End-of-Life Management

Best Practice Guidelines

Version 1.0

SolarPower
Europe

Foreword

Welcome to the first edition of SolarPower Europe's End-of-Life (EoL) Management Best Practice Guidelines. In 2023, over 55 GW of solar was installed across the EU in yet another record-breaking year for the industry. This record should be celebrated, and it means that Europe now has a cumulative installed capacity of 263 GW and one of the oldest solar fleets in the world. A part of the existing fleet will start reaching EoL in the next decade, with increasingly more waste being produced as time progresses. This makes the question of how to handle significant solar PV waste streams, a pressing one. Moreover, what should the industry do with equipment that has been replaced, but still functions? Ensuring quality and circular EoL management of PV waste, is crucial to the sustainability of the industry and public acceptance of solar, as a responsible, clean source of energy.

Over the course of its seven years of operation, the workstream has developed five sets of Best Practice Guidelines, covering Engineering, Procurement & Construction (EPC), Operations & Maintenance (O&M), Asset Management, the Lifecycle Quality Best Practice Guidelines, and now the End-of-Life Best Practice Guidelines.

This document is the result of a year of intensive work by 30 leading solar experts, from over 15 companies. The contributors work across the solar PV industry, and they include EPC and O&M service providers, producer responsibility organisations (PROs), Asset Managers, Asset Owners, manufacturers, legal experts, digital solutions providers, technical advisors, investors and organisations.

The first edition of the EoL Best Practice Guidelines is an industry-first set of recommendations on how to boost the sustainability of solar. With 30 contributors, they constitute the most complete overview of how to handle key components of a solar system once they have reached the end of their useful lives, including their decommissioning and replacement. The guidelines also highlight the key elements of European legislation that apply to waste electrical and electronic equipment (WEEE), and govern the EoL of PV components, going into detail on the collection and recycling schemes that are available to the solar industry. With circularity also becoming an increasingly important theme, the guidelines offer recommendations on how to assess the potential for second life of components of a PV system.

The workstream has been busy in 2023, launching a new digital platform for the Best Practice Guidelines, making them more searchable and accessible than ever before. A new jobs guide for job seekers looking to enter the industry was launched at the SolarPower Summit. There has also been a minor update to the EPC Best Practice Guidelines contracting section that can be found on solarbestpractices.com. Branching out from previous years, the workstream has been involved in adapting the European Agrisolar Best Practice Guidelines to the Indian context, building on the work done on the Indian editions of the O&M and EPC Best Practice Guidelines. This builds on an extremely active 2022, which saw the launch of EPC Best Practice Guidelines – Sub-Saharan Africa edition and the Jordanian versions of the EPC and O&M Best Practice Guidelines.

We thank our members for their extraordinary level of engagement, which reflects the importance of lifecycle quality for the solar industry. We will continue the work in 2024 and invite interested stakeholders to join our community to be part of this undertaking.

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Project Information: The SolarPower Europe O&M Task Force officially started its work in April 2015, and it became the Lifecycle Quality Workstream in 2020, to cover O&M, Asset Management and EPC. It operates through frequent exchanges and meetings. The workstream's flagship reports are the O&M Best Practice Guidelines, the Asset Management Best Practice Guidelines, the EPC Best Practice Guidelines, and the Lifecycle Quality Guidelines. They reflect the experience and views of a considerable share of the European solar industry today. There has been no external funding or sponsorship for these reports.

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List of abbreviations

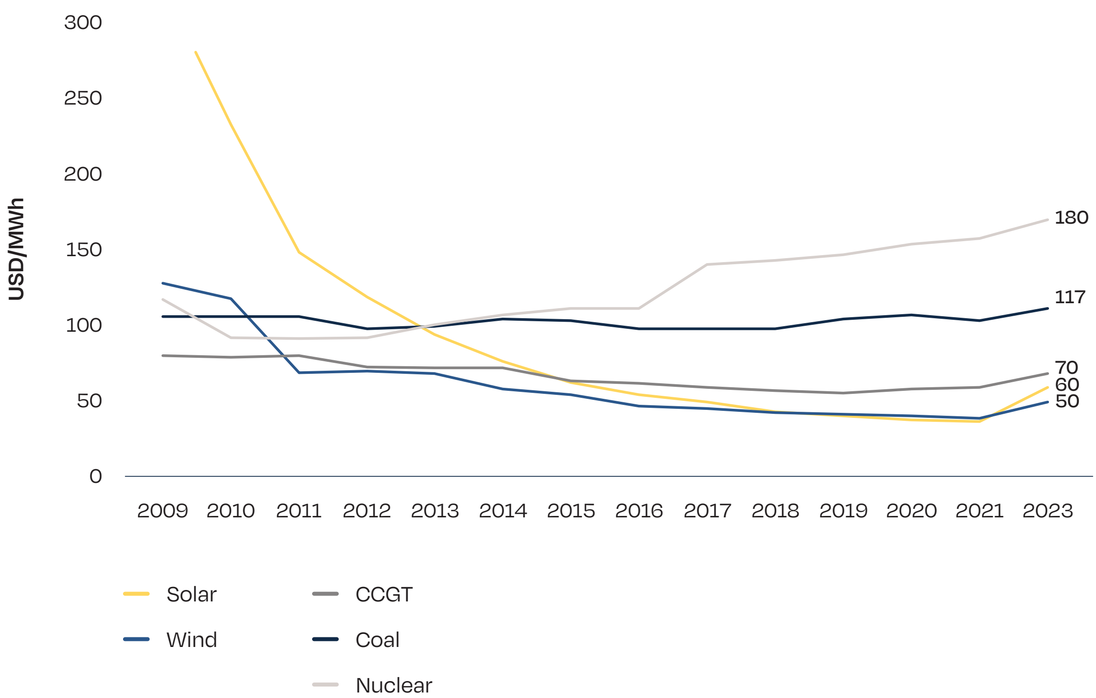
AC	Alternating Current
ANSI	American National Standards Institute
B2B	Business-to-business
B2C	Business-to-clients
BMS	Battery Management Systems
BOM	Bill of Materials
BOS	Balance-of-system
CCGT	Combined Cycle Gas Turbine
C&I	Commercial and Industrial
CEAP	Circular Economy Action Plan
COD	Commercial Operation Date
DC	Direct Current
EL	Electroluminescence
EoL	End-of-Life
EPBT	Energy Payback Time
EPC	Engineering, Procurement & Construction
EPR	Extended Producer Responsibility
EV	Electrical Vehicle
GEC	US Green Electronics Council
GPP	Green Public Procurement
H&SA	Health & Safety Authority
JEA	Japan Environment Association
LMT	Light Means of Transport
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
PID	Potential Induced Degradation
PLR	Power Loss Rate
ppm	Parts Per Million
PPWD	Packaging and Packaging Waste Directive
PPWR	Packaging and Packaging Waste Regulation
PRO	Producer Responsibility Organisation
R&D	Research and Development
RFID	Radio Frequency Identification
RoHS	Directive on the Restriction of Hazardous Substances in Electrical and Electronic Equipment
SLI	Start, Light and Ignition
SMEs	Small Medium Enterprises
SN	Serial Number
STC	Standard Test Conditions
TC 82	Technical Committee 82
WEEE	Waste from Electrical and Electronic Equipment
WFD	Waste Framework Directive

1.1. Rationale, aim, and scope

The European solar industry has experienced unprecedented growth in recent years. Driven by a rapidly decreasing levelised cost of electricity (LCOE) and a redoubling of efforts to accelerate the EU's green transition, solar is beginning to realise its potential as the spine of Europe's new, modern and resilient energy system.

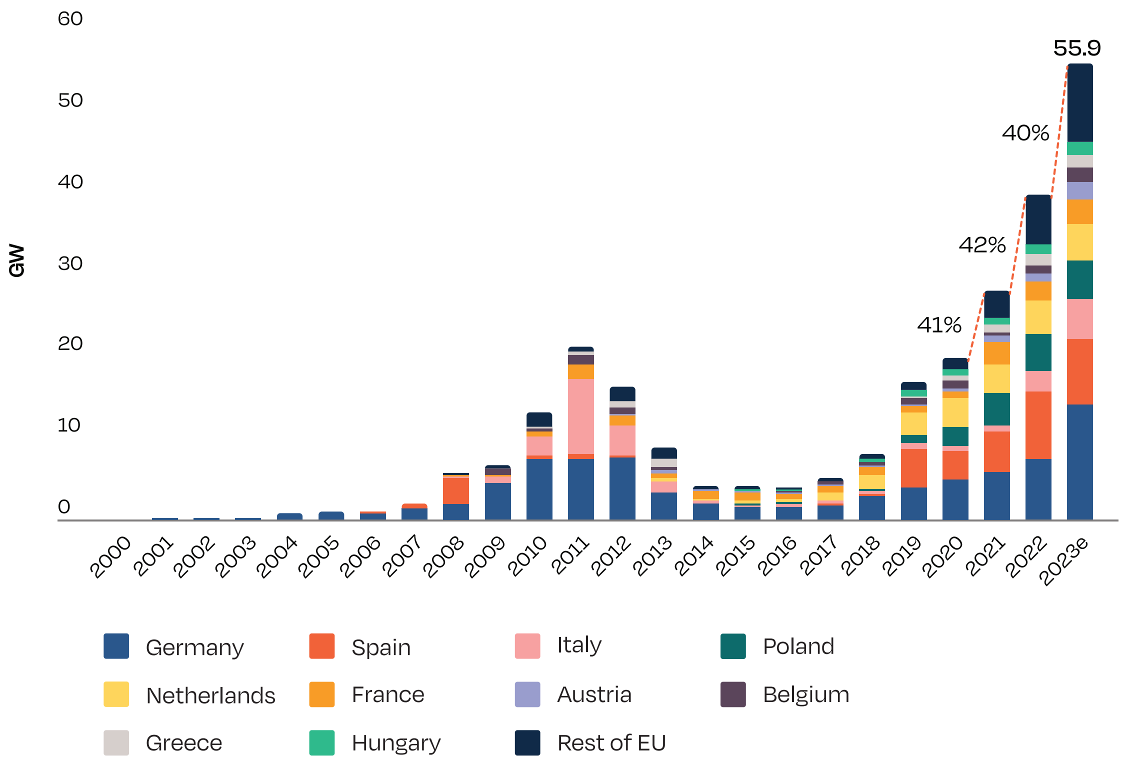
However, this impressive growth poses a key challenge for the industry in the future; namely, what to do once all the solar PV that has been installed begins to reach its EoL. Across the EU, over 260 GW of solar capacity were in operation at the end of 2023, a fleet that is poised to grow to at least 750 GW by 2030, as per the REPowerEU target. Considering that the first PV systems were installed in the early 2000s, and

FIGURE 1 SOLAR ELECTRICITY GENERATION COST IN COMPARISON WITH OTHER POWER SOURCES 2009-2023



SOURCE: Lazard (2023). Historical mean unsubsidised LCOE values (nominal terms, post-tax).

FIGURE 2 EU ANNUAL SOLAR PV INSTALLED CAPACITY 2000-2023



assuming a 30-year operational lifetime for PV modules, it can be expected that solar waste streams will start becoming sizeable around 2030, and will continue growing in the following decades. If poorly managed, the environmental impact of solar waste has the potential to cause serious damage to solar's reputation as an environmentally friendly technology. Similarly, public opinion could potentially turn against the industry as landfills begin to fill up with scrapped solar panels.

These Guidelines detail the final stage of any solar asset's lifecycle. They aim to provide a clear description of the legal obligations that apply to stakeholders of a PV power plant once it reaches EoL and the main methods that they can use to ensure compliance. Through raising awareness amongst the industry of best practice and the innovations taking place, these guidelines also seek to ensure that solar is able to make a valuable contribution to the EU's circular economy aims.

1.2. How to benefit from this document

These Guidelines include an overview of the legislative framework governing waste management and management of waste electrical and electronic equipment (WEEE), drawing out the obligations placed on the solar industry at the EoL stage of a solar asset. Although they have not been tailored to individual stakeholders, the purpose of the Guidelines is similar for all – understanding the mandatory requirements for all stakeholders and the ways to ensure compliance with them. Furthermore, the Guidelines seek to regroup current research and efforts that are being developed to improve the circularity of solar, such as preparation for re-use of PV panels that have been decommissioned during revamping or repowering (for more information on best practices for revamping and repowering, see Chapter 7. *Revamping and Repowering*, in SolarPower Europe's O&M Best Practice Guidelines.) Any stakeholders can benefit from this work and tailor it to their needs without lowering the bar and know what to ask for, offer or expect.

In line with other Best Practice Guidelines from SolarPower Europe the value proposition of this report is its industry-led nature, gathering the knowledge and experience of well-established and leading companies in the field of O&M service provision, recycling and circularity, waste management, utilities, and manufacturers. The scope of the legislation covered in these guidelines covers the utility-scale, commercial and industrial, and residential segments. The Guidelines are based on the experience of companies operating globally (with a focus on Europe) and identify high-level requirements that can be applied in Europe. However, it should be noted that there may be differences in the way that EU directives are transposed into EU Member State national legislation. This is not included and should therefore be considered separately if the Guidelines are to be used in specific countries.

The content covers technical and non-technical requirements, classifying them, when possible, into the following:

1. **Minimum requirements**, below which the approach to waste management is non-compliant with the relevant EU legislation.
2. **Best practices**, which are methods considered state of-the-art, producing optimal results by balancing the technical as well as the financial side.
3. **Recommendations**, which can add to the quality of the service, but whose implementation depends on the considerations of the Asset Owner, such as the available budget and services offered by the original equipment manufacturer.

To differentiate between these three categories, verbs such as "should" indicate minimum requirements, unless specified otherwise, as in, "should, as a best practice" or "as a recommendation".

