Interim Report

Technical support for the development of a recyclability index for photovoltaic products

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Introduction

This Interim report of the study “Technical support for the development of a recyclability index for photovoltaic products”, aims to provide the methodological basis for the development of recyclability scoring systems (also called recyclability indexes) applicable to PV products: PV modules and PV inverters.

This study, commissioned by the European Climate, Infrastructure and Environment Executive Agency (CINEA), DG GROW (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs) and DG RTD (Directorate-General for Research and Innovation), is developed in a comprehensive European policy context aiming to reduce the generation of waste, the consumption of resources and the associated environmental impacts of electric and electronic products, including PV modules and PV inverters.

Among the regulatory measures under preparation for PV products, the following initiatives are relevant for this study:

- ecodesign requirements (under EU Directive 2009/125/EC), promoting the energy efficiency, durability, reparability and recyclability of products;
- energy labelling measures (according to Regulation (EU) 2017/1369), promoting energy efficiency in products.

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

This report is structured in two main chapters. In chapter 1 the results of the literature review are presented, building on the initial literature review provided with the Inception Report. In Chapter 2 the proposed scoring methodology is described, starting from the definition of parameters, the prioritisation of materials and parts and finally the definition of scoring and aggregation methods.

The proposed scoring methodology described in this report will be the basis for the second stakeholder consultation (planned for the 9th of October 2024 in Brussels). A final version of the scoring methodology will be developed, taking into account the comments received from stakeholders at that meeting. Then, the next step of the study foresees a calibration and validation of the scoring systems on real PV products. Eight different PV panel models and eight PV inverter device models that are representative of the market at the time of the study, will be tested against this index by CENER at their testing facilities in Sarriguren (Spain). The scores will serve to calibrate and verify the methodology proposed here.

1 Literature Review

1.1 Literature review on existing scoring systems that include aspects on recyclability

The aim of this part of the study is to analyse other recyclability scoring systems and more general recyclability criteria that are applied at voluntary level both for photovoltaic (PV) modules/inverters or for other product categories. According to this review study, there is no recyclability index for PV modules nor for inverters. Nevertheless, the initiatives described in the following paragraphs can provide interesting insights on how recyclability criteria have been applied to PV and inverters in the context of a more comprehensive sustainability assessment or how recyclability is measured for other product groups (Cradle to Cradle[1], Recyclass[2]). Moreover, scientific literature in the field of recyclability of PV modules and inverters is analysed.

1.1.1 EPEAT and the NSF/ANSI 457 – 2019

The Electronic Product Environmental Assessment Tool (EPEAT) is a label for purchasers (governments, institutions, consumers, etc.) to evaluate the effect of a product on the environment. It assesses various lifecycle environmental aspects of a device (including recyclability aspects) and ranks products as Gold, Silver or Bronze based on a set of environmental performance criteria. EPEAT is based on a mix of mandatory and optional criteria. The optional criteria are used to rank products. It is important to notice that EPEAT is a global tool and for this reason some of the criteria could be already mandatory under EU legislation.

EPEAT covers several categories of products (mainly ICT devices) including PV Modules and PV Inverters. The EPEAT Label for PV modules and inverters is based on the compliance to the NSF/ANSI 457 standard[3].

The NSF/ANSI standard provides a framework and standardized set of performance objectives (criteria) for manufacturers and the supply chain in the design and manufacture of components for PV modules and PV inverters. Criteria relevant for the recyclability assessment are summarised in Table 1 below. Considering the EU context, the main limitation of the take back service criterion (9.1.1) is the geographical diversity that these services could have across EU Member States. The other recyclability criteria proposed by EPEAT are optional. Criteria 5.2.3 and 5.2.4 introduce thresholds for the halogenated substances, however these thresholds could still be not applied if an alternative assessment demonstrates that there are not commercially or technically viable for that application per the requirements of the framework used (Optional Criterion 5.1.5). This approach, in our opinion, is not appropriate for a recyclability index.

Table 1: Recyclability criteria in NSF/ANSI 457 standard

Criterion name	Criterion description	Verification
9.1.1. Required – Product take-back service and processing requirements (corporate)	Manufacturers shall provide a nationwide product take-back service for recycling for products declared and formerly declared to conform to this Standard. In jurisdictions where there are existing laws, regulations, or both, which establish a program for the collection and recycling of products declared and formerly declared to conform to this Standard, demonstration of compliance with those legal requirements meets the requirements of this criterion. The take-back programs should consider the hierarchy of management of used and EOL products based on reuse, refurbishment, materials recovery, or a combination of all three.	The manufacturer may satisfy this requirement by providing the URL for the manufacturer's public website that describes the take-back service in at least one web-based product promotional material;

[1] https://c2ccertified.org
[2] https://recyclass.eu/
[3] NSF International Standard / American National Standard NSF/ANSI 457 - 2019 Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters. Available at https://globalelectronicscouncil.org/wp-content/uploads/NSF-457-2019-1.pdf

