| Project structure | WP1: Development of the work methodology and work plan and management of the contract<br>WP2: Technical development of a scoring system on recyclability<br>WP3: Testing, calibration, and validation<br>WP4: Stakeholder consultation |
| Targeted PV module | All |
| Recycling technology type | Regardless of the recycling technique chosen, this index focuses on the inherent features that make a PV product more recyclable. |
| Targeted and recovered materials | Prioritization of materials and parts is expected in this project. |
| Website information | https://www.pv-recyclability-index.eu/ |



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| Project title | IEMAP: Italian Energy Materials Acceleration Platform |
| Granting agency | Ministry of Environment and Energy Security (MASE) |
| Implementing organisation | Mission Innovation 2021–2024 program agreement signed between MASE and ENEA |
| Project period | 2022–2024 |
| Project objective and target | IEMAP is a tool designed, developed, and implemented by integrating existing technology data. Such a tool aims to identify the most suitable material for a given application.<br><br>Information and technical data implemented in IEMAP refer to various energy material technologies. Regarding PV modules, IEMAP will include information exploitable by a potential investor interested in the construction of recycling plants on the following themes:<br><br>• Delamination treatment of c-Si PV modules by developing a prototype based on a thermo-mechanical (IR) technology (ENEA-BetaTech patent)<br><br>• Recovery of PV cell materials using a hydrometallurgical approach. |
| Project structure | WP1: DataBase Materials for Energy<br><br>WP2: Sustainable materials for electrochemical energy storage<br><br>WP3: Materials for electrolysers<br><br>WP4: Photovoltaic materials<br><br>Lines of activity (LA) focused on PV recycling:<br><br>WP4–LA4.4: Recycling materials from end-of-life modules. Create a laboratory prototype and define a sustainable treatment process for the modules aimed at materials recovery.<br><br>WP4–LA4.5: Recycling materials from end-of-life modules. Experiment on c-Si modules and optimize plant and process parameters for materials recovery.<br><br>WP4–LA4.6: Recycling materials from end-of-life modules. Experiment on modules and implement a sustainable method aimed at materials recovery from c-Si silicon modules. |
| Targeted PV module | c-Si PV modules mounting tempered glass |
| Recycling technology type | Thermal (IR) coupled with mechanical technology |
| Targeted and recovered materials | Thermoplastic comprising polyester from backsheet, silver bromide AgBr, and copper oxalate $CuC_2O_4$, from cells |
| Key points of technology R&D | Low energy consumption and no emissions |
| Website information | https://mission-innovation.it/ |

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| Project title | PARSIVAL Project |
| Granting agency | Intesa San Paolo Vita Fideuram Vita |
| Implementing organization | 9-Tech |
| Project period | 2020–2024 |
| Project objective and target | Improve recycling of PV modules with recovery of high-purity raw material with minimum OPEX. |
| Targeted PV module | c-Silicon module: glass-backsheet; glass-glass |
| Recycling technology type | Thermal-mechanical-chemical |
| Targeted and recovered materials | Glass, aluminium, copper, silver, and silicon |
| Quantitative target | – Recovery rate: 87%<br>– Energy consumption: 100 kWh/t<br>– Costs forecast for the industrial plant: 180 EUR/t |
| Description of technology | 1. PV recognition and removal of the aluminium frame and junction box are performed manually in the pilot plant and will be automated during upscaling.<br>2. Delamination of the glass from PV cells and recovery of copper ribbons in a thermomechanical step. The process begins with an innovative heating treatment where PV modules undergo controlled heating to fully combust the EVA encapsulant efficiently. This step occurs in a specially designed continuous furnace that stands out for its ability to minimize energy losses, highlighting patented technology. The furnace is equipped with a heat exchanger that captures energy from the fumes and a sophisticated cooling system within it that precisely manages the temperature. After heating, a machine removes the copper wirings, and the material is sieved. Finally, the mechanical separation of the PV cells from glass is performed.<br>3. Hydrometallurgical treatment of the PV cells, using ultrasound, to recover silver. The process revolutionizes the recycling of PV cells through a hydrometallurgical treatment in a uniquely designed reactor. This reactor applies high-power ultrasound without harming the PV cells. The innovative method, which is currently patent pending, combines a water and citric acid solution with ultrasound to efficiently recover silver and most of the aluminium paste directly in the solid state. |
| Key points of technology R&D | – Highly efficient process: Leveraging optimized processes and mechanical separation recovers all raw materials with >95% of their economic value, surpassing traditional methods in efficiency and material purity.<br>– Low energy consumption: The process uses controlled combustion of EVA encapsulant for high energy efficiency and incorporates heat recovery, eliminating energy costs and material wear associated with mechanical grinding.<br>– Versatility: In an industrial plant, it will adeptly handle broken modules.<br>– Circular process: It avoids the creation of waste, including hazardous wastewater and plastic fractions, that currently represent a cost for recycling plants. |