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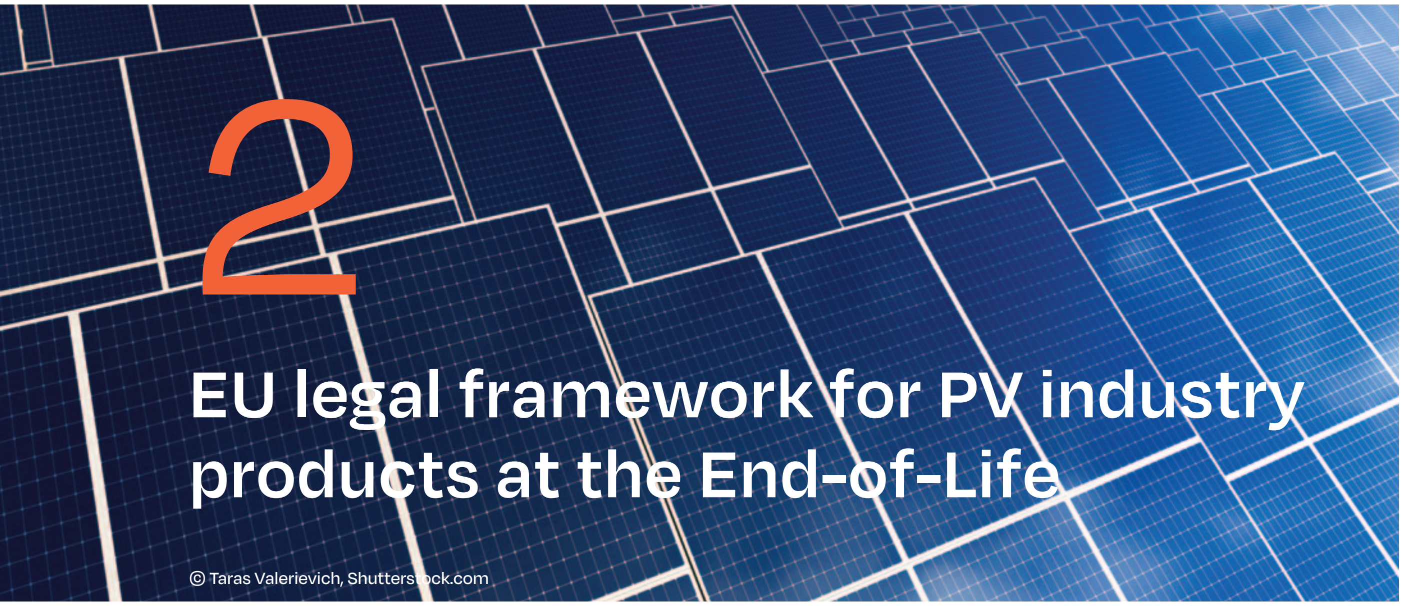

2 EU legal framework for PV industry products at the End-of-Life

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2.1. Quantification of risks

Legally, the handling of EoL products in the PV industry is subject to Extended Producer Responsibility (EPR) policies, which not only cover PV panels but also extend to inverters, storage systems, and their accompanying packaging. It is within this legal context that the industry is tasked with upholding environmental integrity, from the initial stages of product design to the EoL.

This chapter offers a comprehensive analysis of the current EU legislation that pertains to EoL management within the PV industry. It presents the specific legislative requirements imposed on the PV sector, providing a detailed understanding of the regulatory framework governing the industry's responsible EoL practices.

More specifically, the chapter highlights the Waste Electrical and Electronic Equipment (WEEE) Directive, the Battery Directive (soon to be replaced by an updated Battery Regulation), the Waste Framework Directive (WFD), Ecodesign Regulations, and the Packaging Directive. By shedding light on existing legislations and offering insights into future regulatory developments, this chapter aims to provide clarity on the evolving legal responsibilities and environmental accountability for the European PV industry.

2.2. Extended Producer Responsibility

The principle of the Extended Producer Responsibility (EPR) means that whoever places a product on the European market, is also responsible for organising its collection, treatment and financing once these become waste. Therefore, in addition to guaranteeing the quality and safety of the products placed on the European market, producers must also provide for the environmentally sound management of waste from products and packaging.

EPR is one of the main instruments the EU has established to support the development of a **circular economy**, using discarded products as a source for materials that can be re-used, reducing the need to use new raw materials.

EPR has been applicable to PV panels since 2012, when they were included in the scope of the WEEE Directive. Before 2012, the EU Packaging Directive and the Battery Directive imposed EPR obligations on batteries used in photovoltaic installations and packaging in which various PV products are delivered in.

To comply with EPR obligations, producers can choose to do individually, or collectively via Producer Responsibility Organisations (PROs) and compliance schemes. In all cases the obligations require the establishment of collection networks for different types of waste, and the requisite logistics and treatment technologies for enhanced recovery of materials. In this way, EPR helps the development of sustainable waste management and recycling industries that can also bring significant environmental, social and economic benefits.

Compliance schemes guarantee that waste from their participants complies with WEEE, battery and packaging EPR obligations. They are organised on a collective basis, generating cost efficiencies for their members.

2 EU legal framework for PV industry products at the End-of-Life / continued

There are PROs in operation in each of the 27 EU Member States and the UK that adhere strictly to local requirements and regulations.

The collection and recycling networks established by schemes like these include certified operators' equipment with all the quality standards and financial capabilities to meet the relevant collection and recycling requirements.

2.3. Requirements arising for the PV sector from the Waste Framework Directive

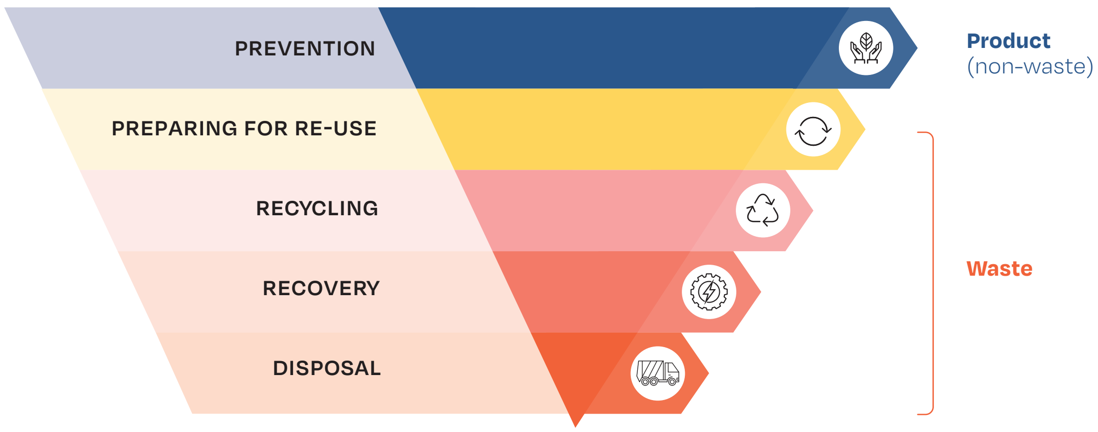
2.3.1. Summary of current producer obligations

The Waste Framework Directive 2008/98/EC (WFD) came into force in 2008, repealing the Directives 75/439/EEC, 91/689/EEC and 2006/12/EC. A consolidated version was published in 2018. This directive outlines the waste management guidelines in the EU and lays down measures to protect the environment and human health. The WFD establishes the key principles for waste management, including a waste hierarchy that orders waste management practices from most desirable to least desirable.

Article 8 of the WFD outlines the concept of **extended producer responsibility** (EPR), which requires producers to take financial and organisational responsibility for the management of waste generated by their products. This is done through the **establishment of EPR schemes that are regulated by Article 8a.** The purpose of Articles 8 and 8a is to promote sustainable waste management practices and to outline the general minimum requirements for EPR schemes that the EU Members States can implement locally.

The EPR schemes must have a clearly defined geographical, product and material coverage without giving preference to those areas where the collection and management of waste **are the most profitable.** They shall also be responsible for ensuring that waste collection systems have an appropriate level of availability within the areas under their geographic scope. They shall have the necessary financial and/or organisational means to meet their obligations and will establish an adequate **self-control mechanism,** supported, where relevant, by **regular independent audits.** In addition, they shall **make information** about the attainment of the waste management targets publicly available.

FIGURE 3 OVERVIEW OF THE WASTE HIERARCHY AS DEFINED IN THE WASTE FRAMEWORK DIRECTIVE



SOURCE: European Commission.

The Member States **shall allow** producers placing products in another Member State to appoint an **authorised representative** on its territory to fulfil their obligations. Member States may also set requirements for this authorised representative, such as registration, information, and reporting requirements, to monitor and verify compliance.

Member States are required to facilitate regular communication among stakeholders such as producers, distributors, waste operators, local authorities, civil society organisations, and social economy actors regarding the implementation of EPR schemes.

2.3.2. Outlook

Despite existing legislation, municipal waste generation has increased over the last decade. Therefore, the European Commission is currently working on a targeted revision of the WFD and has conducted a preliminary analysis to assess its impact, including stakeholder consultations running from January-February 2022.

According to the analysis, low recycling rates, as well as lower quality recyclable materials, are in part due to inefficient waste-collection systems. The Commission defined the scope of the targeted amendment of the WFD in 2023, based on this analysis, and taking into consideration efforts to implement the 2018 Waste Package, and the ongoing reviews of the Packaging Directive, Batteries Regulation, Industrial Emissions Directive, and the Ecodesign for Sustainable Products regulation.

This suite of reforms aims to decrease waste generation, and to improve separate waste collection, as well as avoiding the contamination of recyclable waste. The initiative aims to achieve these objectives by promoting full implementation of waste prevention provisions and recycling, providing additional guidance, and considering regulatory measures. The regulatory measures may include **targets on waste reduction** and/or residual waste reduction, **expanding the role of EPR schemes** in attaining waste-prevention objectives, introducing minimum requirements for source segregation and separate collection of waste, and by expanding EPR schemes to other product categories.

Transposing and implementing new provisions and adapting collection schemes may lead to additional costs at the national and local levels. Producers may also incur costs through adjustments made to existing EPR schemes, or the establishment of new ones. On the other hand, reducing waste could lead to lower waste-management costs and benefit the cost-efficiency of the waste-management sector and secondary raw materials markets.

After the completion of the impact analysis, the European Commission started a public consultation with all relevant stakeholders. The consultation was held to gather feedback and input from interested parties on the proposed changes to the Directive. The consultation ended on 24 August 2022, and the Commission published its Proposal to amend the Directive in July 2023. The feedback period on the proposal lasted until November 2023, and will be presented to the European Parliament and Council to feed into the legislative debate.

2.4. Requirements arising for the PV sector from the WEEE Directive

2.4.1. Summary of current producer obligations

The WEEE Directive introduces EPR which obliges the producer of electronic and electric equipment to finance the collection, treatment, recovery, and environmentally sound disposal of the e-waste. Furthermore, the WEEE Directive promotes the ecodesign of electric and electronic equipment in view of facilitating the re-use, dismantling, and recovery of WEEE, its components, and materials. In the PV industry the producer is normally the equipment manufacturer, or a distributor that has imported the component into an EU Member State's market.

The WEEE Directive distinguishes between equipment used by private households, and that used by professionals when elaborating the financing structure for the management of electric and electronic equipment:

1. Products used **by both – private users and professionals** – are considered as household equipment **(also called B2C equipment)**, thanks to the 'dual notion' and should be registered and reported as such (for example - standard PV panels generating electricity inside in private households and in solar parks are considered as household equipment). Producers or importers of household

equipment are obliged to finance the collection, treatment, recovery, and environmentally sound disposal of WEEE from private households. When a producer places a product on the market, they must provide a guarantee showing that the management of all WEEE will be financed. The guarantee may take the form of participation in appropriate compliance schemes for the financing of the management of WEEE, recycling insurance, or a blocked bank account.

2. Products used **only by professionals (B2B equipment)** generate e-waste in larger quantities, from commercial, industrial, institutional, and other sources. In the case of a large-scale PV system, designed for professional use, the producer of the professional equipment used (e.g., utility-scale inverters, racking systems) must finance the cost of collection, treatment, recovery, and the environmentally sound disposal of WEEE. Producers and users other than private households may conclude agreements defining other financing methods.

The WEEE Directive divides electrical and electronic equipment (EEE) into 6 categories. **PV panels fall under Category 4, dedicated to Large Equipment.** It is worth mentioning that each Member State can set up its own categorisation for PV panels whilst transposing the WEEE Directive into its national legislation. Project developers should always be aware of these differences in the transposition of the WEEE Directive across EU Member States.

The Directive imposes a set of seven obligations on producers of EEE, including PV panels, where the producer must:

1. **Register** in the national WEEE register, in case of distance selling – through the authorised representative.
2. **Finance** the collection and treatment of waste PV panels. This obligation can be fulfilled either individually or by joining a collective scheme.
3. The producer must ensure that private households can return WEEE free of charge.
4. Achieve **annual collection and recovery, recycling targets.**
5. **Report** on a regular basis to the authorities about the quantity of PV panels and inverters put on the market in that country, of the achievement of collection and treatment targets, and waste shipped within or outside the EU.
6. **Mark** the product with a crossed-out wheelie bin. This is designed to indicate to the end-user that the equipment must not be put in the general rubbish but consigned to its own waste stream.

7. **Provide** information for **end-users about the proper disposal** of PV panel waste, the role of the end-user in waste management, the potentially harmful effect of the presence of hazardous substances in EEE, and the meaning of the crossed-out wheelie bin.
8. **Provide** information for **waste treatment plants of the composition of the product**, including the use of the hazardous substances to support proper treatment.

As alluded to above, the WEEE Directive (Art. 7(1)) establishes collection targets that must be fulfilled by producers of e-waste. These include a minimum collection rate to be achieved annually of:

- 65% of the average weight of EEE **placed on the market** in the three preceding years in the Member State concerned, or alternatively **85% of WEEE generated** on the territory of that Member State.

Member States must demonstrate achievement of either one of the collection rates above on an annual basis. Collection rates set in Art. 7(1) do not set individual collection rates for specific product categories, they refer to the national target to be achieved for WEEE in general and not to each one of the different categories.

The WEEE Directive also set **recovery targets and recycling and re-use targets for equipment falling into Category 4 from 15 August 2018** (Art. 11 and Annex V):

- A minimum of 85% of all products under Category 4 must be recovered.
- A minimum of 80% of these recovered products (including PV panels) shall be prepared for re-use or recycled.

These targets are input-based and are calculated by dividing the weight of WEEE entering the recovery or recycling/preparing for re-use facility, by the weight of all separately collected WEEE of the same category, expressed as a percentage (Article 11(2)).

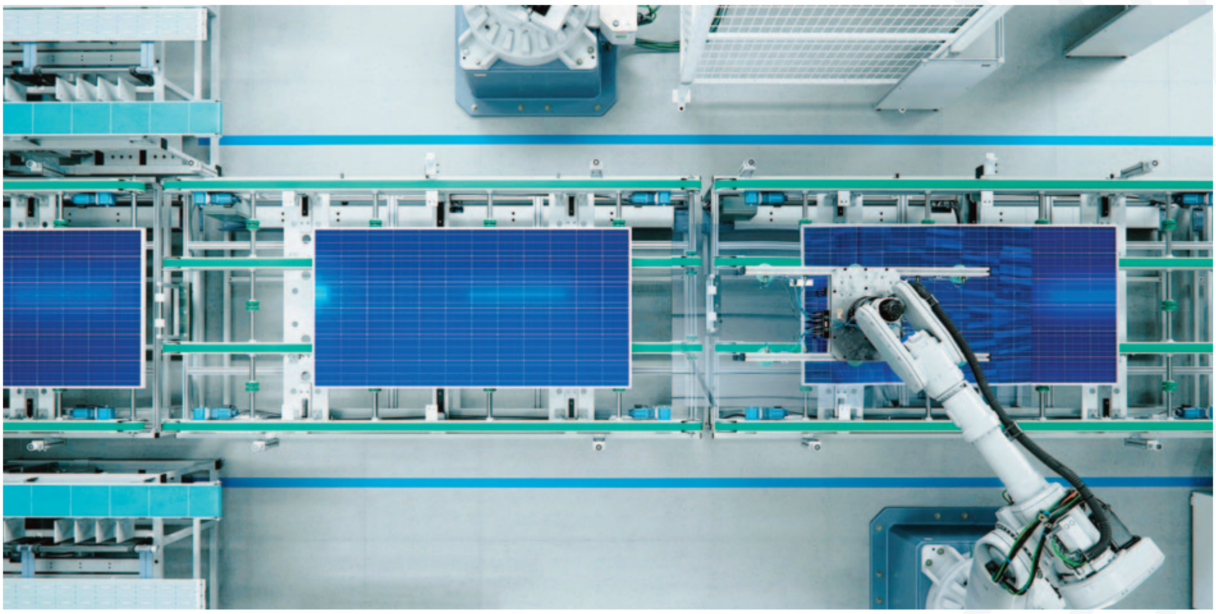
Single countries can apply a different calculation model for the collection target of PV panels due to the very low return rate (actually below 1% of the volume put on the market). This can heavily influence the cost of waste compliance for this category.