Criterion name	Criterion description	Verification
	Manufacturer shall make available information describing the product take-back service, including how to utilize the service: • to customers in product promotional materials (e.g., product specifications, sales documents, product description) and product label or marking; • on the manufacturer's public website, the manufacturer shall declare the URL of the public disclosure.	
9.2.1 Optional – Identification of materials for EOL management (only applicable to PV modules**)**	Manufacturers shall make available to organizations that recycle EOL PV modules identification of the presence of the following substances in the manufacturer's product: 1) for conductor material: • metals and metal oxides. 2) for photoactive substances: • semiconductor materials; • metals and metal compounds; • organometallics; and • nonmetals that are used as photoactive substances. For products 60 kg or less, substances below 2 g in the product are not required to be identified; and for products greater than 60 kg, substances below 4 g in the product are not required to be identified.	a) Demonstration that this information is made available to organizations that recycle EOL PV modules; and b) the list of substances present in each of the applicable components and materials as required in the criterion.
5.2.3 Optional – Bromine, chlorine, and fluorine content in electric cables	If the product contains electric cables which contain greater than 5,000 ppm chlorine or bromine, or greater than 1,000 ppm fluorine, as determined by test method IEC 62321-3-1 and IEC 62321-3-2, the manufacturer shall conduct an alternatives assessment on the substance(s) responsible for the observed bromine, chlorine and/or fluorine levels in accordance with Section 5.1.5.	Verification requirements: a) a list of electric cables; and b) documentation that electric cables meet one of the options below: — test data showing that the cable contains less than 5,000 ppm chlorine, 5,000 ppm bromine, and 1,000 ppm fluorine, or — an alternatives assessment on the chlorine, bromine and/or fluorine present at levels above those stated in the previous option, that meets the requirements for conducting an alternatives assessment in Section 5.1.5.
5.2.4 Optional – Bromine, chlorine, and fluorine content in plastic parts	If the product contains any plastic part exceeding 25 g in weight, which contains greater than 5,000 ppm chlorine or bromine or greater than 1,000 ppm fluorine, as determined by test method IEC 62321-3-1 and IEC 62321-3-2, the manufacturer shall conduct an alternatives assessment on the substance(s) responsible for the observed chlorine, bromine and/or fluorine levels in accordance with Section 5.1.5. The following exemptions apply: • electric cables; and	a) a list of any plastic part (other than exempted parts) exceeding 25 g in weight; and b) documentation of any plastic part (other than exempted parts) exceeding 25 g in weight that meets one of the options below: — test data showing that the part contains less than 5,000 ppm chlorine, 5,000 ppm bromine, and 1,000 ppm fluorine, or — an alternatives assessment on the chlorine, bromine and/or fluorine present at levels above those stated in the previous option.

Criterion name	Criterion description	Verification
	• printed circuit boards (for PV inverters only). If the product does not contain plastic parts > 25 g “NA” may be declared.	that meets the requirements for conducting an alternatives assessment in Section 5.1.5.
10.2.1 Required – Enhancing recyclability of packaging materials	Product packaging shall meet the following requirements: 1) all nonreusable packaging components ≥ 25 g shall be separable by material type, including by plastic material type specified in b) of the verification requirements , without the use of tools, with the exception of labels affixed to plastics bags or wraps, staples, and nails in pallets; and 2) all plastics ≥ 25 g shall be clearly marked with material type in accordance with ISO 11469/1043, ASTM D7611/D7611M, or DIN7, with the exception of plastic films and plastic strapping.	Documentation from manufacturer: a) for requirement 1) manufacturer’s packaging part or assembly drawing, or photographs; and b) for requirement 2) photographs or physical evidence of plastic markings.

1.1.2 Cradle to Cradle Certification

The standard requirements[4] are based on the Cradle to Cradle® design principles outlined in William McDonough and Michael Braungart’s 2002 book, “Cradle to Cradle: Remaking the Way We Make Things”, and provide guidance in five key categories, including “Product Circularity – Products are intentionally designed for their next use and are actively cycled in their intended cycling pathway(s).”

Three levels of performance are defined:

- BRONZE: ≥ 50% of materials by weight are compatible with the intended cycling pathway(s) (i.e., recyclable, compostable, or biodegradable).
- SILVER: 70% of materials by weight are compatible with the intended cycling pathway(s) (i.e., recyclable, compostable, or biodegradable).
- GOLD: ≥ 90% of materials by weight are compatible with the intended cycling pathway(s) (i.e., recyclable, compostable, or biodegradable) and support high-value cycling. This means that the materials are of high quality and are likely to retain their value for subsequent use. If relevant, parts containing these materials are designed for easy disassembly.

Among the recyclability requirements applied in this context there are:

i. The packaging must be compatible for municipal cycling systems,

ii. Plastic materials must be a type that is commonly recycled or composted via curbside pickup (i.e., PET, HDPE, PP, bioplastics) and the material must be accepted by municipal recycling programs in the region(s) where the product is sold,

iii. Materials that are intended for composting must be fully compostable per a C2CPII-recognized compostability standard consistent with the intended cycling pathway(s), and

iv. Materials that are commonly recyclable (e.g., paper, steel, aluminium) must not contain additives or features that are likely to result in low-value (i.e., low-quality) reprocessed material. Additives that may be present in the recycled content used are out of scope for this determination. Exemption: Glass is exempt from this requirement.

[4] https://c2ccertified.org/the-standard

1.1.3 Recyclass

The initiative RecyClass[5] proposes a recyclability classification system (A-F) for plastic packaging.

Design for recycling guidelines are provided for different categories of:

- HDPE Crates and Pellets (see figure below)
- PP Crates & Pallets
- EPS White Goods

The RecyClass Guidelines are based on a traffic-lights system (Figure 1). Green column gathers the preferred design features, that guarantee the best recyclability and quality of the recyclate. Yellow column lists the second choices for each packaging feature, that have been tested or are known to slightly impact the recycling process and/or the quality of the recyclate. Red column classifies the detrimental and disqualifying features that should be avoided when designing packaging, as these strongly impact the recycling process and/or the quality of the recyclate.