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| Website information | https://www.9tech.it/progetti/parsival/?lang=en |

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| Project title | Circularity of Photovoltaic systems by Recycling, Repairing, and Reusing photovoltaic modules (FOTOVOL3R) |
| Granting agency | Ministerio de Ciencia, Innovación y Universidades (MICIN, AEI), PID2020-118417RB-C21 |
| Implementing organization | CIEMAT, with the collaboration of Ministerio para la Transición Ecológica y el Reto Demográfico (MITERD), Escuela Técnica Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas de la Universidad Politécnica de Madrid (UPM) |
| Project period | Sep. 2021–Aug. 2025 |
| Project objective and target | Study of the EOL options of PV energy generators (current techniques for recycling and repair of PV modules) and the development of techniques for characterization and repair of PV modules as well as verification of the viability of the repaired modules in real installations. Two no less important aspects of this project are the analysis of the life cycle of the developed processes (LCA) and the evaluation of the social perception of PV energy. |
| Project structure | <u>WP1 Management</u><br>1.1 Administrative management<br>1.2 Technical management<br><u>WP2 Recycling</u><br>2.1 Estimation of the PV module waste to be recycled in Spain<br>2.2 State of the art of recycling techniques<br>2.3 LCA of the recycling of PV modules<br><u>WP4 Reparation of defective PV modules</u><br>4.1 Diagnosis of defective modules coming from PV plants; characterization techniques<br>4.2 Reparation techniques for damaged PV modules<br>4.3 Characterization of repaired modules<br><u>WP5 Reuse of repowered PV modules in a PV installation</u><br>5.1 Characterization of selected repaired PV modules in the laboratory<br>5.2 Installation of a PV plant with repaired modules<br>5.3 Comparison of performance of system with repaired modules and a conventional one<br>5.4 Sustainability and circularity of the repowering of PV modules<br><u>WP6 Public perception of PV modules in Spain</u><br>6.1 Desk research<br>6.2 Public acceptance: Survey with members of the public<br>6.3 Consumer acceptance: Qualitative study with domestic PV module consumers |

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| | 6.4 Recommendations for communication<br><u>WP7 Communication and dissemination</u><br>7.1 Scientific dissemination<br>7.2 Social dissemination |
| Targeted PV module | Crystalline Si |
| Targeted and recovered materials | Repaired modules, recovered completed modules |
| Description of technology | Repairing modules by using mechanical methods and characterization of selected repaired PV modules in the laboratory and real installations. Estimation of PV module residues using Weibull function, life cycle of the developed processes using LCA, and evaluation of the social perception of PV energy using surveys and statistical methods. |
| Key points of technology R&D | – Estimation of PV module residues<br>– Repairing PV modules<br>– Verification of the viability of the repaired modules in laboratory and real installations<br>– Life cycle of the developed processes (LCA)<br>– Evaluation of the social perception of PV energy. |
| Website information | https://projects.ciemat.es/es/web/fotovol3r/inicio |