The WEEE Directive does not define specific categories for PV components, such as inverters and modules. Therefore, EoL management varies depending on the EU Member State in question and their national regulations. Usually, inverters are considered and handled as "household electronics" or "consumer electronics" by e-waste companies and a financial contribution must be paid by the inverter manufacturer to a national system to ensure proper management of the inverter at the EoL stage. National regulations differ in criteria (levels, weight, sizes, etc.) and a difference between industrial and household e-waste is often made. However, the boundaries between the different power capacities are not always clearly defined or harmonised. Therefore, a clearer or more harmonised distinction between power capacities for electronics (what is "household"? What is "commercial"?) could facilitate the management of inverters' waste for the relevant stakeholders.

2.4.2. Outlook

The Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) 2023/0025 (COD) aims to amend Article 12, paragraphs 1, 3 and 4, Article 13(1) and Article 15(2) of the WEEE Directive as a follow-up to the judgement of the Court of Justice of the European Union in case C-181/20. The proposal maintains the full effectiveness of the EPR provisions. However, the EPR obligations currently placed on producers cannot be applied retroactively to PV equipment that was put on the market of a Member State before it was included in the scope of the WEEE Directive.

The proposal also aims to amend Article 14(4) and Article 15(2) to update the reference to the European standard EN 50419 by replacing it with the revised version of this standard, adopted in 2022. These proposed targeted amendments do not relate to any other policy provision in the WEEE area.



On October 6, 2022, the European Commission decided to evaluate the progress made under the WEEE Directive 2012/19/EU. The evaluation of the WEEE Directive is expected to provide evidence on whether the Directive is still fit for purpose, to explore any untapped potential for simplification and burden reduction as well as help to determine whether a review is needed. The evaluation report will be guided by the following three questions:

1. To what extent was the implementation of the WEEE Directive successful and which were the main problems and the main challenges and why?
2. Did the EU intervention make a difference?
3. Is the intervention still relevant given developments since its entry into force?

The evaluation will cover the implementation of the WEEE Directive along with the related secondary legislation and any related measures and good practices taken at the national level in all Member States. It will pay particular attention to aspects for which implementation has been particularly challenging, such as:

1. Meeting the WEEE collection targets.
2. Ensuring the proper treatment of WEEE, and a related level playing field.
3. Applying the Extended Producer Responsibility requirements (in particular for online sales).
4. Combating illegal activities and substandard practices in the whole WEEE management process.

Moreover, the evaluation will consider and collect evidence on all relevant legal (e.g., legal coherence and consistency with related legislation), environmental, economic, social, employment, health and technological aspects and developments relating to the generation and management of WEEE. It will provide an overview of the current situation and provide clear points of comparison against which to judge changes, progress and challenges faced.

2.5. Requirements arising for the PV sector from the Battery Directive

2.5.1. Summary of current producer obligations

The Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EC (the Battery Directive) entered into force in September 2006. The Directive distinguishes between portable batteries and accumulators and industrial and automotive batteries and accumulators. According to the Directive, **batteries and accumulators** used in connection **with PV Power Plants and other renewable energy applications** are considered as **industrial batteries and accumulators** and are defined as follows:

'Industrial battery or accumulator' means any battery or accumulator designed for exclusively industrial or professional uses or used in any type of electric vehicle.

The Directive sets the minimum **collection target** for EU Member States of 45% for all batteries by 26 September 2016. Member States shall adapt collection rates on a yearly basis according to a specific scheme defined in the Directive.

The Directive also establishes the following **minimum recycling targets**:

- 65% by average weight of lead-acid batteries and accumulators.
- 75% by average weight of nickel-cadmium batteries and accumulators.
- 50% by average weight of other waste batteries and accumulators.

The Directive established two basic requirements addressing the **producers of industrial batteries and accumulators** directly:

- **Collection**: producers, or parties acting on their behalf, must take back waste batteries from end-users, independently of their chemical composition and origin. At the same time, the legislation does not forbid the collection of waste industrial batteries by independent third parties.

- **Financing**: producers, or parties acting on their behalf, must finance the collection, treatment and recycling of all waste industrial batteries and accumulators they have collected. On the other hand, producers are also allowed to conclude financing agreements with the users, in this way deviating from this financial obligation.

2.5.2. Outlook

To modernise the EU legislative framework for batteries and accumulators, a Battery Regulation, which will repeal Battery Directive, was proposed for discussion and published for consultation in December 2020. Contrary to a Directive, which needs to be transposed into national laws, a Regulation has direct effect and enters into force on a set date in all the Member States.

Beginning in June 2023, the European Battery Regulation will gradually replace Directive 2006/66/EC. It will be implemented in all EU Member States simultaneously for the common purpose of minimising the harmful effects of batteries on the environment.

For the first time, the new requirements will cover the entire lithium battery life cycle (from extraction of the raw material to production, design, labelling, traceability, collection, recycling and re-use). Batteries will be divided into the following groups, depending on the application for which they are designed:

1. Portable and sealed batteries weighing 5 kg or less.
2. Portable batteries for general use, rechargeable and non-rechargeable.
3. LMT (light means of transport) batteries sealed and weighing 25 kg or less.
4. SLI (start, light and ignition) batteries for automotive use.
5. EV (electric vehicle) batteries, designed to provide power for traction of hybrid or electric vehicles.
6. Industrial batteries and all other batteries weighing over 5 kg not for use on vehicles or light means of transport.

Under the Battery Regulation, 'Industrial battery' means any battery:

- Designed specifically for industrial uses, or
- Intended for industrial uses after being subject to preparation for re-use or repurposing, or
- Any other battery with a weight above 5 kg that is not an LMT battery, an electric vehicle battery or an SLI battery.

Apart from modifying the definition of an industrial battery and inserting the new ones, the proposed Regulation suggests various changes and improvements in terms of **design, minimum performance levels and general take-back obligations.**

Detailed EPR obligations

Contrary to the Battery Directive, the Regulation details the obligation to provide **EoL information** to the end user, as well as information on safety and protection measures for distributors and other economic operators.

According to the Regulation, producers can choose whether to comply with EPR on an individual basis, or via a PRO, which can modulate producer fees against environmental criteria. Both individual and collective systems must have **authorisation** from the competent authorities to operate on the market.

Collection of industrial batteries must be organised by producers or collection points - organised in cooperation with distributors and operators carrying out re-use, repurposing, treatment and recycling facilities, as well as public authorities - free of charge for the end-users.

The following new minimum recycling efficiencies are introduced by the Regulation:

No later than 31 December 2025

- 75% by average weight of lead-acid batteries.
- 65% by average weight of lithium-based batteries.
- 80% by average weight of nickel-cadmium batteries.
- 50% by average weight of other waste batteries.

The recycling efficiency refers to the percentage of the entire battery that is recycled. It is calculated on the basis of the overall chemical composition (at elemental/compound level) of the input and output fractions. 'Input fraction' refers to the components of the battery entering the recycling process and 'output fraction' refers to the components that are produced from the input fraction as a result of the recycling process.

No later than 31 December 2030

- 80% by average weight of lead-acid batteries.
- 70% by average weight of lithium-based batteries.

A new requirement related to a minimum recovery level of specific materials in the recycling process is also introduced:

By 31 December 2027

- 90% of cobalt, copper, lead, nickel and 50% of lithium shall be recovered.

By 31 December 2031

- 95% of cobalt, copper, lead, nickel and 80% of lithium shall be recovered.

The Regulation also provides the exact information that the registration application of battery producers shall contain and sets a deadline for the issuance of registration numbers.

In addition, it obliges the producers of industrial batteries to **report** to the competent national authorities annually on the batteries made available on the market of the Member State, as well as the data on collections and deliveries for preparing for re-use or repurposing, and for treatment.

Recycled content

60 months after entry into force of the Regulation or 24 months after the entry into force of the delegated act establishing the methodology for the calculation and verification of the share of recycled metals, whichever is later, **industrial batteries with a capacity above 2 kWh, except those with exclusively external storage**, that contain cobalt, lead, lithium or nickel in active materials will be accompanied by **technical documentation containing information about the share of metals recovered** from waste.

96 months after entry into force of the Regulation, the technical documentation of industrial batteries with a capacity above 2 kWh, except those with exclusively external storage, will demonstrate the following **minimum recycled shares**:

- 16% for cobalt.
- 85% for lead.
- 6% for lithium and nickel.

156 months after entry into force of the Regulation:

- 26% for cobalt.
- 85 % for lead.
- 12% for lithium.
- 15% for nickel.

New information and labelling requirements

36 months after the entry into force of the Regulation or 18 months after the entry into force of the implementing act, batteries will be marked with a **label containing general information on the battery** including, **hazardous substances contained in the battery other than mercury, cadmium or lead, as well as critical raw materials.**

Additionally, 42 months after entry into force of the Regulation, batteries will be marked with a **QR code** providing access to:

- The **battery passport** for industrial batteries with a capacity above 2 kWh.
- The **general information** referred to above, wheelie bin, chemical symbols, declaration of conformity, the report on due diligence policies and the information regarding the prevention of waste and the management of waste batteries.

Labels and QR codes will be applied directly to batteries 12 months after the date of entry into force of the Regulation. **Stationary battery energy storage systems** that use a battery management system will contain in their battery management system current data on the **parameters for determining the state of health and expected lifetime** of batteries. The information stored will be made available to the end-users, as well as the third parties engaged in the repurposing of the batteries.

Conformity of batteries

The Regulation also lays down the requirements concerning the conformity assessment procedure. All batteries, before being placed on the market or put into service in the EU, will undergo **conformity assessment.** After that, the **EU declaration**, confirming a battery's compliance with the requirements of the Regulation, will be drawn up and **CE marking** will be affixed to the battery.

Repurposing and remanufacturing

The Regulation also establishes requirements applicable to the repurposing and remanufacturing of industrial batteries. This obliges those engaged in repurposing and remanufacturing processes to ensure that those batteries comply with all relevant requirements established in the Regulation and those related to product design, environmental, human health protection and transport safety in other EU legislation.

Supply-chain due diligence for raw materials

From 24 months after entry into force of the Regulation, economic operators that place batteries on the market will be obliged to comply with the newly established supply chain due diligence obligations. The proposal establishes a **turnover threshold for this requirement at EUR 40 million.**

According to the Regulation, *'battery due diligence means the obligations of the economic operator, in relation to its management system, risk management, third-party verifications and surveillance by notified bodies and disclosure of information with a view to identifying, preventing and addressing actual and potential social and environmental risks linked to the sourcing, processing and trading of the raw materials and secondary raw materials required for battery manufacturing including suppliers in the chain and their subsidiaries or subcontractors that perform such activities.'*

Battery passport

From 42 months after entry into force of the Regulation, each industrial battery with a capacity above 2 kWh placed on the market or put into service shall have a **digital battery passport**, which shall be **accessible through the QR code.** The battery passport shall include information on the basic characteristics of the battery, the battery model and information specific to the individual battery.

In case of repurposing or remanufacturing, the party responsible for putting the repurposed or remanufactured battery on the market or into service will be responsible for the data provision in the passport.

2.6. Requirements arising for PV sector from Packaging Directive

2.6.1. Summary of current producer obligations

The European Packaging and Packaging Waste Directive 94/62/EC (1994) (PPWD) entered into force on June 30, 1996. This Directive covers all packaging placed on the European market, including industrial, commercial, service, and household packaging, regardless of the material used. The legal act aims to prevent the generation of packaging waste and minimise its environmental impact.

The provisions are legally binding only for Member States, not producers. Therefore, the exact obligations that producers must comply with vary depending on how PPWD has been transposed in each EU Member State. Thus, the obligation to finance the collection, recovery, recycling, and re-use, and the accompanying registration and reporting processes, among others, are subject to national legislation.

Considering two possible applications of PV products, one being residential use, characterised by smaller PV panels, and the second being larger, or utility-scale solar installation, PPWD defines two different types of packaging, to which PV products could belong:

1. For household PV panels, the **sales or primary packaging**, defined as packaging conceived so as to constitute a sales unit to the final user or consumer at the point of purchase.
2. For industrial solar installations, the **transport packaging or tertiary packaging**, defined as packaging conceived so as to facilitate handling and transport of a number of sales units, or grouped packaging to prevent physical handling and damage during transportation. Transport packaging does not include road, rail, ship and air containers.

In terms of Member State responsibilities, they shall take the necessary steps to:

1. Encourage the increase in the share of **reusable packaging** placed on the market and of systems to reuse packaging in an environmentally sound manner (deposit-return schemes; setting of qualitative or quantitative targets; use of economic incentives; setting up of a minimum percentage of reusable packaging placed on the market every year for each packaging stream). Establish systems to provide for the **return and/or collection** of waste packaging from the consumer, other final user, or from the waste stream in order to channel it to the most appropriate waste management alternatives.
2. Aim for the re-use or recovery of packaging including recycling of the packaging and/or packaging waste collected against the following minimum targets:
   a. 60% of the weight of packaging waste will be **recovered or incinerated** at waste incineration plants with energy recovery.
   b. Currently a minimum of 55% of the weight of packaging waste will be recycled. This figure will rise to 65% as of 31 December 2025, and again to 70% as of December 2030, with a ceiling of 80%.

c. The following **minimum recycling weight targets for packaging materials** will be attained:

   i. Glass: currently - 60%, from 31 December 2025 – 70%, from 31 December 2030 – 75%.

   ii. Paper and cardboard: currently - 60%, from 31 December 2025 – 75%, from 31 December 2030 - 85%.

   iii. Metals: currently - 50%, from 31 December 2025 - 70% of ferrous metals and 50% of aluminium; from 31 December 2030 - 80% of ferrous metals and 60% of aluminium.

   iv. Plastics – currently - 22.5 %, from 31 December 2025 – 50%, from 31 December 2030 – 55%.

   v. Wood: currently - 15%, from 31 December 2025 – 25%, from 31 December 2030 - 30%.

3. Ensure that users of packaging, in particular consumers, obtain the necessary information about the return, collection and recovery systems available to them, their role in contributing to re-use, recovery and recycling of packaging and packaging waste, the meaning of markings on packaging currently on the market, and the appropriate elements of the management plans for packaging and packaging waste.

4. Establish **databases on packaging and packaging waste** to enable Member States and the European Commission to monitor progress towards the objectives.

2.6.2. Outlook

Currently, the *Regulation on packaging and packaging* waste (PPWR), that will **repeal PPWD**, is expected to be published at the end of 2023 and enter into force one year after its publication date.

PPWR will create one legal instrument with uniform application across the EU Member States. This new regulation will set requirements over the entire lifecycle of packaging, related to:

- Environmental sustainability.
- Harmonised labelling.
- **Extended Producer Responsibility systems**, collection, treatment and recycling of packaging waste, registration and related reporting requirements, modulation fees among others.