RecyClass **HDPE Crates & Pallets**

		YES - FULL COMPATIBILITY	CONDITIONAL - LIMITED COMPATIBILITY	NO - LOW COMPATIBILITY
	MATERIAL COMPOSITION (AMOUNT OF **PO** IN THE PACKAGING)	A >= 95%, B >= 90% and all packaging features are FULLY compatible with recycling	C >= 70% and all packaging features are FULLY compatible with recycling	D >= 50%, E >= 30% and all packaging features are FULLY compatible with recycling
	DESCRIPTION (TEST PROTOCOL)	Materials that passed the testing protocols with no negative impact OR materials that have not been tested (yet), but are known to be acceptable in PE-HD or PP recycling	Materials that passed the testing protocols if certain conditions are met OR materials that have not been tested (yet), but pose a low risk of interfering with PE-HD or PP recycling	Materials that failed the testing protocols OR materials that have not been tested (yet), but pose a high risk of interfering with PE-HD or PP recyclin
	DESCRIPTION (METHODOLOGY)	In case of at least one limited compatibility one penalty is applied, lowering the recyclability class from A to B or from B to C	In case of at least one limited compatibility one penalty is applied, lowering the recyclability class from C to D	In case of at least one limited compatibility one penalty is applied, lowering the recyclability class from D to E or from E to F
MAIN BODY	MATERIALS*	HDPE, Multilayer PE with HDPE prevalence (LLDPE, LDPE, MDPE)	PP <= 10 wt%	Multilayers HDPE with PLA, PVC, PS, PET, PETG; 10 wt% < PP <= 30 wt% (-2 classes); PP > 30 wt% (-3 classes)
MAIN BODY	COLOURS	Light colours	Dark colours	Non NIR-detectable colours
MAIN BODY	ADDITIVES	Additives that are unavoidable in processing (stabilizers, antioxidants, lubricants, nucleating agents, peroxides) and density remains < 0,97 g/cm³	Mineral fillers (CaCO3, talc) not increasing density more than 0,97 g/cm³	Additives changing the material density > 1 g/cm³,Flame-retardant additives, plasticizers, Bio-/oxo-/photodegradable additives
ATTACHMENTS	COVERING SYSTEM	PE	PP	Any other
DECORATION	INKS	Non-bleeding inks compliant with EuPIA Exclusion Policy		Inks that bleed, Inks non-compliant with EuPIA Exclusion Policy, PVC binders
DECORATION	LABEL MATERIALS**	Low size labels in PE (all with density < 1 g/cm³); Avoid multilple labels	Low size labels in PP, PO (with density < 1 g/cm³); Low size labels in PET, PETG, PLA, PS (all with density > 1 g/cm³); Low size labels in Paper without fibreloss; Low size PO-foamed labels; Low size In-Mould-Labels in PE (except bleeding inks); Avoid multiple labels	Labels that hinder the recognition of the PE; Labels in non PO-materials with density < 1 g/cm³; Paper labels with fibreloss during recycling process; Cardboard or paper In-Mould-Labels; Aluminium; Metallised labels; PVC
DECORATION	ADHESIVES FOR LABELS	Water soluble adhesive (@ less than 40°C); Water releasable adhesive (@ less than 40°C)	Non-water soluble or non-releasable adhesive approved by RecyClass in combination with filmic PO labels	Non-water soluble adhesive (@ less than 40°C); Non-water releasable adhesive (@ less than 40°C)
DECORATION	DIRECT PRINTING	Laser marked	Direct printing (low extent of printing)	

RECYCLED CONTENT: No change in the recyclability assessment. A separate 'Recycled Plastics Traceability Certification' based on a Chain of Custody approach is available with RecyClass.

* Polymer resin can be either fossil-or bio-based, virgin or recycled . If different grades of the same polymer are present, weights should be cumulated.
** The surface coverage of a low size label is currently under definition.

Last update: July 2023

Figure 1: Summary of the recyclability assessment under Recyclass. Source: https://recyclass.eu/

1.1.4 French Recyclability score

In terms of consumer information, the "Anti-waste for a circular economy law" (AGEC) (2020)[6] requires producers of new equipment to:

- display the sorting instructions for the new equipment they put on the market;
- display the recyclability and other Environmental Qualities and Characteristics (EQC) of products marketed under Extended Producer Responsibility (EPR) schemes.

This obligation is set out in article 13 of the AGEC law and established in the French Environment Code:

Art. L. 541-9-1. – In order to improve consumer information, producers and importers of waste-generating products shall inform consumers, by means of marking, labelling, display or any other appropriate process, about their environmental qualities and characteristics, in particular the incorporation of recycled material, the use of renewable resources, durability, compostability, reparability, reusability, recyclability and the presence of hazardous substances, precious metals or rare earths, in coherence with European Union law. [...]

This information has to be made available to consumers in a "product sheet".

[5] https://recyclass.eu/
[6] The anti-waste law for a circular economy (AGEC Law). Available at: https://www.ecologie.gouv.fr/loi-anti-gaspillage-economie-circulaire#:~:text=La%20loi%20anti-gaspillage%20pour%20une%20%C3%A9conomie%20circulaire%20entend,les%20ressources%20naturelles%2C%20la%20biodiversit%C3%A9%20et%20le%20climat.?lang=en

According to the AGEC Law, this information *has to be made available in digital format and, where applicable, in accordance with the procedures defined by the law decree, by display, labelling or any other legible and comprehensible format, at the moment of purchase* [...].

In France, for all household EPR schemes, it is compulsory to display all EQCs on the product sheet for all new equipment. This sheet must be entitled "Product sheet on environmental qualities and characteristics".

Recyclability criteria are defined by law (Decree no. 2022-748)[7]. Recyclability is defined as the capacity to effectively recycle waste from identical or similar products. Recyclability is characterized for these wastes by:

- The ability to be efficiently collected on a regional scale, via the population's access to local collection points.
- The ability to be sorted, i.e. directed towards recycling channels for recycling.
- The absence of elements or substances that interfere with sorting and recycling or limit the use of recycled material.
- The capacity for the recycled material produced by the recycling processes implemented to represent more than 50% by mass of the waste collected.
- The capacity to be recycled on an industrial scale and in practice, in particular by guaranteeing that the quality of the recycled material obtained is sufficient to ensure the sustainability of the application markets, and that the recycling chain can justify a good capacity to take on products that can be integrated into it.

Decree n°2022-748 establishes a phased implementation according to the number of units placed on the French market (MSM) and associated sales (CA):

- January 1st, 2023: Producers with sales > €50m and MSM > 25,000 units / year
- January 1st, 2024: producers with sales > €20 M and MSM > 10,000 units / year
- January 1st, 2025: manufacturers with sales > €10 and MSM > 10,000 units / year

The French legal framework obliges to use the recyclability assessment methods provided by the relevant EPR schemes.

The following evaluation parameters are based on the simplified calculation rules developed by Ecologic[8] for Electric and Electronic Equipment (EEE). To qualify as a "produit majoritairement recyclable" (product recyclable to a great extent), EEE must meet the following requirement:

1) Requirement for battery extraction

"The battery or accumulator must be able to be removed from the device safely by an operator, without damaging the battery or accumulator in a way that increases the risk of a thermal or chemical incident, with commercially available tools as defined in EN45554."