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| Project title | Recycling of silicon for new solar generation (RESILIENS) |
| Granting agency | Spanish Agencia Estatal de Investigación MCIN/AEI/10.13039/501100011033 |
| Implementing organization | Instituto de Energía Solar – Universidad Politécnica de Madrid. Together with Universidad Complutense de Madrid, Universidad Autónoma de Madrid, IMDEA Nanociencia. |
| Project period | Dec. 2022–Nov. 2024 |
| Project objective and target | The main objective of RESILIENS is to establish a feasible and environmentally meaningful technology that allows the recovery of silicon and metals from discarded PV devices and their reutilization in the manufacturing of new PV cells. Guided by an advanced compositional, optical, and electrical characterization program at the various process steps, it addresses the complete removal and recovery of metal contacts, the recrystallization of the metal-free recycled material, and the fabrication of PV cells with the recovered silicon. |
| Project structure | WP0: Management and dissemination<br>WP1: Metal recovery<br>WP2. Silicon recrystallization<br>WP3: PV cells from recycled silicon<br>WP4: Cost and environmental evaluation |
| Targeted PV module | Crystalline Si |
| Recycling technology type | Chemical route for the recovery of metals, Cz crystallization for the recovery of the silicon. |
| Targeted and recovered materials | Metal contacts, silicon |
| Description of technology, possible step by step | Alkaline treatments were optimized following a careful design-of-experiments process, allowing for complementary removal and recovery of metals from front and rear contacts without damaging the quality of the demetallized substrates.<br>Monocrystalline wafers were grown from silicon fragments of old multicrystalline wafers showing improvements in lifetime values after a phosphorus diffusion gettering conditioning process, rendering them compatible with high-efficiency PV cell architectures. |
| Key points of technology R&D | The validation of demetallization and recrystallization processing of old Si-based PV cells and substrates for their reinjection into the PV technology value chain |
| Website information | https://www.ies.upm.es |

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| Project title | PVReValue - Holistic recycling of PV modules |
| Granting agency | Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology of Austria |
| Implementing organization | Montan University Leoben (leading organization)<br>[Scientific partners]<br>OFI (Austrian Research Institute for Chemistry and Technology), Polymer Competence Center Leoben GmbH, Silicon Austria Labs GmbH, Technical University of Vienna<br>[Industry partners]<br>Circulyzer GmbH, MGG Polymers GmbH, Perndorfer Maschinenbau KG, Peter Seppele GmbH, SOLAR-ERNTE Photovoltaik, Sonnenkraft GmbH |
| Project period | Jan. 2023–Dec. 2025 |
| Project objective and target | To develop a holistic processing and recycling process for PV modules, consisting of the following steps—(1) input characterization, (2) composite separation, (3) processing, (4) output characterization, and (5) recycling of the output fractions—to achieve a recycling rate of more than 95% by weight. |
| Project structure | WP 1: Project management<br>WP 2: Input characterization<br>WP 3: Composite separation<br>WP 4: Processing and output characterization of inorganic fraction<br>WP 5: Processing and output characterization of organic fraction<br>WP 6: Utilization of the output fractions |
| Targeted PV module | Crystalline Si modules, glass-backsheet, and glass-glass modules |
| Recycling technology type | Mechanical, thermal, testing optical, and chemical approaches |
| Targeted and recovered materials | Glass (as a pane), metals, silicon, and exploring options for organic components |
| Quantitative target | Target is a recycling rate of more than 95 wt%. |
| Description of technology | Step 1: Material characterization and layer-thickness measurement<br>Step 2: Multistage compound separation with water jet, milling, or thermal treatment of glass-backsheet modules; testing laser delamination and dielectric heating for glass-glass modules<br>Step 3: Complex combination of further mechanical and/or chemical processing methods for the recovered fractions to generate high-quality recyclable secondary raw materials in a functioning circular economy |
| Key points of technology R&D | Key point is a layer-by-layer separation of the PV module during the delamination process. This enables the complete separation of the backsheet from other components to avoid fluoropolymer in the other fractions. |
| Website information | https://www.avaw-unileoben.at/de/forschung/projekte/pvrevalue |

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| Project title | Crucial metal recycling from waste solar cells and reuse in manufacturing for the sustainable solar energy industry |
| Granting agency | Swedish Energy Agency |
| Implementing organization | Chalmers University of Technology (coordinator) |
| Project period | Apr. 2020–Nov. 2024 |
| Project objective and target | Technology development for recycling of silver, indium, gallium, and molybdenum from CIGS PV cells.<br>Technology development for recycling of silver from Si-PV cells.<br>Validation of recycled silver utilization as powder.<br>Verification of indium-tin-oxide production from a recycled source. |
| Project structure | The research project focuses on the development of innovative, simple, and mild chemical processing approaches for metal recovery from PV modules.<br>WP1: Delamination-thermal treatment<br>WP2: Extraction of valuable metals from PV cells<br>WP3: ITO powder production<br>WP4: Silver purification and its particle production |
| Targeted PV module | CIGS and silicon cells/modules |
| Recycling technology type | The project covers thermal, mechanical, and supercritical fluid treatment for delamination, hydrometallurgical treatment for metal recovery |
| Targeted and recovered materials | Targeted materials: silver, indium, gallium, molybdenum |
| Quantitative target | >95% |
| Key points of technology R&D | Simple recycling of silver from various PV cells with some approaches |
| Website information | https://research.chalmers.se/en/project/9483 |