The PPWR retains design requirements from the Packaging Directive and introduces some new ones. Packaging producers, importers, and those service providers that help them fulfil their obligations must ensure that the **packaging complies** with the following:

2 EU legal framework for PV industry products at the End-of-Life / continued

- It has been **designed and manufactured** in accordance with the applicable requirements (substance limits, recyclable content, packaging minimisation, among others).
- It is **labelled** in accordance with the applicable requirements.
- It undergoes the relevant **conformity assessment procedure.** This can be carried out by a third party, but all packaging must have the relevant **technical documentation and declaration of conformity.**
- If required, a producer must assign an **authorised representative** to ensure the fulfilment of their obligations under the PPWR.

In accordance with PPWR all packaging shall be **recyclable.** To be considered recyclable it needs to comply with the following:

- Recyclability must be central to design as of 2030.
- It must be effectively and efficiently separated and collected.
- It must be able to be sorted into defined waste streams without affecting the recyclability of other waste streams.
- Once it has been recycled, the resulting secondary raw materials are of sufficient quality to substitute primary raw materials.
- It can be recycled at scale by 2035.

Producers **must demonstrate compliance** of this requirement through an EU declaration of conformity.

PPWR modifies the recovery and recycling targets set in PPWD and adds new categories of targets (minimum recycled content in packaging, prevention of packaging waste and re-use targets). Table 1 on the following page shows an overview of those targets established in PPWR.

TABLE 1 OVERVIEW OF MINIMUM RECOVERY AND RECYCLING TARGETS IN PPWR

TARGET	2025	2020	2035	2040
Minimum recycled content	n/a	35%	n/a	n/a
Recycling and promotion of recycling (Member States).	By 31 December 2025, a minimum of 65% of the total weight of all packaging waste generated. By 31 December 2025, the minimum percentages by total weight of the following specific materials contained in packaging waste generated: 50% of plastic. 25% of wood. 70% of ferrous metals. 50% of aluminium. 70% of glass. 75% of paper and cardboard.	By 31 December 2030, a minimum of 70% of the total weight of all packaging waste generated. By 31 December 2030, the minimum percentages by total weight of the following specific materials contained in packaging waste generated: 55% of plastic. 30% of wood. 80% of ferrous metals. 60% of aluminium. 75% of glass. 85% of paper and cardboard.	n/a	n/a
Prevention of packaging waste targets.	n/a	5%	10 %	15 %
Re-use target for transport packaging in the form of pallets, plastic crates, foldable plastic boxes, pails and drums.	n/a	From 1 January 2030, 30% of this type of packaging used is reusable packaging within a system for re-use.	n/a	From 1 January 2040, 90% of this type of packaging used is reusable packaging within a system for re-use.
Re-use targets for transport packaging for the transport and delivery of non-food items made available on the market for the first time via e-commerce.	n/a	From 1 January 2030, 10% of this type of packaging used is reusable packaging within a system for re-use;	n/a	(b)from 1 January 2040, 50% of this type of packaging used is reusable packaging within a system for re-use.
Re-use target for transport packaging in the form of pallet wrappings and straps for stabilisation and protection of products put on pallets during transport.	n/a	From 1 January 2030, 10% of this type of packaging used is reusable packaging within a system for re-use.	n/a	From 1 January 2040, 30% of this type of packaging used for transport is reusable packaging within a system for re-use.

Providers of online platforms, allowing consumers to conclude distance contracts with producers, must obtain the following information from producers offering packaging to consumers located in the EU:

1. The producer's registration information for the consumer's home market, including their registration number.

2. A self-declaration from the producer, committing to only offer packaging compliant with PPWR.

PPWR allows producers to either comply with their obligations individually, or through a Producer Responsibility Organisation (PRO).

Producers will be obliged to register themselves. They shall, to that end, submit an application for registration in each Member State where they make packaging available on the market. The producer's registration obligations must be fulfilled by an appointed representative for EPR compliance.

Producers or Producer Responsibility Organisations shall ensure that end-users have access to the following information regarding the prevention and management of packaging waste in that market:

- The role of end-users in contributing to waste prevention, including any best practices.
- Re-use arrangements available for packaging.
- The role of end-users in contributing to the separate collection of packaging waste materials, including handling of packaging containing hazardous products or waste.
- The meaning of the labels and symbols affixed, marked or printed on packaging.
- The impact on the environment and on human health or safety of persons of inappropriate discarding of packaging waste, such as littering or discarding in mixed municipal waste, and the adverse environmental impact of single-use packaging, in particular plastic carrier bags.
- The composting properties and appropriate waste management options for compostable packaging.

2.7. Requirements arising for the PV sector from the Ecodesign regulations and voluntary ecolabels

The EU legislation does not currently address the ecodesign of PV panels or inverters.

Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 **(RoHS Directive)** on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast) lays down rules on the restriction of the use of 10 hazardous substances in electrical and electronic equipment (EEE). PV panels are excluded from the scope of the RoHS, according to the following definition in Art. 2.4. *"Photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications".* Nonetheless, certain manufacturers strive to differentiate themselves by emphasising the absence of substances restricted under RoHS, such as lead, cadmium and phthalates.

2.7.1. Preparatory study for PV Ecodesign and Energy Labelling

In November 2020, the Joint Research Centre of the European Commission published a Preparatory study for solar photovoltaic modules, inverters and systems to *provide policy makers with the evidence basis for assessing whether to implement four policy instruments: Ecodesign, Energy Label, Ecolabel and Green Public Procurement (GPP) for photovoltaic products.*

One of the focus points of the study was existing Ecodesign instruments in the EU. The study confirmed that there are currently **no CE marking conformity requirements, or related European harmonised testing standards**, established at EU level specifically for solar PV panels or inverters. However, the manufacturers of the PV panels and inverters need to consider requirements that establish market entry criteria related to:

- Construction products in accordance with Regulation (EU) No 305/2011,
- Electromagnetic compatibility in accordance with Directive 2014/30/EU,
- Low voltage electrical equipment in accordance with Directive 2014/35/EU, and
- Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) in accordance with the recast Directive 2011/65/EU.

These all set requirements that apply to PV panels, inverters, and other components of PV systems when these enter the market of the European Union. They also require AC and DC power supply systems to conform with these regulations.

EU Green Public Procurement (GPP) criteria for the solar photovoltaic product group does not currently exist.

The same study identified the following international, **voluntarily Ecolabel criteria** that applied to some extent to PV products:

- TÜV Rheinland established criteria for PV panels under its Green Product Mark Ecolabel. These are likely adapted from EPEAT, the Ecolabel scheme of the US Green Electronics Council (GEC).
- Japan Environment Association (JEA) and Korea Environmental Industry & Technology Institute developed criteria for consumer products

incorporating photovoltaic cells. Similarly, Singapore Environment Council developed criteria only for consumer products.

- The German national Ecolabel, the Blue Angel, has included criteria for inverters since 2012.
- The American National Standards Institute (ANSI) established ecolabelling criteria for PV panels in ANSI standard 457, developed by NSF International with the support of the US Green Electronics Council (GEC).
- The US non-profit organisation Cradle to Cradle Products Innovation Institute has established a certification for the inherent sustainability of products and their component materials.

The Blue Angel is an ecolabel established by the German government in 1978, pioneering the development of product performance criteria for a broad range of consumer products.

The 2012 Blue Angel criteria for **inverters** apply to string and multi-string inverters with an output power of up to 13.8 kVA, that are designed for use in grid-connected PV power systems. Excluded from the product group are inverters integrated into a module (micro-inverters) and inverters designed for use in stand-alone systems. The eight technical criteria are:

1. Energy efficiency
2. Reactive power capability
3. Material requirements including plastic and electronic components
4. Recycling and disposal
5. Safety
6. Electromagnetic compatibility
7. Noise emissions

The criteria are all pass or fail and currently no licences have been awarded.

Previous attempts to develop criteria sets by the Blue Angel for PV **systems and modules** have not been successful.

Establishing criteria for PV systems ran into difficulty when no agreement could be reached on the assessment of energy yield and the restriction of hazardous substances. There was also no consensus on the methods for performing comparative analyses of system performance, instead designers were offered a range of options and software tools.

The module criteria were to include requirements relating to module quality (with reference to IEC 61215 and IEC 6164621), the Energy Payback Time (EPBT) of the product, the marking of components for recycling purposes, and a requirement for RoHS compliance which would have excluded certain PV-technologies containing lead or cadmium. Similarly, agreement could not be reached on how to measure performance.

Since 2015, the US organisation NSF International, with the support of the Green Electronics Council (GEC), has been leading a process to develop environmental criteria for photovoltaic modules. The result of this was the publication of ANSI standard 457, which is set to become an EPEAT standard as part of the global ecolabelling scheme for IT products. Given the global success of the EPEAT standards for ICT equipment, this new standard has potentially wider significance than just within the USA.

The standard contains product performance criteria, environmental and social, and consists of the following seven performance categories:

1. Management of substances
2. Preferable materials use (declaration of recycled content in product)
3. Life cycle assessment
4. Energy efficiency & water use
5. EoL management & design for recycling
6. Product packaging
7. Corporate responsibility

Like all EPEAT standards three levels of performance can be achieved – bronze, silver and gold. The bronze level is intended to reflect the performance of the top third of the market. For EPEAT Bronze only mandatory criteria met, for Silver at least 50% of optional criteria are met and for Gold at least 75% of optional criteria are met.

The **Cradle to Cradle** programme is a **third party verified labelling scheme** in the USA that aims to determine the extent to which the design and material composition of a product are able to facilitate future recycling. Two major solar PV panel manufacturers are currently listed as having products certified according to the US Cradle to Cradle scheme – Sunpower and Jinko Solar.

The programme's criteria are grouped according to the following attributes:

- **Material health**: Use of materials that are safe for human health and the environment through all use phases.
- **Material reutilisation**: Product and system design for material reutilisation, such as recycling or composting.
- **Renewable energy and carbon management**: Use of renewable energy in production.
- **Water stewardship**: Efficient use of water, and maintenance of water quality at production sites.
- **Social fairness**: Company strategies for social responsibility. Certification is in four tiers of attainment - Basic, Silver, Gold, and Platinum levels. The certification program applies to materials, sub-assemblies and finished products.

2.7.2. Outlook

After its initial preparatory study, the European Commission published a regulatory initiative, named "Environmental impact of photovoltaic modules, inverters and systems" in September 2021. It focuses on feasibility of regulatory approaches for the environmental impact of photovoltaic products (panels, inverters and systems) based on **Ecodesign** Directive 2009/125/EC and **Energy Labelling** Regulation (EU) 2017/1369.

The impact assessment analyses regulatory solutions with the aim of:

- Fostering panel and inverter designs that have improved **long-term energy yield, circularity** (i.e., improved ability to be repaired and recycled) and smart readiness.
- Taking **low quality** products off the market that can lead to **higher life cycle costs.**
- **Closing the information gap** (in terms of availability and reliability) on products available on the EU market, to support the consumers and other market actors, such as SMEs, in the recycling and re-use sectors, in getting comparable information on module energy yield, module performance long-term degradation and life-cycle energy impacts.
- **Optimising and increasing** the energy yield of small PV installations (indicatively less or equal to 20 kW) by enabling consumers to make an informed choice based on the performance of system designs offered by retailers and installers.

After a public consultation that ran from September-December 2022, the European Commission is currently summarising the inputs and drafting the relevant regulatory instruments. Based on this legislative process, new EU rules introducing PV Ecodesign and Energy Labelling requirements are expected to be finalised in the course of 2024.

3 Transition from operations to End-of-Life

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With the increase in the installed capacity of solar energy worldwide, the volumes of photovoltaic (PV) modules that will be decommissioned in the coming years are drawing increasing attention. In Europe, this topic is especially important for two main reasons: (i) the WEEE Directive, which categorises and sets precise targets for the collection and recycling of all WEEE, including PV panels under category 4, and (ii) the fact that many large PV fleets are approaching the end of their designed technical life (20-25 years) or being revamped/repowered with newer technology.

Today, PV panels are contributing significantly to the first step in the waste hierarchy, prevention of waste. With product guarantees of ten years and performance guarantees of over 20 years, PV panels are very effective at ensuring that society avoids the impacts of waste and the related costs for many years.

When PV systems are decommissioned, it is possible for the lifetime of PV panels to be extended during a 'second life', which is acknowledged under the Waste Framework and WEEE Directives as re-use.

Nevertheless, recycling is the default strategy for decommissioned PV panels in Europe. However, it is estimated that in the next 10-15 years, more than 50% of the PV panels considered as "waste" could be re-used because they are still functional. This would be on condition that the re-use is done under environmentally sound, qualitative and safe conditions.[1] This is in line with the principles of circularity, which aim at maximising the usage of equipment before reaching the recycling stages (for more information on recycling PV components, refer to Chapter 4. Takeback and recycling programmes).

The work presented in this chapter is meant, therefore, to increase awareness and understanding of the current state-of-the-art practices regarding the EoL management of PV panels, generally carried out by O&M service providers on behalf of the PV plant's owners and identify best practices that could guide and align all stakeholders. The guidelines proposed here are meant to bring consensus, improvements, and recommendations for more efficient waste management measures. They also aim to contribute to the proper, transparent and organised reduction of PV waste, thus supporting the transition to a more sustainable and circular PV sector.

3.1. The PV-waste challenge

During the operation phase of large-scale PV plants, there are three main activities that contribute to the generation of decommissioned PV panels and inverters:[2]

i. Preventive and corrective maintenance

ii. Revamping and repowering interventions

iii. Disposal, i.e., when the owner of the PV panels or inverters discards, is willing to discard or must discard these products

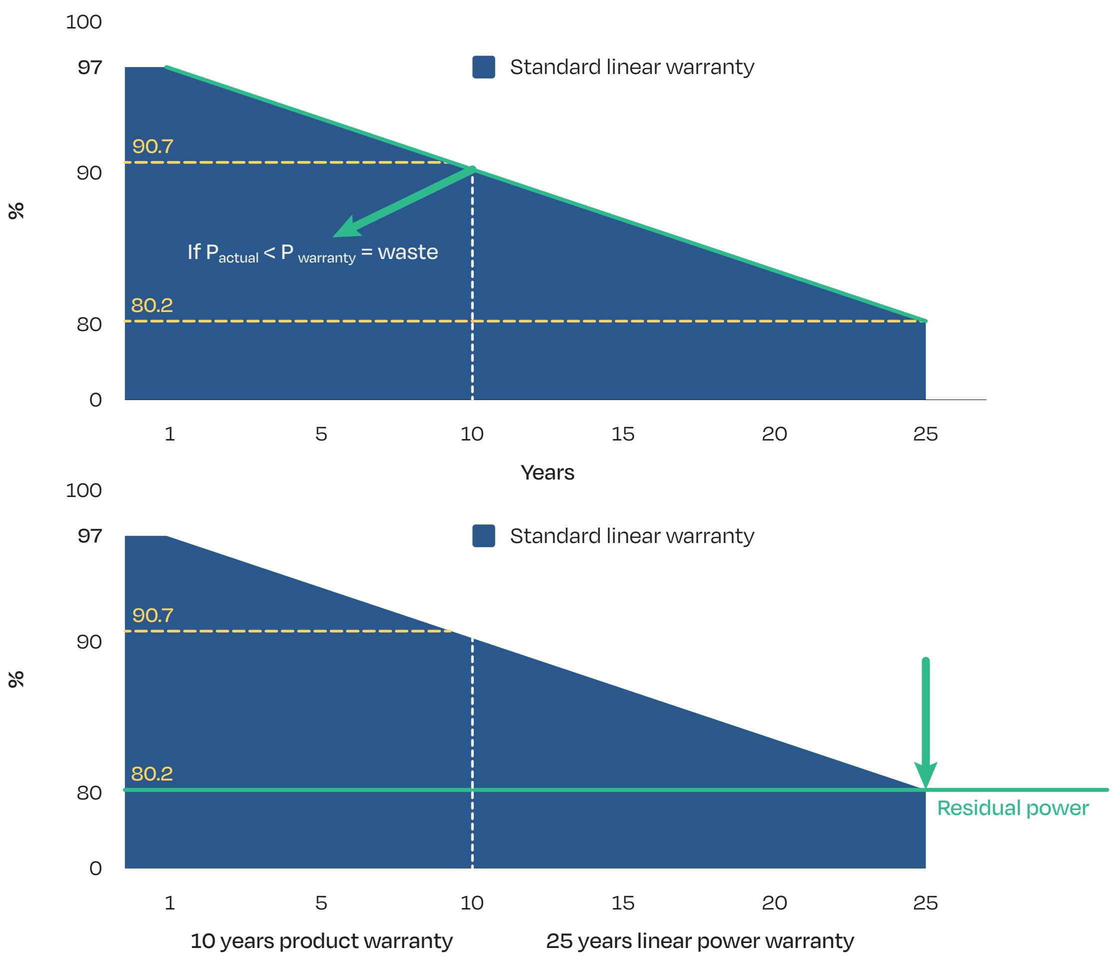
1 Oviedo Hernandez *et al.*, 2022.