Therefore, equipment containing one or more batteries or accumulators encapsulated, over moulded or crimped into the device is not considered recyclable. If a battery or accumulator is attached by an easily reversible mean (e.g. adhesive) or attached to a component that can itself be easily removed (e.g. battery soldered to an electronic board that can be safely removed), the requirement is considered to be met. This requirement does not apply to mobile phones.

2) Products presumed to be recyclable to a great extent

The method provides a list of products eligible for this "presumption of recyclability", with the associated average compositions and tolerances.

3) Recyclability of materials

The method provides a table that qualifies the recyclability of the main materials (Figure 2) and components (Figure 3) used in EEE in order to carry out a material balance of the product's recyclability.

[7] France Law relating to consumer information on the environmental qualities and characteristics of products generating waste (including recyclability score) (decree n°2022-748) available at: https://www.ecologic-france.com/recherche-generale/recyclability-concept-and-obligations.html
[8] , Ecologic (ecologic-france.com)

	Materials recyclability			
Green list				
All metals and metal alloys	YES			
ABS not filled with BFR and density < 1.1	YES			
PS not filled with BFR and density < 1.1	YES			
PE not filled with BFR and density < 1.1	YES			
PP not filled with BFR and density < 1.1	YES			
Orange list				
Products categories	cat. 1	cat. 4 & 8 (if > 50 cm)	cat. 5, 6 & 8 (if < 50 cm)	cat. 2
WEEE collection flow	LHA-cold	LHA-non-cold	SHA	Screens
ABS-PC not filled with BFR and density < 1.1	NO	NO	YES	YES
PMMA not filled with BFR	NO	NO	NO	YES
Concrete	NO	YES	NO	NO
Glass	YES	NO	NO	NO
Red list				
All plastics filled with BFR or with density > 1.1 (excepted PMMA)	NO			
All BFR-filled plastics	NO			
Expanded foams	NO			
Rubbers, silicones, elastomers	NO			
Ceramic	NO			
Glass ceramics	NO			
Wood	NO			
Textiles	NO			
Gas	NO			
All materials not listed elsewhere	NO			

Figure 2: Classification of materials recyclability by material (green list = fully recyclable, orange list = recyclable under specific conditions, red list not recyclables). From: “Anti-waste for a circular economy law” AGEC French law. Note: The following acronyms are included in Figure 1: BFR = Brominated Flame Retardants; ABS = Acrylonitrile Butadiene Styrene; PC is Polycarbonate, PMMA =Polymethylmethacrylate; PS = Polystyrene; PE = Polyethylene; PP = Polypropylene; LHA = Large household appliances; LHA no-cold means Large household appliances excluding cooling appliances (dishwasher, washing machine, cookers, etc.); SHA = small household appliances.

For some complex components, where their detailed material composition is unknown to the producer at the time of the assessment, default ratios are proposed (Figure 3) to model these components, based on average compositions. In the case where the detailed material composition of these components is known by the manufacturer, the material recyclability rates presented in Figure 2 above should be applied.

	Default ratios for complex components			
Product categories	cat. 1	cat. 4 and 8 (if > 50 cm)	cat. 5, 6 and 8 (if < 50 cm)	cat. 2
WEEE flows	LHA-cold	LHA-non cold	SHA	SCREENS
Electric motors	95%	95%	95%	95%
Compressors	95%	95%	NA	NA
HDDs	NA	NA	95%	95%
Printed circuit boards (generic)	30%	30%	30%	30%
Printed circuit boards (rich)[8]	NA	NA	50%	50%
Electrical cables	30%	30%	30%	30%
LCD panels - excluding metal parts	0%	0%	0%	0%
Capacitors	0%	0%	0%	0%
Mercury-containing components	0%	0%	0%	0%

Figure 3: Default Rations of recyclable materials in some complex components. From: "Anti-waste for a circular economy law" AGEC French law.

4) Disruptive linkages

When the material balance calculated results in a product recyclability between 50% and 60%, the method requires to verify the absence of recycling disrupting linkages (Figure 4), which could limit the product recyclability below the 50% threshold. According to current knowledge, this verification is only required for recyclable plastic parts linked to other materials (other recyclable plastic or other material: metals, etc.).

Disruptive linkages: gluing, overmoulding, co-injection, crimping, heat or ultrasonically insertion

Non-disruptive linkages: screwing, clipping, riveting

HELPS

Cas studies	Simplified rules
Plastic foot overmoulded on a metal tube (example: washing machine foot)	- metal tube: recyclable -plastic foot: not recyclable
Concrete ballast overmoulded in a plastic shell	- concrete ballast: not recyclable - plastic shell: not recyclable
Plastic frame overmoulded on a glass plate (example: refrigerator shelf)	-plastic frame: not recyclable - glass : recyclable
Layer of metal bonded to a layer of plastic (e.g. door and storm door of a washing machine top)	- metal : recyclable - plastic : non-recyclable
Metal tube encapsulated in PUR foam (example: refrigerator probe)	- metal tube : recyclable - PUR foam : non recyclable
Plastic-metal composite panels (e.g. thermal insulation)	- plastic layer : non recyclable - metal layer : recyclable
Aluminium foil bonded to a block of expanded polystyrene (EPS)	- EPS : non recyclable - aluminium foil : recyclable
Metal screw in plastic handle	- metal screws : recyclables - plastic handle : recyclable (the effect of screws is considered marginal in terms of material loss)
Metal insert in a plastic overmould	- metal : recyclable - plastic overmoulding : non recyclable

Figure 4: Assessment of the disruptive linkages under the French Recyclability Score method. From: "Anti-waste for a circular economy law" AGEC French law.

1.1.5 Mandatory Recyclability Requirements for Displays

Although the Ecodesign Regulation for Electronic Displays[9] does not include any scoring system, relevant examples of recyclability criteria are provided in the regulation:

- Marking of plastic components

Plastic components heavier than 50 g:

(a) Shall be marked by specifying the type of polymer with the appropriate standard symbols or abbreviated terms set between the punctuation marks '>' and '<' as specified in available standards. The marking shall be legible.

For the following plastic components no marking is required:

(i) packaging, tape, labels and stretch wraps;

(ii) wiring, cables and connectors, rubber parts and anywhere not enough appropriate surface area is available for the marking to be of a legible size;

(iii) PCB assemblies, PMMA boards, optical components, electrostatic discharge components, electromagnetic interference components, speakers;

(iv) transparent parts where the marking would obstruct the function of the part in question.