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| Project title | SolVind Policy Innovation Lab |
| Granting agency | Swedish Energy Agency |
| Implementing organization | RISE, Research Institutes of Sweden (coordinator) |
| Project period | May 2024–Dec. 2025 |
| Project objective and target | Policy development for circular management of:<br>• Wind turbine blades: Value chains for developed technologies<br>• PV modules: Recycling and value chains.<br>The project focuses on analyzing the status and future conditions for PV module recycling in Sweden and on policy development to facilitate or force more circular management of PV modules. No technology development is part of this project. |
| Project structure | WP1: Project management, dissemination, meetings<br>WP2: Circular management of wind turbine blades<br>WP3: Policy and wind turbine blades<br><u>WP4: Circular management of PV modules</u><br><u>WP5: Policy and PV modules</u> |
| Targeted PV module | In principle, considering all PV modules—but the focus is on mainstream crystalline PV modules. |
| Recycling technology type | No technology development in this project |

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| Project title | CircSolar: Paneling the Path to Circular Sunpower |
| Granting agency | Vinnova |
| Implementing organization | Axfoundation together with project partners KTH Royal Institute of Technology, Svea Solar, El-Kretsen, Stena Recycling, and REMONDIS. |
| Project period | 2023-10-27–2026-10-27 |
| Project objective and target | The goal of the CircSolar project is to develop a proposal for a new national system for the circular management of PV modules. |
| Project structure | WP1: Project Management<br>WP2: System Analysis<br>WP3: Future Scenarios<br>WP4: Circular Roadmap<br>WP5: Communication |
| Targeted PV module | Primarily monocrystalline |
| Recycling technology type | Primarily thermal/mechanical |
| Targeted and recovered materials | All |
| Website information | https://www.axfoundation.se/en/projects/circular-solar-panels-circsolar |

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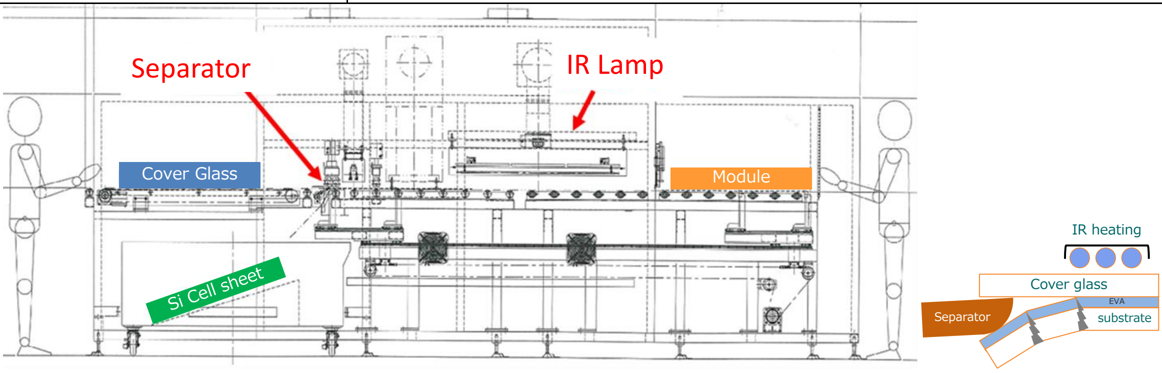
| Project title | Demonstration of environmentally friendly material recycling technology for crystalline Si and CIGS PV modules |
| Granting agency | NEDO/METI |
| Implementing organization | Solar Frontier K.K. |
| Project period | 2020–Mar. 2025 |
| Project objective and target | In addition to the "laminated glass PV modules," the scope will include "crystalline Si PV modules" that demonstrate material recycling technology with low environmental impact.<br>- Material recycling rate: 80%<br>- Disassembly process cost including profit from the sale of materials: less than 3 JPY/W. |
| Targeted PV module | CIGS and crystalline Si |
| Recycling technology type | Mechanical and chemical |
| Targeted and recovered materials | Glass (full-scale), metals, plastics |
| Quantitative target | Cost: <3 JPY/W (when treated: 200 MW/year, 15–16 kt/year)<br>Material recovery rate: >80% |
| Description of technology | By cutting the EVA layer using a separator, cover glass is separated without breakage.<br>EVA/cell/EVA/backsheet layer is crushed and treated by chemicals.<br>Metals and plastics are recovered. |
| Key points of technology R&D | Development of technology for efficient recovery and cleaning of all materials with low environment impact.<br>Development of recycling applications and quality evaluation technology for all materials.<br>Demonstration of the technology at a demonstration plant. |