2 ETIP PV, 2022.

PV devices are considered as waste when they are no longer able to perform their originally intended function, even after repair. Recyclates are legally considered waste as well, however, recyclates are secondary raw materials that have been generated by means of the recovery of waste or are generated in the disposal of waste and are suitable for the production of products. When it comes to PV panels, the solar industry usually considers them as waste when power drops below a guaranteed level (see Figure 4) or as part of an insurance claim after damages from severe weather events (e.g., hail).

In addition, when a PV panel reaches the end of its natural technical life (after at least 25 years of operation), it is estimated that it still possesses approximately 80% of its initial power generation capacity that could be exploited by giving the module an extended, or second life.[3]

FIGURE 4 CURRENT PRACTICES BASED ON WARRANTY TERMS



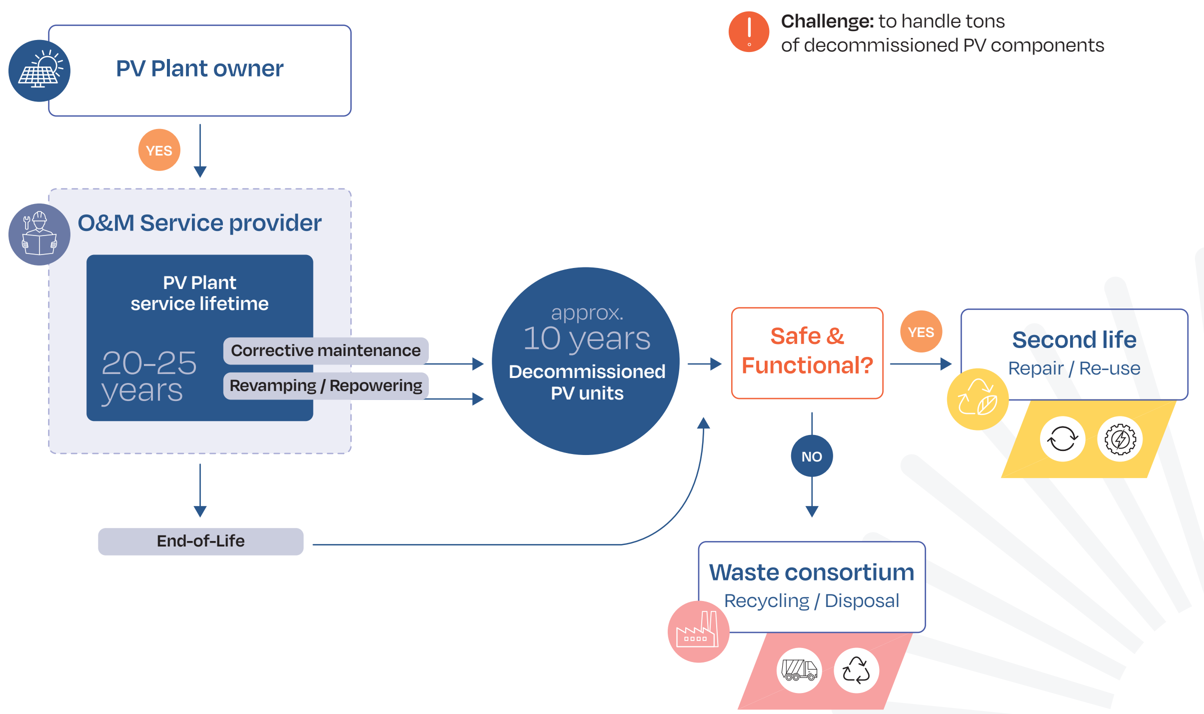
SOURCE: BayWa r.e..

3 Majewski *et al.*, 2021.

Currently, the very first European PV fleets, installed during the boom of feed-in tariff schemes, have passed midlife (10+ years old) and we are experiencing an unprecedented increase in revamping and repowering activities aimed at improving the performance of existing assets through the replacement of old PV panels and inverters with new ones. This contributes to an increasing number of panels being decommissioned before they reach the end of their natural lifetimes, as would have been envisioned in the project's original financial model.

The *premature* replacement of PV panels presents new opportunities for optimising the performance of existing PV assets without requiring new land. At the same time, however, it poses challenges for O&M service providers, local waste consortia and recyclers who must collect and properly handle the incoming volumes of decommissioned PV panels. Is recycling the only option or a second life can be explored (Figure 5)?

FIGURE 5 THE PV WASTE CHALLENGE AND THE SECOND LIFE OPPORTUNITY



SOURCE: BayWa r.e..

3.2. Management of decommissioned PV panels: current practices

It is common practice in the utility-scale sector that when PV systems need to be decommissioned, it is the O&M service provider that often activates the process of dismantling and disposal on behalf of the plant owners, providing mainly legal/administrative support and logistics. The decommissioned PV panels and/or inverters are then collected by an approved waste collecting company who ships these to a treatment facility to be processed in line with to the relevant national and local legislative framework.[4] A more detailed process is shown in Figure 6 below.

3.3. The re-use market: opportunities and challenges

From the previous section, we learned that it is common practice that decommissioned PV systems enter the waste stream directly and are processed to recover materials. However, some studies and experts have enabled a discussion about defining what constitutes a 'reusable' PV panel or inverter and under which conditions these products can be transformed into qualitative, safe and environmentally sound second-hand products.[5]

FIGURE 6 END-OF-LIFE MANAGEMENT - THE STATE-OF-THE-ART

Activities	Agreement on service / offer & contract	Selection of waste operator	Dismounting & Storage on-site	Collection & transportation	Disposal & Recycling	Management of EoL documentation
Stakeholders involved	O&M service provider & plant owner	O&M service provider & plant owner	O&M service provider	Waste operator	Waste operator	O&M service provider, waste operator & local authorities
Documentation exchange	• Service contract • Declaration by PV plant owner that decommissioned components are waste	• Acceptance order from O&M service provider or PV plant owner • Invoice issued by the PV waste operator	• SN number list	• Shipment order • H&SA clearnace	• Transfer of ownership	• Certificate of proper disposal

Disposal and Recycling are currently the mainstream options

SOURCE: BayWa r.e..

4 Oviedo Hernandez *et al.*, 2022.

5 Majewski *et al.*, 2020, Tsanakas *et al.*, 2020, Lempkowicz *et al.*, 2021, Dodd *et al.*, 2020, Godinho Ariolli, 2021, Salim *et al.*, 2019, Van Der Heide *et. al.*, 2022, Van Opstal and Smeets, 2023.

The main reasons for preparing functional PV panels or inverters for re-use are connected to the opportunities and advantages that this practice can bring such as the examples mentioned below and in Figure 7. However, beyond the opportunities and advantages, the business perspective should be considered as well. Preparing functional PV panels or inverters for re-use not only unlocks economic benefits but also serves as a means of complying with existing legislation and bolstering the reputation of companies for sustainability and circularity.

The opportunities and advantages of preparing functional PV panels and inverters for re-use are:

- Preventing them from prematurely entering the waste stream.
- Reducing the amount of waste generated by the PV industry.
- Reducing the unnecessary extraction of valuable raw materials and enabling the recovery of relevant elements, such as metals.
- Decreasing the environmental impact of the PV sector and improving energy access, especially in poorly connected areas.

Furthermore, according to the Waste Framework Directive's waste hierarchy, re-use has a higher priority than recycling, recovery, and disposal, coming just after waste prevention. Thus, ideally, recycling would only be considered when qualitative, safe and environmentally sound preparation for re-use is not possible, such as in situations where the components are damaged and cannot be repaired. However, to comply with the principles of circularity and sustainability, preparation for re-use can only take place when there is a set of technical conditions that define when a PV panel is 'reusable' (e.g. minimum threshold of electricity output, minimum amount of testing, identity card accompanying each PV panel prepared for re-use and conditions under which a re-use centre for PV panels can operate). In other words, decommissioned PV panels should only reach the recycling phase when these are no longer functional nor safe for second-hand usage.

FIGURE 7 THE POTENTIAL OF RE-USE

Goal: to extend the lifetime of decommissioned PV components with **residual value**

SOURCE: BayWa r.e..

6 Oviedo Hernandez *et al.*, 2022, Majewski *et al.*, 2020, Tsanakas *et al.*, 2020, Lempkowicz *et al.*, 2021, Dodd *et al.*, 2020, Godinho Ariolli, 2021, Salim *et al.* 2019, Van Der Heide *et al.* 2022)

3.3.1. Challenges

There are some challenges hindering the development of a preparation for re-use market. One of them being the legislation, more specifically, the interconnection between the Waste Framework Directive 2008/98/EC, the WEEE Directive 2012/19/EU and the Waste Shipment Regulation 1013/2006/EC. Preparation for re-use is acknowledged as one of the steps in the waste hierarchy of managing WEEE, and there is a target of 80 % preparation for re-use and recycling for all products (equipment) under Category 4 'Large equipment' in the WEEE Directive.[7] However, the majority of operators currently trading second-hand PV panels are not familiar with the three waste legislations described above. Moreover, the lack of an international standard, norm or technical specification related to the preparation for re-use of PV panels means that the second-hand PV panel market currently operates in a grey area, explaining why it is not yet widely developed.[8]

Currently, the practice of exporting second-hand PV panels to low-income countries with less comprehensive waste regulations is creating a major environmental concern, particularly as their collection and proper treatment may not be as easy to guarantee after their second life. Moreover, the dangers posed to people by exporting potentially unsafe PV panels entails significant ethical issues. The top destinations of second-hand PV panels are the Sahel-countries, Afghanistan, Pakistan, the Palestinian Territories and Turkey.[9] A rather small (around 10 MWp) and temporary market still exists in (Western) Europe where feed-in tariff regulations often require "very similar" replacement modules in case of damage.[10] Overall, re-used or repaired PV panels are not competitive for new residential, commercial and utility-scale PV installations in high-income countries or even in developing countries with government incentives to deploy PV.[11] The lack of a performance guarantee, functionality, and concerns over the safety and quality of used PV panels, as well as the lack of rules and standards on labelling and testing, are seen as the main barriers for the development of the second-hand market.[12] Moreover, the low prices of new PV modules further weaken the economic argument for a second life market.[13]

To tackle some of these challenges, a guideline for preparing PV panels for re-use was published in 2022 by the H2020 European-funded project CIRCUSOL[14, 15] This guideline was a short update of an initial proposal described in the PV CYCLE Study of 2020.[16] It contains a first attempt to define the steps needed for the application of several testing methods with the aim of defining what a functional PV panel is and ensuring sufficient quality and safety while still being cost-effective. This document is now being used as a baseline by the *IEC Technical Committee (TC)* 82, which is currently drafting a Technical Report. The result shall then become the basis for the TC 82 to decide if a Standard or Technical Specification is required. Soren is also currently having a working group developing a set of technical criteria for PV re-use.

3.4. Guidelines for preparing for re-use

"Preparing for re-use" is defined in the European Waste Framework Directive 2008/98/EC as "checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing".[17] This section will discuss suggestions to inspire these operations based on existing guidelines, technical discussions in the IEC Technical Committee 82 and on the experiences of actors in the PV sector.

The focus will be given to simple and smart logistics (handling and packaging) and targeted *quality assurance* procedures, contributing to the identification of functional PV components eligible for re-use (with or without repair), thus preventing them from entering the waste stream prematurely.

7 Large Equipment means Washing machines, Clothes dryers, Dish washing machines, Cookers, Electric stoves, Electric hot plates, Luminaires, Equipment reproducing sound or images, Musical equipment (excluding pipe organs installed in churches), Appliances for knitting and weaving, Large computer-mainframes, Large printing machines, Copying equipment, Large coin slot machines, Large medical devices, Large monitoring and control instruments, Large appliances which automatically deliver products and money, Photovoltaic panels.

8 Tsanakas *et al.,* 2020, Godinho Ariolli, 2021.

9 Tsanakas *et al.,* 2020, Godinho Ariolli, 2021, Van Der Heide *et al.* 2022.

10 Tsanakas *et al.,* 2020, Van Der Heide *et al.* 2022.

11 See 2.

12 See 2.

13 Majewski *et al.,* 2020, Tsanakas *et al.,* 2020, Lempkowicz *et al.,* 2021, Dodd *et al.,* 2020, Godinho Ariolli, 2021, Salim *et al.,* 2019, Van Der Heide *et al.,* 2022.

14 https://www.circusol.eu/files/Deliverables/D3-2_Labelling_and_certification_protocols_for_second_life_PV_modules.pdf

15 Oviedo Hernandez *et al.,* 2022, Van Der Heide *et al.,* 2022).

16 See 2.

17 Van Der Heide *et al.,* 2022.

3.4.1. PV panels

To qualify for re-use, PV panels should undergo functionality testing procedures that are technically feasible, cost-effective and adapted for the second-hand market, giving priority to safety over performance. To be prepared for re-use, PV panels functionality should be tested on-site according to specific technical criteria (e.g. IEC 61215). On the contrary, replicating the same qualification procedures for new PV panels should be avoided because it would be too costly and technically very challenging.

The suggested tests and steps proposed for the preparation of PV components for re-use are illustrated in Figure 8[18] and described below.