(b) Components containing flame retardants shall additionally be marked with the abbreviated term of the polymer followed by hyphen, then the symbol 'FR' followed by the code number of the flame retardant in parentheses. The marking on the enclosure and stand components shall be clearly visible and readable.

- Cadmium logo

Electronic displays with a screen panel in which concentration values of Cadmium (Cd) by weight in homogeneous materials exceed 0,01 % as defined in Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment, shall be labelled with the 'Cadmium inside' logo. The logo shall be clearly visible durable, legible and indelible. The logo shall be in the form of the following graphic Figure 5:

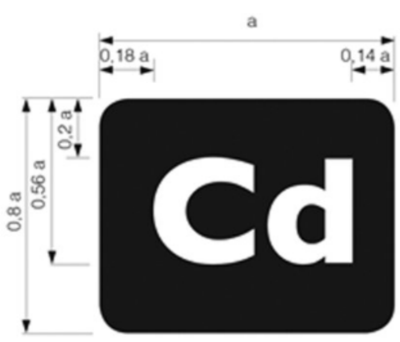
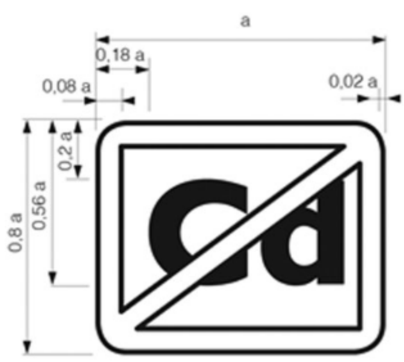
Cadmium inside	Cadmium free
	

Figure 5: Cadmium logo for displays according to the Ecodesign Regulation for Electronic Displays.

The dimension of 'a' shall be greater than 9 mm and the typeface to be used is 'Gill Sans'.

[9] Commission Regulation (EU) 2019/2021 of 1 October 2019 laying down ecodesign requirements for electronic displays

An additional ‘Cadmium inside’ logo shall be firmly attached internally on the display panel or molded in a position clearly visible to workers once the external back cover bearing the external logo is removed.

A ‘Cadmium free’ logo shall be used if concentration values of Cadmium (Cd) by weight in any homogeneous material part of the display do not exceed 0,01 % as defined in Directive 2011/65/EU.

1.2 Scientific Literature

1.2.1 "Evaluation of Products at Design Phase for an Efficient Disassembly at End-of-Life" by Mahdi Sabaghi

In this article published in the Journal of Cleaner Production (Sabaghi et al.2016), the focus is on enhancing the end-of-life disassembly of products, specifically in the context of aircraft design. The study introduces a hybrid methodology, combining Design of Experiment (DOE) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), to evaluate disassemblability indices. This approach proves valuable for decision-makers and designers seeking to improve the recyclability and recoverability of products.

Key Takeaways for PV Recyclability Index Development:

- **Identification of Significant Parameters:** The article identifies crucial parameters influencing disassembly tasks, such as "Accessibility" and the "Quantity and variety of connections." This insight can be applied to identify analogous parameters in the context of photovoltaic (PV) systems.
- **Utilization of Hybrid Methodology:** The hybrid DOE-TOPSIS methodology proposed in the study offers a practical and systematic approach. This methodology can be adapted to assess the recyclability index of PV systems, where parameters specific to solar panels' design and composition are crucial.
- **Categorization of Disassemblability Indices:** The categorization of disassemblability indices into "difficult to disassemble," "mild to disassemble," and "easy to disassemble" provides a structured way to evaluate and communicate the recyclability index. A similar categorization based on the characteristics of PV components can be applied.
- **Consideration of Design for Modularity:** The article emphasizes the importance of designing for modularity, allowing for the clustering of components with high disassemblability. This principle can be translated into the design of modular PV systems, facilitating easier disassembly and recycling.
- **Applicability Across Industries:** The methodology proposed by Sabaghi is highlighted as applicable across industries. The methodology can be transferred to the field of PV systems, while acknowledging the unique characteristics and challenges associated with solar panel technologies.

1.2.2 "A Design for Disassembly Tool Oriented to Mechatronic Product Demanufacturing and Recycling,"

In this Claudio Favi's paper (Favi et al. 2019) the importance of end-of-life (EoL) management in reducing waste and conserving resources is emphasized. Favi discusses three main perspectives guiding designers and engineers in EoL management: compliance with regulations, reduction of environmental impact across the product lifecycle, and the potential for profits through circular business models.

Key Insights:

- **Product Design for Sustainability:** The article underscores that product design is pivotal in achieving benefits related to EoL management. Design features such as material selection, shape, dimensions, product architecture, functionalities, and modularity should be assessed considering the entire product lifecycle.
- **Focus on Disassembly for Sustainability:** The Design for Disassembly (DfD) methodology is highlighted as a crucial approach. DfD involves simplifying de-manufacturing operations, reducing disassembly time and cost, and recovering significant quantities of components and materials. This approach is essential for the development of sustainable business models.
- **Challenges with Existing DfD Approaches:** Favi identifies practical limitations with existing DfD tools, emphasizing that many tools consider disassembly time as an input parameter and lack in providing effective disassembly time calculations. Real conditions of the product during disassembly are often not considered.

- **Introduction of LeanDfD Tool:** Favi introduces a new design for disassembly framework and software tool called LeanDfD. This tool aims to be user-friendly for technical departments during the product development process. It focuses on calculating the disassembly sequence and effective disassembly time using simple equations, robust data, and a 3D CAD viewer.
- **Innovation:** Knowledge Repository (Liaison Database (DB)): An innovative aspect of LeanDfD is the introduction of a knowledge repository called Liaison DB. This repository classifies and links mechanical liaisons with features and standard disassembly times. This time-based analysis enables robust disassembly estimations.
- **Metrics Assessment:** LeanDfD is designed to assess various metrics, including the disassembly time of target components, cost, and recyclability ratio. The tool contributes to identifying criticalities, guiding the redesign stage with specific suggestions based on the identified criticalities.
- **Holistic Approach:** The ultimate goal of LeanDfD is to link three main aspects: effective disassembly time, identified criticalities, and redesign suggestions. This holistic approach contributes to the product de-manufacturing and recycling process.