*Source: provided by NEDO*

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| Project title | Technology development for PV module recycling by low-temperature pyrolysis method |
| Granting agency | NEDO/METI |
| Implementing organization | Tokuyama Corporation |
| Project period | 2020–Mar. 2025 |
| Project objective and target | A technology to suppress the generation of soot by thermally decomposing resin in a ceramic filter placed under a PV module and using a catalyst is developed.<br>Using this technology, a recycling process for commercialization will be developed and both a disassembly treatment cost (including profit on sale) of 3 JPY/W or less and a resource recovery rate of 80% or more will be achieved. |
| Targeted PV module | Crystalline Si |
| Recycling technology type | Thermal (pyrolysis) |
| Targeted and recovered materials | Glass (full-scale), metals |
| Quantitative target | Cost: <3 JPY/W (when treated: 200 MW/year, 15–16 kt/y)<br>Material recovery rate: >80% |
| Description of technology | After removal of Al frame and terminal box, PV module is sent to a pyrolysis furnace.<br>Full-scale glass without breakage and metals are retrieved. |
| Key points of technology R&D | Determine the specifications of ceramic filters and catalysts under optimal thermal decomposition conditions.<br>Develop a recycling process that can be operated continuously.<br>Ensure the quality of glass after thermal decomposition that can be recycled into flat glass. |

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| Project title | Integrated Technology & Demonstration of Efficient Circular for Recycling of EOL PV Laminated Parts (Application Demonstration Category) |
| Granting agency | Ministry of Industry and Information Technology of the People's Republic of China |
| Implementing organization | China Electronics Standardization Institute, Huaneng Clean Energy Research Institute, Yingli Energy (China) Co., Ltd., Changzhou Ruisai Environmental Technology Co., Ltd., China Testing & Certification International Group Co., Ltd., and 10 consortium units.<br><br>Led by China Electronics Standardization Institute. |
| Project period | Starting 2023 |
| Project objective and target | Researching and developing standards and policy recommendations of PV module recycling, PV product carbon footprint. Building a PV industry carbon emission database and carbon footprint accounting system. Researching and developing PV module recycling technology and equipment, demonstrating the application of PV module recycling. Promoting the PV module recycling at an industry scale, standardized development, and helping China's PV industry with green and low-carbon development. |
| Targeted PV modules | Crystalline Si |
| Website information | http://www.cesi.cn/202304/9185.html |
| Other remarks | This project was initiated at the end of 2022, formally launched at the beginning of 2023, and is currently in the research stage. The research progress and results related to the project have not yet been made public. |

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| Project title | End-of-Life, highly efficient, low-cost and eco-friendly recycling technology for silicon PV panels |
| Granting agency | The Australian Renewable Energy Agency (ARENA) |
| Implementing organization | The University of New South Wales |
| Project period | 2020–2024 |
| Project objective and target | The project aims to develop a highly efficient, low-cost, closed-loop recycling system to recover valuable metals and silicon from EOL PV modules, leveraging interdisciplinary expertise in pyro-/hydrometallurgy, PV, and off-gas/wastewater treatment, in collaboration with industries in Australia and overseas. |
| Project structure | 1. Recycling process design, optimization, and scale-up from lab to pilot scale<br>2. PV module waste pyrolysis mathematical model and prototype development<br>3. PV module leaching process optimization in the stirring system using a combined experimental and numerical method<br>4. Effective material separation by physical sieving-modelling-assisted experimental study |
| Targeted PV module | c-Si |
| Recycling technology type | Multiscale numerical models: mechanical, chemical, and thermal |
| Targeted and recovered materials | Si, Ag, Al |
| Quantitative target | Targeting >95% silver (Ag), copper (Cu), silicon (Si) recovery; energy consumption <25 kWh/kWp |
| Description of technology | The system integrates a high-temperature pyrolyser to remove the binding material from modules at high efficiency and productivity, low-temperature leaching reactors using less toxic chemicals to recover valuable metals at high efficiency, and customized waste treatment units to treat/reuse harmful waste gas and wastewater. |
| Website information | https://arena.gov.au/projects/efficient-low-cost-eco-friendly-solar-pv-recycling-technology/ |