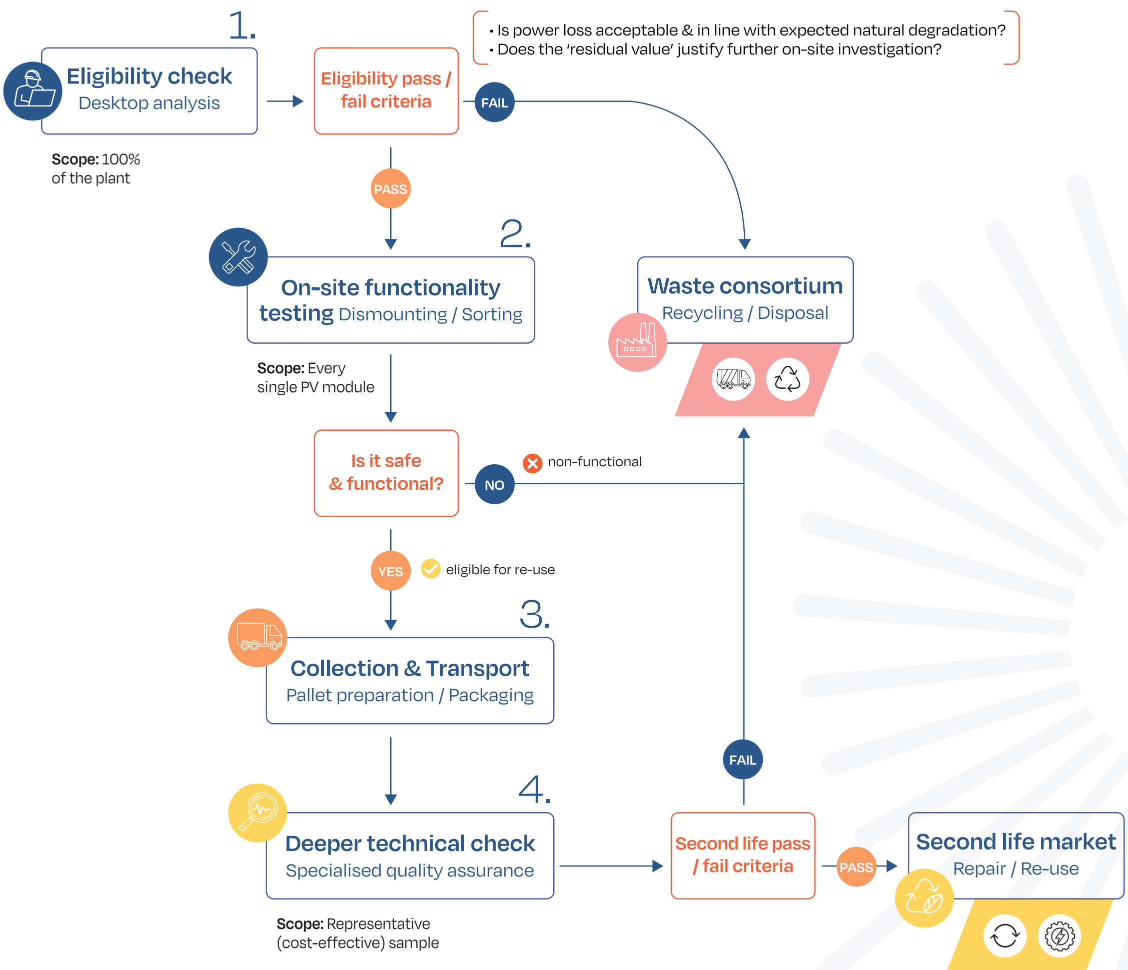
BOX 1

How do we define a functional PV module?

PV modules convert the Sun's energy into electrical energy. They can be classified as functional when:

1. They can perform this primary function without posing a risk for the operators, the environment and to the system they form part of and;
2. Their performance follows a natural degradation according to the manufacturer specifications.

FIGURE 8 PROCEDURES FOR PREPARATION FOR RE-USE



SOURCE: BayWa r.e..

18 Van Der Heide *et al.*, 2023.

1. **Eligibility check** (desktop analysis before going on-site)

   This consists of an analysis based on electrical and weather variables and maintenance information (O&M historical data) to calculate and/or estimate the performance loss of the entire plant or sub-sections of it (at transformer, inverter or string level). This check is meant to be done in the office to decide whether it makes sense to perform additional checks on-site. Additionally, known failures should be assessed based on annual or monthly reports and punch lists made available by the O&M service provider and/or Asset Manager, such as IR thermographic and I-V curve measurement campaigns, commonly done contractually at least once a year. Following this logic, O&M service providers that follow high-quality monitoring practices (according to international standards) and with quality assurance evidence in their hands, should be able to avoid costly diagnoses.

   Please note that this check should make the most out of all the already existing documentation that defines the history of the plant, not limited to O&M data only. This approach will minimise additional costs.

Suggested eligible pass/fail criteria:

- Is power loss acceptable and in line with expected natural degradation?

  Example: The Power Loss Rate (PLR) of a module, calculated with the last 5 years of monitoring data, is estimated to be 10%/year, which deviates greatly from the 0.8 %/year defined by the manufacturer. The module does not qualify for re-use and is sent to be recycled.

- Does the 'residual value' justify further on-site investigation?

  Example: During a revamping project of a 10-year-old plant, it is verified that the PLR is in line with the expected annual degradation rate provided by the manufacturer. Furthermore, the module type holds a high value for a specific asset owner because it is no longer available on the market and can be used as spare part. It is then decided to go ahead and continue with the re-use preparation steps.

Practical example

After a PV plant has been damaged by a severe weather event such as hail, based on the significant decrease in performance (calculated by the O&M service provider using monitoring data) and based on third party investigations done on behalf of the insurance company (e.g. electroluminescence (EL) imaging of a representative sample of the plant), it is estimated that a very high percentage of modules (ca. 80%) are affected by cell breakage caused by excessive mechanical impact. Therefore, it is concluded that the decommissioned PV modules are not eligible for re-use and no further resources should be spent on additional on-site investigations.

2. On-site functionality testing

This step is meant to be carried out by site technicians shortly before and/or while decommissioning PV panels (e.g., during revamping or repowering activities). It includes dismounting, sorting, and on-site temporary storage.

Functionality testing should be done for every single panel, including but not limited to:

- Dedicated visual inspection (supported by a checklist that covers known failures that can be detected with the naked eye), according to *Standard IEC 61215* (minimum illumination 1000 lux).
- Insulation resistance test at string box level or panel level if feasible (according to *IEC 62446-1 "Requirements for testing, documentation and maintenance"*).
- (Desirable) low-cost infrared thermography with hand-held device or smartphone (according to *IEC-TS 62446-3-2017 "Outdoor infrared thermography"*).

Suggested functionality criteria:

- Is the PV panel affected by a severe failure such as, but not limited to: damaged frame, broken glass, damaged cables and connectors, backsheet cracking/chalking, delamination/bubbles and/or corrosion?
- Has the PV panel failed the insulation resistance test, posing a potential risk to human health?

Please note that this step should take advantage of the fact that field technicians are already on-site executing module substitutions (e.g., due to corrective maintenance or revamping/repowering activities). In this way, the time spent on-site is optimised as little extra effort is needed. Once the panels are dismounted and the functionality testing is completed, sorting into two main categories is possible: non-functional and eligible for re-use.

3. Collection and transportation

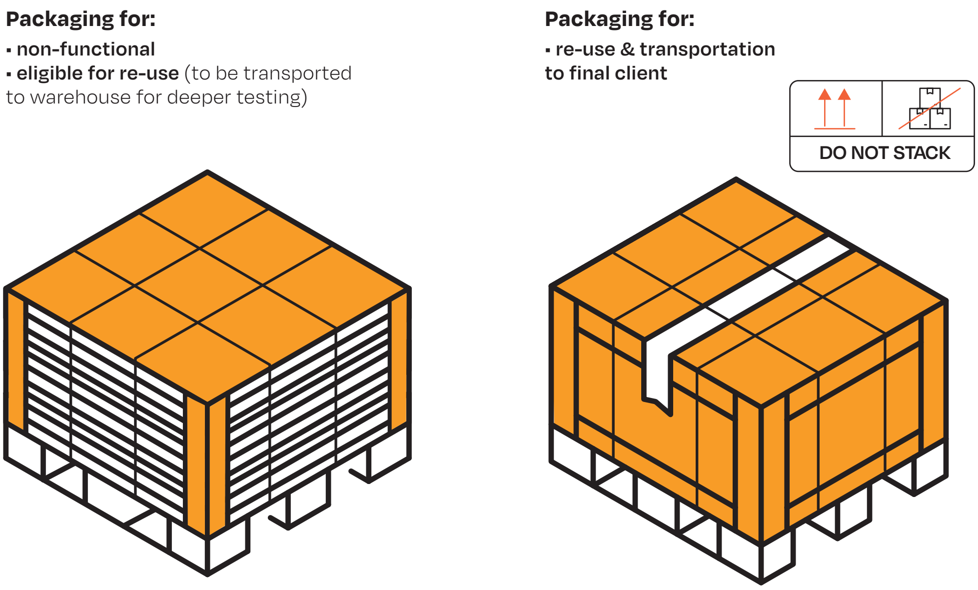
Once the PV panels have been piled up into two different categories (non-functional and eligible for re-use), it is time for proper pallet preparation and packaging, to avoid further damage and ensure that the shipment is not confused with e-waste. It is suggested that a differentiated packaging procedure is done for functional and non-functional panels (see Figure 9). To minimise extra packing costs during revamping activities, it is advised to re-use the pallets and cardboard of the new batches of panels being installed.

BOX 2

The importance of proper handling and packaging

Logistics (from dismounting to proper packaging and pallet shipping) is not only fundamental to prevent handling and transportation damage but also to avoid the risk that PV modules eligible for re-use are 'confused' with e-waste by customs authorities or highway police. Special attention should be paid to the minimum requirements for shipments of used products laid down by the *WEEE Directive - Annex VI (Minimum Requirements for Shipment)*, designed to avoid unwanted transportation of e-waste to countries where recycling schemes are weak or non-existent.

FIGURE 9 SUGGESTED DIFFERENTIATED PACKING APPROACHES FOR NON-FUNCTIONAL MODULES AND THOSE DESTINED FOR RE-USE



SOURCE: BayWa r.e..

4. Deeper technical check

This last step will provide definitive and accurate evidence on the health status of panels that have been categorised as eligible for re-use in previous steps. Specialised quality assurance procedures (see Figure 10) should be applied to a representative sample to ensure that costs are kept at a manageable level. Based on this check, the final value and price a of PV panel can be set and agreed with the final client.

Suggested second life pass/fail criteria:

- Is the PV panel affected by failures such as severe PID (Potential Induced Degradation) and microcracks?
- Does the PV panel have 'enough' residual value for its second life according to its final usage?
- Does the panel's actual power justify its price?

Practical example

After a deeper technical check, it is established that the actual power of the sample tested is 60% of the original nameplate and that PV panels can be placed on the second-hand market at a price 50% lower than new(er) PV panels. The used PV panels are then sold to a local installer that specialises in small rooftop and carport applications.

FIGURE 10 SPECIALISED QUALITY ASSURANCE PROCEDURES FOR MODULES DESTINED FOR RE-USE

Visual inspection

- Visual inspection is a non-destructive assessment, which provides information regarding optical appearance of PV modules. It can be used as a contactless method for diagnosing some thermal and electrical failures in PV modules.

1. IEC 61215

IR thermography

- Infrared (IR) imaging is a non-destructive measurement technique, which provides fast, real-time, and two-dimensional distribution of characteristic features of PV modules. It can be used as a contactless method for diagnosing some thermal and electrical failures in PV modules.

2. IEC TS 62446-3:2017

STC measurements

- Measurements of PV array I-V characteristics under actual on-site conditions and their extrapolation to Acceptance Test Conditions (ATC, i.e., STC) can provide data on power rating and verification of installed array power and performance relative to design specification.

3. IEC 61215 & IEC 609044

EL imaging

- EL is an optical procedure for a qualitative assessment of module failures. EL is particularly suitable for the detection and tracking of crack related issues, which can occur for example during module transportation.

4. IEC 60904-1-13

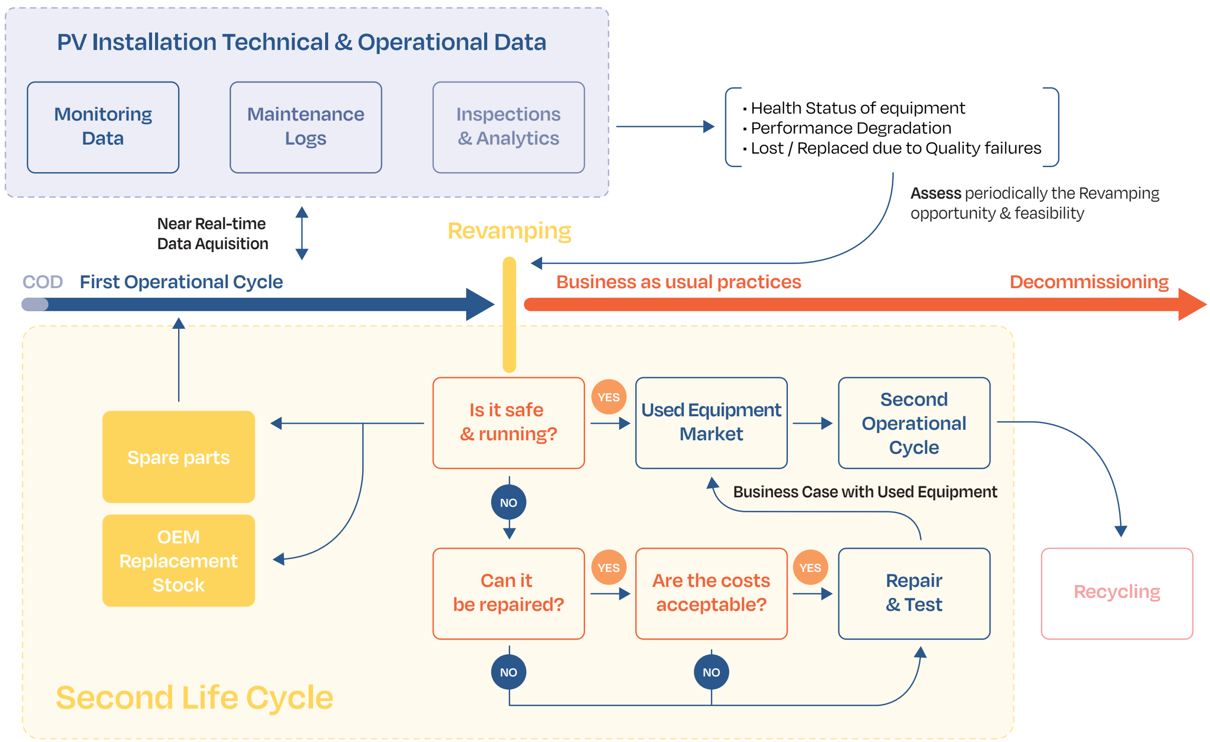
Insulation testing

- The insulation test measures currents between the electrically conductive parts in the modules and cables to ground. These residual currents must not exceed certain limit values in order to protect people, environment and the system itself.

5. IEC 61215

SOURCE: PI Berlin.

FIGURE 11 THE SECOND LIFE CYCLE



SOURCE: Sunrock.

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3.4.2. PV inverters

In contrast to PV panels, inverters are easier to repair by simply replacing the defective elements of the device. There are several options possible:

- On-site repair: depending on the manufacturer, it is possible to replace defective pieces such as fans, or very specific electronic components.
- Replace and take back: the decommissioned inverter is replaced by a new one (same model or an updated version) and the defective one is sent back to the manufacturer's repair centre (when possible). If it is not repairable, then it is sent to be recycled (see chapter 5). If it can be repaired, it is then stored for re-use by another customer.