Key Insights for Developing a PV Recyclability Index:

- **Quantitative Assessment Methodology:** quantitative approach is employed to assess product disassemblability and recyclability. Consider adopting a systematic, data-driven methodology for evaluating recyclability aspects in photovoltaic (PV) systems.
- **Integration with CAD Systems:** the assessment tool is integrated with CAD systems, allowing for the direct import and visualization of 3D models. Explore ways to integrate the PV Recyclability Index with design tools to enhance usability during the development of photovoltaic systems.
- **Database for Knowledge Management:** The article highlights the use of a Liaison Database for storing knowledge about mechanical liaisons. Develop a knowledge management system for the PV index, capturing crucial information such as material properties, component connections, and recycling considerations.
- **Time-Based Evaluation:** Favi introduces a time-based approach to evaluating disassemblability. A time-based metrics can be considered for the PV Recyclability Index
- **Identification of Criticalities**: Favi's tool is adept at identifying criticalities in disassemblability. A PV Recyclability Index should pinpoint critical aspects in the recyclability of PV systems, facilitating targeted improvements.
- **Tailoring to PV Systems:** While Favi applies the methodology to a washing machine, the PV Recyclability Index should be tailored on the unique characteristics of photovoltaic systems, considering factors like module design, materials, and end-of-life processes specific to solar technology.
- **Usability for Design and Redesign:** Favi suggests that the tool is suitable for redesign projects. The PV recyclability index that we are proposing has a different perspective/application: is not meant to be a tool for manufacturers, but it is expected to provide information to the users and recyclers.
- **Feedback and Integration with Eco-Knowledge Management:** Favi explores ways to provide valuable feedback to PV system designers.. Again, this is not the intention of the recyclability index under this study.

1.2.3 "Manufacturing and Assembly for the Ease of Product Recycling: A Review"

Shahhoseini et al. (2023) explores the interplay between design and sustainability, emphasizing factors like ease of assembly, disassembly, recycling, and end-of-life (EoL) treatments. Utilizing Google Scholar, a comprehensive literature review on design for manufacturing and assembly was undertaken. Keywords such as "DFMA," "facility of recycling," "EoL," and "product design" guided the search, resulting in the identification of 115 articles initially. After screening based on titles and abstracts, 26 articles were chosen, and further refinement based on full-text examination yielded a final selection of nine articles.

Leal et al. 2020, proposed an innovative index amalgamating design from recycling and design for recycling to fortify the circular economy. This innovative approach establishes a forward and targeted connection between end-of-life chain stakeholders and product designers. Design for recycling identifies product aspects with low recycling efficiency, offering precise design guidelines. Design based on recycling allows the use of recycled materials from economic, technical, and environmental perspectives. The competitive manufacturing landscape often neglects waste disposal costs, as highlighted by Battaia et al.(2018).

Vanegas et al. introduced a technique assessing the ease of product separation, supporting the circular economy. Their proposed Ease of Disassembly Metric (eDiM) method calculates disassembly time, offering flexibility for different products. Aguiar et al. (2017) suggested a design tool evaluating product recyclability, providing a comprehensive review of a product's design stage. Favi et al. presented an approach to evaluate and improve End-of-Life (EoL) performance based on four indicators, reducing material and industrial waste.

Fatima et al. (2018) combining the DFMA approach with sustainable design, employing 3D scanning and CATIA software. Yadav et al. (2018) explored how designers use Design for Assembly factors to estimate a product's recyclability index, demonstrating a high correlation between assembly time and product recyclability.

Methodology:

The review focused on design for assembly and disassembly, design for EoL, design for ease of recycling, and the sustainability of the final product.

Results:

In short, here are key points and recommendations extracted from the literature in this review:

- **Design for Recycling and Circular Economy:** Leal et al. (2020) introduced an innovative index combining design from recycling and design for recycling to strengthen the circular economy. This forward and targeted connection between end-of-life chain stakeholders and product designers is crucial for a comprehensive PV recyclability index.

- **Ease of Disassembly and Circular Economy Support:** Vanegas et al. (2018) developed a technique for determining the ease of product separation, supporting the circular economy. Their proposed Ease of Disassembly Metric (eDiM) method, calculating disassembly time, offers flexibility for different products. This can be relevant for the PV index, especially if disassembly is a key aspect of PV recycling.

- **Recyclability Assessment Tool:** Aguiar et al. (2017) suggested a design tool for assessing the recyclability of products. This tool provides a thorough review of a product's design stage, indicating strengths and weaknesses. Developing a similar tool specific to PV systems could be beneficial for evaluating recyclability.

- **Integration of DFMA for Sustainability:** Fatima et al. (2018) advocated combining the Design for Manufacturing and Assembly (DFMA) approach with sustainable design. Employing 3D scanning and software for simplifying product structures is a strategy that might be relevant to PV module design.

- **Recyclability Index Development:** Yadav et al. (2018) explored how designers use Design for Assembly factors to estimate a product's recyclability index. This study demonstrated a high correlation between assembly time and product recyclability. Developing a recyclability index for PV systems could involve similar considerations, linking ease of assembly to recyclability.

- **Consideration of Lifecycle Stages:** The articles stress the importance of considering different stages of a product's life cycle, including pre-production, production, consumption, and end-of-life stages. Tailoring PV recyclability index to address factors at each of these stages will provide a comprehensive assessment.

- **Geographical and Temporal Analysis:** Consider the geographical and temporal trends mentioned in the articles. Understanding the global context and how sustainable design approaches have evolved over time can inform the applicability and relevance of the PV recyclability index.

1.2.4 “The Design Value for Recycling End-of-Life Photovoltaic Panels”

Through a Design for Recycling (DfR) and a Design for Durability (DfD), Calì et al. (2022) identified in this study the optimal materials, the best geometries and geometric proportions as well as the most convenient geometric and dimensional tolerances in the couplings between the layers and the components that comprise the panel. These design strategies aim to attain the most current, efficient and effective solutions for recycling end-of-life (EoL) PV panels and for longer durability.