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|---|---|
| Project title | Highly efficient, mobile, and flexible recycling technology for PV panels |
| Granting agency | New South Wales Environment Protection Authority (NSW EPA) |
| Implementing organization | The University of New South Wales |
| Project period | 2022–2024 |
| Project objective and target | This R&D project aims to develop a highly efficient, mobile, and flexible recycling technology to recover valuable metals, glass, and silicon from EOL PV modules, leveraging University of New South Wales, Sydney University, and University of Technology Sydney interdisciplinary research expertise in reactor and system design, PV modules, catalysis, metallurgy, etc., and collaborating with leading PV industry across the supply chain. The project is internationally innovative and advanced and will be technically achieved by combining computer modelling for reactor design and scale-up, experiments for chemistry/catalysis design, and system prototyping for effective demonstration with technology assessments. |
| Project structure | 1. Lab-scale fundamental studies<br>2. Pilot-scale and simulation studies. |
| Targeted PV module | c-Si |
| Recycling technology type | Thermal, mechanical, chemical |
| Targeted and recovered materials | Silver, copper, silicon, and glass |
| Quantitative target | The project targets more than 95% silver, copper, silicon, and glass recovery; energy consumption at less than 30 kWh/kWp; and a stable run greater than 8 hours. |
| Description of technology | After lab-scale fundamental studies, the reactors will be scaled-up to pilot and then virtually trialled through simulations to industry scale for fitting into transportable containers with an optimized layout. The expected outcomes include lab-scale prototypes and a virtual industry-scale system. The up-scalable computer models and technology assessment will provide a competitive and sustainable PV module recycling solution toward NSW's circular economy. |
| Website information | https://www.epa.nsw.gov.au/working-together/grants/infrastructure-fund/circular-solar-trials |

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|---|---|
| Project title | Electrically Enhanced Recycling Process for EOL Si PV Cells |
| Granting agency | The Australian Renewable Energy Agency (ARENA) |
| Implementing organization | Swinburne University of Technology |
| Project period | 2020–2024 |
| Project objective and target | The project aims to provide a novel technology solution that contributes to the production of solar-grade silicon (99.9999%) from secondary silicon raw materials. The pyrometallurgical process to be investigated involves the application of external electricity through electrodes placed across molten silicon and slag phases. This technology could remove impurities (such as B and P) at faster rates and higher amounts compared to the regular refining or current Si production process and promote the recovery of high-value precious metals (including Ag paste) from EOL PV, making the overall recycling process economically attractive. |
| Project structure | 1. Thermodynamic Modelling and Assessment<br>2. Measurement of Distribution Coefficient of Boron and Phosphorus<br>3. Kinetics of Boron Removal from Silicon during Slag Treatment<br>4. Melting of End-of-Life PV Module<br>5. Multi-Stage Slag Treatment<br>6. Behaviour of Silver-Silicon Alloy during Silver Separation. |
| Targeted PV module | c-Si |
| Recycling technology type | Pyrometallurgy |
| Targeted and recovered materials | Si, Ag |
| Quantitative target | Impurities (phosphorus and boron) removal (>90%)<br>Ag recovery in Si (>90%) |
| Description of technology | The project investigates experimentally, computationally, and fundamentally the electrically enhanced Si-slag refining process and determines thermo-electrical properties of minor elements P, B, and Ag. Equilibrium and kinetic experiments will be conducted at laboratory scale without and with applied electricity to determine the influence of the electrical potential on the properties of the system and minor elements. In addition, a pilot-scale reactor will be designed, constructed, and tested to verify and investigate the influence of electricity on a larger scale to silicon refining by using synthetic pure materials and industrial PV module scrap as raw materials. Simultaneously, the fundamentals behind the phenomenon will be clarified and models to correlate electricity with the minor element kinetics and equilibrium will be constructed. |
| Website information | https://arena.gov.au/projects/electrically-enhanced-recycling-process-for-eol-si-pv-cells/ |

Technology Collaboration Programme
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