With repair and/or replace options, stakeholders (manufacturers, installers, O&M service providers) can postpone the EoL phase of the inverter, instead of sending it for e-waste treatment immediately. These options of repair and exchange of inverters are not systematically considered or used by stakeholders due to a lack of information or awareness, even though they could bring additional value.

3.4.3. Communication Devices

In the context of photovoltaic systems, communication devices, like power plant controllers and sensors, are crucial components. To manage their EoL and recycling responsibly, it is essential to establish a well-documented lifecycle management process during installation. Collaboration with all stakeholders, including the EPC service provider, manufacturers and other relevant teams, will ensure a sustainable approach. Providing adequate training and documentation to employees about device updates and replacements is crucial for efficient management. Conducting a thorough risk assessment helps prioritise replacements and upgrades. Additionally, considering the potential for re-use before recycling or disposing of devices is important. Following these guidelines fosters environmentally conscious practices, contributing to the overall sustainability of renewable energy infrastructure.

Criteria for EoL

Determining the end of the operating phase for a communication device involves considering various critical factors:

- **Availability of spare parts and repair services:** If the manufacturer or third-party suppliers discontinue providing spare parts or repair services for the device, it becomes challenging to maintain and repair it in case of failure. The lack of access to essential components may render the device obsolete and unsuitable for continued use.
- **Security updates and firmware upgrades:** The continuous availability of security updates and firmware upgrades is crucial for safeguarding the device against evolving cyber threats. When a manufacturer stops providing updates, the device may become susceptible to security vulnerabilities, posing potential risks to the entire system.
- **Safety requirements and regulatory compliance:** In the ever-changing landscape of safety standards and regulations for photovoltaic systems, communication devices must adhere to the latest requirements. If a device no longer meets the necessary safety standards or fails to comply with updated regulations, it becomes imperative to consider replacing it with a more suitable and compliant alternative. Ensuring that all communication devices meet the required safety criteria is crucial for maintaining the overall integrity and reliability of the PV installation. By staying up to date with safety standards and regulatory changes, you can proactively address potential safety concerns and optimise the performance of the entire system.
- **Reliability and frequency of failures:** Frequent failures, or an increasing need for repairs are strong indicators that a communication device has reached its EoL. A device that is no longer reliable can disrupt operations, leading to downtime and hampering system efficiency.
- **Compatibility with other devices and protocols:** In a dynamic technological landscape, seamless integration with other devices and protocols is crucial. If a communication device is no longer compatible with newer systems, it can hinder the overall performance and functionality of the entire setup.
- **Calibration support and discontinued manufacturer support:** Communication devices equipped with sensors requiring periodic calibration for accuracy must receive ongoing support from the manufacturer or authorised service providers. If calibration services are discontinued or not available within the recommended timeframe, the device's accuracy may be compromised, making it unsuitable for critical applications. Similarly, the EoL indication is evident when the manufacturer no longer provides support for the communication device due to its age or business closure. This lack of support may lead to challenges in obtaining replacement parts, updates, or technical assistance when issues arise, necessitating device replacement considerations.
- **Irreparable physical damage:** Irreparable physical damage, such as severe impact, water damage, or other catastrophic events, can render a communication device incapable of fulfilling its intended function. In such cases, the device is deemed to have reached the end of its life. Devices with significant physical damage may pose safety hazards, malfunction, or fail to operate as intended, making them unsuitable for continued use.

Process and recommendations for End-of-Life devices

When a communication device reaches its EoL in a PV system, several essential steps need to be taken to ensure proper handling and transition. The process begins by checking the documentation outlined in the lifecycle management process. This documentation should include comprehensive details about all installed devices, such as specifications, purchase dates and installed firmware or software versions. Internal instructions for preparations for recycling or re-use should also be available, along with information about possible recycling processes with local partners or an agreed recycling process with the manufacturer or EPC service provider. The contact information of the party responsible for initiating the relevant EoL process must be readily accessible.

1. To minimise disruption during the replacement process, backups of the data and configuration from the affected device should have been created and made available. This ensures that the responsible O&M service provider can properly replace the device without losing crucial data and with minimal downtime.

2. Depending on who determines the EoL situation, various stakeholders need to be alerted. The O&M service provider and the owner should be informed of the device's status. If the manufacturer is involved in the EoL process, they must also be notified downstream.

3. For proper documentation, key information such as the manufacturer, model, serial number, purchase date and software/firmware version of the EoL device should be recorded. Any notes regarding the internal recycling process, whether conducted by the company itself or the manufacturer, must also be documented.

4. The documentation needs to be passed on from the O&M service provider to the responsible vendor or team handling the recycling or re-use of the components.

5. In some cases, there may be a need to close the O&M contract for the specific device. This should be addressed within the internal lifecycle management process. The O&M service provider should be informed of the device's replacement and, if applicable, the cessation of support for the specific device.

6. Additionally, data protection measures are crucial to safeguard customers' sensitive information. Proper erasure or destruction of sensitive data from communication devices is essential to protect customers' information and prevent data breaches. After decommissioning, thorough data erasure or physical destruction protocols should be implemented to ensure that confidential information remains protected throughout the EoL process.

By following these steps and adhering to the documentation and data protection measures, the EoL phase of communication devices in a PV system can be managed effectively and responsibly, ensuring a seamless transition and adherence to regulatory requirements.

Reusing communication devices

When a communication device reaches its EoL but does not yet qualify as waste, there are several considerations for potential re-use or repurposing.

In recent years, the proliferation of PV systems has led to a surge in the number of communication devices utilised in these installations. Designed for long lifespans, there is currently a limited supply of EoL devices available on the market. Consequently, there are no established markets or providers to process, refurbish, and resell these devices. However, with the continually increasing number of PV systems and associated communication devices, this landscape is poised to change in the coming years.

As the industry evolves, opportunities for second life and re-use of these communication devices may emerge. Depending on the provider and operator of PV installations, internal applications in which these devices could still serve a purpose might be identified. Amidst this dynamic environment, exploring the potential for reusing EoL devices could offer sustainable and cost-effective solutions, benefitting both the industry and the environment. Below are key considerations and potential ways of re-using communications devices.

- Sensors and Guaranteed Lifetime

  Reusing sensors can be challenging due to the manufacturer's promised guaranteed lifetime or measurement correctness. As these devices often have specific lifespans, their re-use might not be feasible, especially in critical applications where accurate measurements are crucial.

- Devices in Different Applications

  For devices like power plant controllers or network devices, there might be opportunities for re-use in smaller power plants with lower security or availability requirements. These devices could also find use in other areas such as electric vehicle charging stations, where their functionalities may still be suitable, despite not meeting the current owner's requirements for security, encryption, or other protocols.

- Categorising Functional and Non-Functional Devices

  Creating a matrix to categorise functional and non-functional devices can aid in making re-use decisions. Several possible reasons can render devices no longer usable:

  - Devices that are no longer supported by the manufacturer, with support to the product being discontinued, a lack of software updates, or

unavailability of spare parts due to the manufacturer's closure, should be considered for recycling. The potential risk may outweigh the benefits of keeping them in operation.

- Damaged or non-functioning devices can be evaluated by the manufacturer to determine if a module or part can be replaced. If applicable, the device could be repaired and re-used; otherwise, it should be considered for recycling.
- Devices that no longer meet new requirements can potentially be repurposed for other fields of application or purposes where their functionalities are still relevant and useful.
- Devices with expired calibration, or where calibration services have been discontinued, should not be used in environments where reliable measurements are required, making recycling the appropriate course of action.

3.4.4. Batteries

To harness solar energy effectively, the challenge of its intermittent nature must be solved. To integrate solar power on a large scale into the electrical grid, utility-scale PV plants with advanced grid-friendly features are needed to ensure stability and reliability. Batteries come into play as crucial energy storage devices within solar systems, capturing surplus energy. This continuous power supply minimises PV curtailment and facilitates cost-effective integration of more solar power. These batteries, including lead-acid, lithium-ion, and flow batteries, offer a range of benefits for solar energy storage.

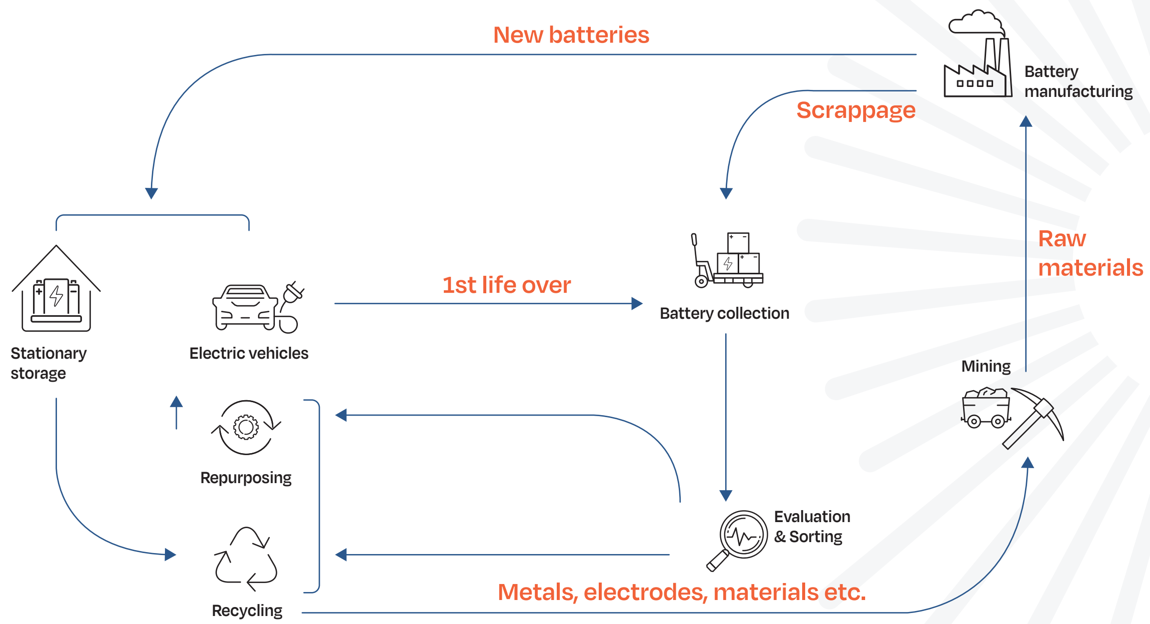
Repurposing

Repurposing old batteries at the end of their life to different applications is a huge boost to circularity.

After use a battery can still retain up to 70% of its original capacity and be installed in several other applications that are less demanding. Possible applications are at fast-charging stations, rooftop and microgrid storage systems.

A key long-term driver for lithium-ion battery repurposing in particular will reducing the pressure on critical raw material value chains.

FIGURE 12 FLOW OF THE LI-ION MATERIAL



SOURCE: lightsourcebp.

3.4.5. Racking systems and trackers

A crucial facet of managing the complete lifecycle of these plants involves dealing with the balance-of-system (BOS) equipment, which encompasses among others (inverters, junction boxes, wires, frames, and mounting equipment) racking systems and trackers. As the PV industry continues to grow, the importance of addressing the EoL aspects of these BOS components becomes increasingly evident. Among the BOS equipment, trackers and racking systems play a pivotal role, not only in optimising the efficiency of solar panels during their operational lifespan but also in the sustainable management of these components once they reach the end of their utility. Generally speaking, the management of racking systems and trackers is in accordance with the waste hierarchy of the Waste Framework Directive 2008/98/EC, including the (1) best possible avoidance of metal waste and other waste (2) best possible re-use of metals and raw materials, (3) recycling of metals or raw materials at local recycling centers, and the (4) disposal of residual materials in accordance with local legal regulations.

System maintenance and repair are essential to ensure the continued functionality of solar power plants. This may involve replacing tracking parts if they were part of the original design, among other necessary repairs. However, it's not just about maintaining these components; it's also about finding ways to extend their useful life and reduce waste.

One key approach is the prioritisation of secondary use or re-use of these equipment components. The re-use of recovered materials, especially racking systems and trackers, offers the opportunity to reduce manufacturing costs, making PV modules and BOS equipment more affordable on the primary market. Moreover, recovering materials allows diverting valuable resources like silicon, silver, cadmium, tellurium, aluminum, and copper from landfills. However, the lack of standardised testing and disassembly processes poses challenges for ensuring safe and reliable re-use.

Decommissioning marks the final chapter, requiring the removal of the PV array and balance-of-plant elements, restoration of the land, and responsible disposal or recycling of materials. For instance, metal rack parts are often put into roll-off dumpsters sorted by aluminum, steel, and copper.

In this entire cycle, minimising waste is a paramount goal to ensure the long-term sustainability of solar energy systems. Proper management of BOS equipment, including trackers and racking systems, is

integral to not only the efficient functioning of solar power plants but also the preservation of valuable resources and the reduction of environmental impact. As the industry evolves, a focus on EoL considerations for BOS equipment becomes ever more crucial in maintaining the clean energy transition.

Re-use

The re-use of recovered materials could reduce manufacturing costs and could reduce the cost of PV modules and BOS equipment on the primary market. Secondary use of PV system equipment could reduce disposal of reusable products, while resource recovery of modules, BOS equipment (e.g., junction box, wires, frame, mounting equipment), and manufacturing scrap can divert valuable materials, such as silicon, silver, tellurium, cadmium, aluminum, and copper, from landfills.[19]

There is no standardised testing process in place to determine the safe and reliable re-use potential of BOS equipment.[20] There is also no standardised process in place for the repair of BOS equipment.

Repair

Repairs specific to racking systems and trackers within PV plants encompass a range of essential activities. These maintenance efforts are vital to ensure the continued functionality and efficiency of these components throughout their operational lifespan.

In case PV plants incorporate trackers in their original design, there may arise a need to replace particular tracking components that have worn out or developed malfunctions over time, thereby ensuring the continued efficiency of the trackers

Racking systems, responsible for supporting and positioning solar panels, may necessitate repairs to rectify issues arising from factors like erosion or wear and tear, ensuring the integrity of the PV array is upheld.

Decommissioning

During decommissioning, racking systems and trackers are often handled by stacking PV modules on pallets or placing them in shipping containers. Meanwhile, metal rack components, including those related to trackers, are frequently sorted into roll-off dumpsters categorised by material type, such as aluminum, steel, and copper.