The International Energy Agency (IEA) emphasizes that PV panels must be designed to return the embedded raw materials or, at least, to provide secondary raw materials that can be entirely used for other applications.

The requirements assessed as critical by the IEA Photovoltaic Power Systems Programme (PVPS) are functionality, longevity, durability, reliability and cost. The Design for Recycling (DfR) must support and improve these aspects.

The first action to be implemented is to eliminate, or at least minimize, the product materials that are difficult to recycle and that are non-reversible adhesives. The composition of the backsheet deserves particular attention, which represents the last layer at the bottom of the photovoltaic solar panel, consisting of a polymer or a combination of polymers. For this, a provision should be made for the use of totally recyclable polymers.

The use of encapsulants should be minimized to facilitate the disassembly of the modules. The use of appropriate sealants in the aluminium frame will allow for the separation of the EoL modules without damaging the components.

The second column of Table 2 lists the materials for each PV panel component, identified by the authors, which today are completely recyclable.

Table 2: Recyclable materials for PV panel components and their physical and mechanical characteristics

Layer	Material (Completely Recyclable)	Thickness h [mm]	Young's Modulus E [GPa]	Poisson Coefficient v [-]	Thermal Conductivity [W/m °C]	Specific Heat Capacity [J/kg °C]	Density [kg/m^3]
Frame (1)	Aluminum	20 ÷ 40	69	0.31 ÷ 0.34	204	996	2707
Cover (2)	Tempered Glass	3 ÷ 7	70	0.22	1.8	500	3000
EVA (3) and (5)	Plastic Material	0.45 ± 0.05	0.015 ÷ 0.08	0.48 ÷ 0.49	0.35	2090	960
Photovoltaic Cells (4)	Copper Silicon Silver	0.4 ± 0.1	115 131 83	0.33 ÷ 0.36 0.26 ÷ 0.28 0.37	148	677	2330
Backsheet (6)	Tedlar	0.1 ± 0.05	2.1 ÷ 2.6		0.2	1250	1200

The costs and benefits of recycling, especially when externality costs resulting from environmental pollution are considered, are of difficult estimation. This study provides an estimation of the total cost of recycling [€] (Table 3) based on material values taken from the work of Markert et al., 2020.

Table 3: Cost of recycling, material value and net profit.

Material	Weight [kg]	Costs of Recycling [€/kg]	Total Cost of Recycling [€]	Material Value [€/kg]	Total Material Value [€]	Net Profit [€]
Tempered glass	15	2.54	38.1	150 ÷ 525	2250 ÷ 7875	2211.9 ÷ 7836.9
Plastic	2.8	0.22	0.616	3.08 ÷ 5.88	8.62 ÷ 16.46	8 ÷ 15.84
Aluminum	2	6.62	13.24	0.94	1.88	−11.36
Silicon	1	3.04	3.04	25 ÷ 30	25 ÷ 30	21.96 ÷ 26.96
Copper	0.14	32.17	4.5	0.14 ÷ 1.12	0.02 ÷ 0.16	−4.48 ÷ −4.34

Excluding the failures that occur immediately after construction (infant failure) and the midlife failure, which can be shown to affect the failure of the PV panels with negligible percentages, the main causes that lead more or less slowly and/or instantly to the drastic decrease in the efficiency of the panel and/or its decommissioning were collected and listed by the authors in Table 4 below.

Table 4: Damage/failure causes in PV panels

Failure Cause	Estimated Frequency	Description	Method to Avoid Damage
Falling debris, breakage for impacts and micro-cracks	High	Scratches and breakage due to falling hail, debris, including whole branches, acorns, twigs, etc. Consequences of incorrect production, shipment and installation.	Produce small PV panels/small PV modules. Make bars in the panels.
Internal corrosion (rust) and delamination	High	Rust occurs when moisture penetrates the panel. Moisture leads to corrosion that becomes visible as a result of darker stains on the panel.	Make airtight or watertight panels by vacuum-rolling the components of the panels (the glass layer, solar cells and EVA sheets).
Water damage	Medium	Water damage caused by deterioration or old age.	Panel completely sealed.
Hotspot	Medium	Spots on PV panels caused mainly by poorly welded connections or as a result of a structural defect in the cells.	Control of the absolute quality of the cells during assembly.
Contamination of snail traces	Low	It is a defect related to the discoloration of the panel. The causes that generate this defect are multiple, including the formation of microscopic cracks in the panel and the use of silver paste of defective frontal metallization.	Limit the mechanical and thermal stress of the panel (even during installation). Silver paste quality controller.
PID (Potential Induced Degradation) effect	Low	Due to a voltage difference between the panel (grounded) and the grounding.	Monitor the voltage difference.

All elements, except for the junction box and the frame, are inserted at the time of assembly into a laminator, whose temperature reaches 145°. In a vacuum process, the ethylene vinyl acetate (EVA) is heated and fixes the parts together, isolating the PV cells to preserve them from external deterioration agents. In this process, **it is very important that the last layer of EVA is perfectly adherent and positioned correctly**, since, if of low quality and/or positioned incorrectly, it can cause the **formation of small air bubbles** between the layers that can affect the correct production of the panel.

Over time, the thermo-mechanical stresses end up leading to the delamination of layers of EVA from the photovoltaic cell layer and the backsheet layer due to the creep phenomenon.

Finally, A parametric failure event (FE) numerical model was developed, considering the thicknesses of different panel layers and overall dimensions as parameters. A layer of silicone rubber was introduced at the interface between layers and support to enhance adhesion and reduce thermo-mechanical stresses.

Results and Findings:

- **Critical Component:** The PV cell layer was identified as the most critical component in TMF simulations.
- **Role of Silicone Rubber Layer:** Using a proper thickness (hs) of the silicone rubber layer significantly increased the safety factor (by more than 40%) and the total life cycle of the PV panel.
- **Durability Improvement:** The silicone rubber layer not only increased the safety factor and total life cycle but also enhanced impact resistance and coupling conditions.
- **Optimal Geometric Parameters:** Through optimization, the authors identified the best values of geometric parameters that ensured the greatest total life of the PV panel.
- **Influence of Thermal Stress:** The study highlighted that thermal stress, with a daily stress frequency, had a greater influence on durability compared to mechanical stress.