19 Salim *et al.* 2019; Mulvaney 2019; Xu *et al.* 2018; Dominguez and Geyer 2017; Weckend, Wade, and Heath 2016.

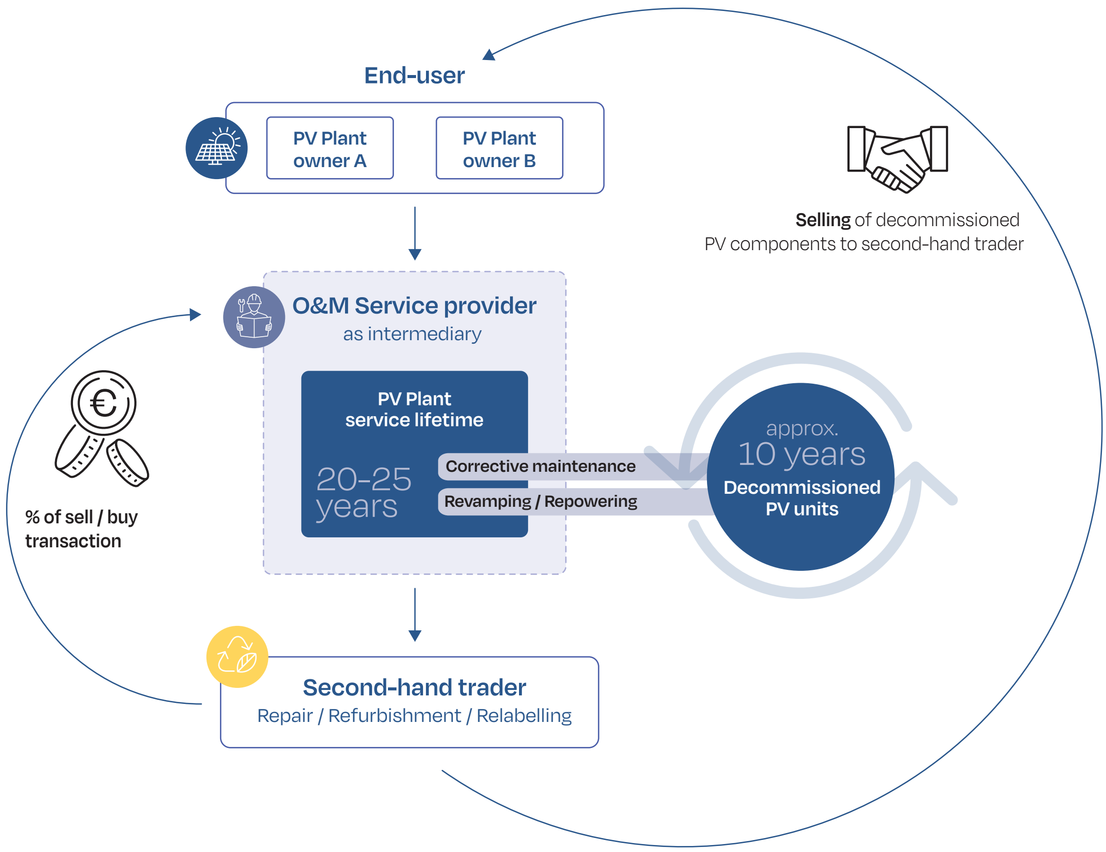
20 Heath *et al.* 2020; CPUC 2019b; ASES 2020.

3.5. Second life business models

Circular business models can enable resource efficiency, lifetime extension and re-use of products, and have the potential to capture the residual value from by-products or 'waste'. However, circular business models covering the re-use of PV panels lack visibility.[21]

B2B (business-to-business) and B2C (business-to-clients) re-use models in the PV sector are already seen in some European countries, where second-hand traders play a key role as a facilitator through online market platforms, for example. Traders might also be involved in repair and relabelling activities (Figure 13).

FIGURE 13 SECOND LIFE BUSINESS MODEL FOR A SECOND-HAND TRADER



SOURCE: BayWa r.e..

21 Van Opstal and Smeets, 2023.

BOX 3

Examples of circular business models focused on re-use:

- **B2B models (business to business)**: e.g., B2B models (business-to-business): e.g., turnkey solutions (service-centred approach) for commercial and industrial (C&I) rooftops, carports (parking lots), leasing, charging stations for e-mobility and public lighting (road, bus stops), etc.
- **B2C models (business to clients)**: e.g., B2C models (business-to-clients): e.g., trading of decommissioned PV components for households' rooftops (product-centred approach) through an e-commerce platform for installers, leasing, etc.
- **Donation models**: e.g., donation of decommissioned PV components for charity institutions in underdeveloped regions for off-grid applications (irrigation, lighting, clinics, schools).

3.6. Outlook and innovative trends

Currently, there are some initiatives being explored by companies and research institutes[22] that can potentially help prevent PV panel waste, such as:

- The use of advanced data analytics to predict defects, avoid failures and improve efficiency, reducing the need to replace PV panels or inverters earlier than expected. Example: building information modeling (BIM), digital twin, 3D modelling, new wireless technologies for monitoring, big data analytics.
- Repair techniques for PV panels applied in the field. Example: retrofit of anti-reflective coating and repair of backsheets.
- Digital tools and smart cost-efficient and reliable solutions. Examples: integrating Radio Frequency Identification (RFID) in PV panels to facilitate reverse logistics, optimised tracing of their bill of materials (BOM) details, maintenance interventions, repairs, etc.

22 Oviedo Hernandez *et al.*, 2022.

4 Takeback and recycling programmes

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With increasing numbers of PV panels due to reach the end of their operational lives in the near future, recycling and takeback programmes will be pivotal for the responsible management of PV waste. Recycling becomes an option when re-use and repurposing (as outlined in Chapter 2) have been exhausted. It serves as the means to recover valuable materials from PV components, relieving pressure on supply chains for these materials and minimising waste.

This chapter will explore the role of Producer Responsibility Organisations (PROs) in managing the responsible disposal and recycling of PV components, the challenges and obstacles faced in the pursuit of sustainable and efficient recycling processes and, lastly, the recycling and take back processes of PV components (notably for PV modules, inverters, communication devices and batteries).

4.1. Recycling challenges

Over the past two decades, the production of solar panels has witnessed a remarkable surge. As these panels near their EoL, an unprecedented waste management challenge has emerged. It is projected that PV waste will account for a substantial portion, ranging from 4% to 14%, of the total electricity generation capacity by 2030 and could reach 60 to 80 million tons by 2050. This poses serious questions about whether current recycling technologies will be advanced enough to deal with PV panels, and whether they exist at the scale required to absorb these new waste streams.

There are three primary PV recycling processes: mechanical, chemical, and thermal. However, a common drawback of most recycling methods is that they generate secondary raw materials with reduced purity and integrity compared to the original components used in PV manufacturing. This is particularly true for solar glass.

The recovery of silicon, a crucial material in PV solar panels, is of strategic importance due to the stringent purity requirements for solar-grade silicon. The process of refining metallurgical-grade silicon into solar-grade silicon is resource- and energy-intensive, imposing both economic and environmental costs.

Notably, silver stands out as one of the most valuable materials in PV panels, constituting 42% of their theoretical value. Glass is the heaviest component in PV panels by far and represents the largest fraction by weight among all components. Lastly, encapsulant materials composed of non-recycled polymers, often derived from fossil sources, can have a significant negative environmental impact. They are challenging to recycle due the low maturity of the current processing methods.

While PV module recycling techniques have developed significantly in the past decade, full commercialisation and high material recovery rates, especially for the prevalent c-Si PV technology, is yet to be achieved. Support for technological development can enhance performance and increase recycling value. Not only is the recovery of materials from discarded PV modules crucial, but the quality of these materials is also important, as it often falls short of maximising their potential value. Advancements in technological development have the potential to bridge this gap, enabling more efficient recovery of raw materials and components.

4.2. Takeback processes for different components

4.2.1. PV panels

There are various EoL options for PV panels, depending upon their condition, type, and the available recycling infrastructure. For instance, upcycling is a technique aiming to transform waste materials into new products of a greater value or quality. It is a promising practice in terms of environmental benefits and reduction in WEEE, however it is still relatively limited. Where second life, re-purposing or upcycling routes have been exhausted, then recycling or landfill disposal are the two remaining alternatives, with recycling being the next preferred option. Resource conservation is a cornerstone of sustainable development. The recycling of EoL PV modules and the focus on the recovery and re-use of critical minerals and valuable materials, offers several environmental and economic advantages.

Dependent on the available recycling technologies, silicon, glass, aluminium, copper, silver, indium, and tellurium, can be recovered, processed, and prepared for re-use across various industries. This contributes to reducing the need for further extensive mining and extraction, preserving natural ecosystems and habitats, and supporting a more sustainable supply chain, whilst also reducing the economic strain associated with volatile commodity prices.

Recycling also consumes less energy than producing new materials from scratch, reducing the potential greenhouse gas emissions of the upstream supply chain and the volume of waste entering landfills and incinerators. By doing so it prevents unnecessary pollution, mitigates the risk of contamination of the environment and frees up valuable landfill space.[23]

Of the recycling technologies available, the most basic involves the separation of the major components. This usually includes the glass, which can be cleaned and re-used, the aluminium frames and junction boxes, encapsulant materials which can be processed for energy recovery and the PV cells which can be processed to extract silver and copper.

Advanced recycling involves more sophisticated and innovative techniques to maximise the recovery of valuable materials and minimise environmental impact. Advanced recycling may involve automated disassembly processes, laser technology to selectively remove encapsulant materials, selective chemical etching to allow recovery of high-purity silicon wafers, or hydrometallurgical processes to recover valuable metals more efficiently.

PV module technology is advancing all the time. Designing for recyclability, reducing the use and consumption of critical and rare resources, improving manufacturing processes to increase PV module lifespan and integrity, and adopting circular economy principles are all vital steps toward achieving a more sustainable and circular PV industry.

4.2.2. Inverters

As PV inverters are complex electronics with capacitors, coils, valuable metals, and other elements, their EoL processing is of particular relevance and importance. Proper EoL management of PV-inverters can help the recovery of valuable metals, facilitate the implementation of circular economy principles (by reusing recovered components), limit supply dependencies and environmental impacts across the value chain (at the EoL but also at resource extraction with secondary raw materials).

As best practice, once an inverter has reached EoL, it should be returned to the manufacturer for analysis and confirmation that the device is no longer usable and that no repair is possible. From there it can be collected and treated according to the EPR compliance plan of the producer (the inverter manufacturer).

If this is done collectively through a PRO, or another compliance scheme, the inverter manufacturer must make information on possible recycling methods available. This should include instructions for dismantling and the materials that can be recovered. Ensuring a high-level of detail in the information provided is key to ensuring that the most appropriate EoL solution is chosen. As best practice, manufacturers should design inverters that provide for easy dismantling and material recovery, with the information on how to do so stored in a QR code, or in some other form of "product passport" that is readily available for recyclers. For these reasons, inverter manufacturers are seeking to promote repairability and exchange as much as possible with a dismantlable design and the presence of a repair centre (for more

23 Human health risk assessment methods for PV, Part 3: Module disposal risks, International Energy Agency (IEA) PVPS Task 12, Report T12-16:2020. ISBN 978-3-906042-96-1.].

information on inverter repairs, refer to section 3.4.2. PV inverters). Support and strong common ground in Europe are also needed for recycling.

4.2.3. Communication Devices

To ensure compliance with relevant regulations, it is vital that consumers check that manufacturers of communications devices for PV systems comply with the WEEE Directive. Contacting the manufacturer for more information about their recycling process and partnerships is recommended to ensure proper handling of the devices.

As communication devices provide key linkages between all the different elements of a PV system, their disposal is covered by several parts of the legislative framework described in Chapter 2. EU Legal Framework for PV industry products at End-of-Life. For example, when handling communication devices with batteries, manufacturing and disposal will be governed by the Battery Directive. As the directive is transposed into each EU Member State's national law, there are differences in the exact requirements between each country. Verifying the laws and regulations that apply to different communications devices in each market that a company operates in is crucial.

In conclusion, prioritising responsible recycling practices and implementing the robust data protection practices detailed in section 3.4.3 Communication Devices, is essential for environmental stewardship and customers' data privacy. Manufacturers and users alike must work together to ensure that these devices are recycled responsibly at the end of their lifecycle, contributing to a greener and more secure future in the photovoltaic industry.

4.2.4. Batteries

Currently, approximately 95-97% of the lithium-ion battery recycling market is made up of small-format batteries, found in consumer electronics. The recycling of these batteries is reasonably lucrative and straightforward as most of this small hardware uses lithium cobalt oxide cathodes. Separating lithium and cobalt is relatively simple due to their different physical properties, namely distinct solubilities and melting temperatures. However, current practises are neither portable nor scalable, posing significant problems as the volume of waste and different types of materials that are expected to be generated in the next few years are significant.

Evolution, dimension, and materials

The volumes of waste batteries coming from PV systems will be larger format than the ones linked to the consumer electronics. The deployment of large-format Li-ion packs will soon take off because of the widespread expansion of stationary storage that will

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accompany the growing penetration of solar and other renewables. Large format batteries are projected to account for approximately 90-93% of the recycled battery market by 2030, or roughly 1.4-1.9 million metric tons annually.

Recycling process

The most expensive part of the battery recycling process is the method used to extract the desired metals from the scrap material, the figure below indicates the order of the key EoL operations.

Then, following mechanical treatment, each material undergoes one of two possible processes, which get their names from the key step used to extract the metals from the battery material.

- Pyrometallurgic process: this consists of heating the components at a high temperature to extract the valuable material .
- Hydrometallurgy process: materials are extracted using liquid chemical extraction to remove the valuable ones.

Recycling Li-ion battery packs includes recycling new scrap

It is not only batteries that are damaged, or have reached their EoL that get recycled. Around 6.5-8.5% of the material used for manufacturing large format battery cells is scrapped. New scrap is easier to process and can be more profitable to recycle.

Competitive landscape

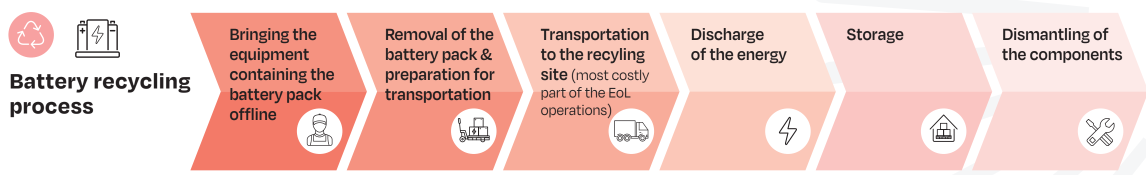
The recycling industry of the large format batteries will face competition from several agents, some already present:

- Metal Miners, Refiners
- Battery recyclers
- Battery manufacturers (expansion from Lead-Acid)

This competition is expected to be influenced by the fluctuations and sensitivity to the value of materials recovered from batteries. There will exist minimum per metric ton for a certain recycling of lithium ferrophosphate or lithium ferro manganese nickel or nickel manganese cobalt or sodium battery be profitable. And as mentioned before size, mix and transportation distance are a large fraction of Li-ion battery recycling economics. It will shape the facilities more profitable than others; early developers of large regional centres may cut costs substantially leading to the creation of entry barrier the new entrants.

To complicate the equation and as result of the strong R&D to launch novel batteries with higher capacity, higher volumetric and gravimetric density, safer and with more cycling there will exist relevant changes in the main components of the large format batteries, at least in the next 10-15 years.

FIGURE 14 KEY EOL OPERATIONS OF THE BATTERY RECYCLING PROCESS



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Annexes with country specific guidelines:

1. PV CYCLE. www.pvcycle.org – PV CYCLE offers collective and tailor-made waste management and legal compliance services

2. Landbell Group/European Recycling Platform. Homepage - Landbell Group (landbell-group.com), Home - About European Recycling Platform - ERP Global (erp-recycling.org) Look also at single country specific guidelines: Germany, Denmark, Spain, Italy, Poland.

3. WEEE Forum. WEEE Forum (weee-forum.org)

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