- **Impact Analysis:** An impulse force analysis with an impact on the edge of the panel showed that, with the proposed design and maintenance methodology, PV panels could last up to 40 years or more.

Implications for PV Recyclability Index Development:

- The study provides insights into the design aspects that significantly impact the durability of PV panels, which can be crucial for the recyclability index.
- Understanding the role of specific layers, such as the silicone rubber layer, in reducing stresses and enhancing durability can inform the design of recyclable PV systems.
- Consideration of factors like impacts and daily thermal stresses in the TMF simulations aligns with real-world conditions, contributing to a more comprehensive recyclability assessment.
- The optimization approach for geometric parameters can be valuable for developing guidelines within the recyclability index for optimal PV panel design.
- The study emphasizes the importance of specific materials and their properties, providing insights into recyclability aspects related to material selection and performance.

1.2.5 "The End of Life of PV Systems: Is Europe Ready for It?"

This paper (Bošnjakovíc et al., 2023) provides a description of the barriers to recycling of PV modules. Among the barriers, there is the complexity and variety of materials and designs used in PV module designs. Due to the differences in each material's characteristics, several recycling techniques are needed. Because of this, it is challenging to separate and collect the PV modules' precious elements.

Also, this paper highlights the need to improve the design of PV systems for easier recycling by applying the approach of "Design for Recycling" (DfR) and "Design for the Environment". It is essential for product designers to be aware of possibly relevant recycling techniques in order to maintain a high level of recyclability. This facilitates the implementation of DfR in cases where the manufacturer is also a recycler for its own products.

1.2.6 "A critical review of the circular economy for lithium-ion batteries and photovoltaic modules – status, challenges, and opportunities".

The article from Heath et al., (2022) discusses the challenges of material supply, end-of-life management, and environmental impacts for the projected growth of PV capacity in the United States, which could exceed 1 TW by 2050. To address these challenges, the development of a circular economy is proposed, focusing on retaining material value and recycling at the end of product life. The review synthesizes literature on circular economy pathways for solar PV and lithium-ion batteries (LIBs), highlighting key insights, gaps, and opportunities for future research and implementation.

Some useful hints from this paper [8]:

- **Encapsulants:** The economic and environmental burdens associated with recycling PV modules can be decreased by eliminating ethylene-vinyl acetate (Saint-Sernin et al. 2008), using non-adhesive release layers between the ethylene-vinyl acetate and the glass layers (Doi et al. 2003), and substituting ethylene-vinyl acetate with alternatives that can be eliminated at lower temperatures during recycling.

  Alternatives to lead- based solders (e.g., electrically conductive adhesives (Oreski et al. 2021; VDMA 2020) and tin-bismuth- based solders) (De Rose et al. 2017) will help prevent the potential release of lead to the environment at end of life and could potentially prevent modules from being classified as hazardous waste, with its accompanying increase in cost of recycling and disposal. PV modules can be designed to include recyclable materials which enables more efficient recycling at end of life.

- **Labels of materials and other attributes:** Digital technologies such as RFIDs, material passports, QR codes, bill of materials, and ecolabels (Arup 2020; Chowdhury and Chowdhury 2007) can help embed and communicate data on the material origin and constitution, design, and technical specifications of the PV system between manufacturers, installers, and recyclers. This communication and transparency of data can help stakeholders in the use phase to select appropriate maintenance and repair activities, and in the EOL phase to select suitable processes to transport and subsequently repair, refurbish, remanufacture or recycle the PV module.

- **The use of Tedlar backsheets**, which contain fluorine, may increase the cost of high-temperature recycling operations by requiring additional emission control equipment to manage fluorinate emissions (Aryan, Font-Brucart, and Maga 2018).

List of possible trade-offs

- Fluorine-free backsheets could have lower durability than fluorinated backsheets (DuPont 2020).
- Replacing silver with copper metallization could negatively impact the durability and performance of the Si PV module.
- Replacing indium tin oxide with Al-doped zinc oxide could impact the durability and conductivity of this layer.
- Frame-free designs for PV modules can negatively impact the economic feasibility of downstream PV recycling operations since revenues from resale of recovered aluminum are significant.
- Lead-free and low-temperature soldering alternatives may have lower thermal fatigue resistance than conventional lead-based solders (Spinella and Bosco 2021), which could impact module dur-ability and performance.

1.2.7 Emerging waste streams – Challenges and opportunities

According to this report from Oko Institute (2021):

- Photovoltaic modules contain highly valuable materials of economic interest, such as silver, copper, aluminum, and critical raw materials like indium and germanium which are technically difficult to recover.
- By recycling the cover glass (70-75% of the weight) and the aluminium frames (10-15 % of the weight) the legally prescribed recycling quota is already reached; however, the separated remaining portion of silicon, silver contacts, tin, and heavy metal containing solder (lead) is usually burned together with the plastic foil. (Fraunhofer ISE, 2020). This means that there is still high potential for the PV sector to recover further valuable and scarce resources, including silver, copper, indium, gallium, tellurium, silicon etc. (Weckend et al., 2016; Pavel et al., 2017).
- About 95 % of the mass of resources in PV modules (e.g. glass, copper, aluminum, etc.) have the potential to be recycled, however, apart from aluminum and glass, the remaining module scrap, including silicon, silver contacts, tin, and heavy metal containing solder (lead) usually undergoes thermal treatment in incineration plants.
- Main challenges in PV recycling, both in economic and technological terms, are the delamination, separation and purification of the silicon from the glass and the semiconductor thin film.
- Challenges for the recycling of PV modules are hazardous substances such as cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride. Furthermore, according to lifecycle assessments, cadmium (Cd) and tellurium (Te) are the main contributors to the negative impact on mineral, fossil and renewable resource depletion.
- Logistic constraints arise due to necessary work on a panel at a height of 20 meters which is often not anticipated at the design or installation stage of PV modules.

1.2.8 Additional literature indicated by stakeholders:

PV module eco-design: new incapsulant for high sustainablility and reciclablility of photovoltaic value chain (Photorama EU Project).

This study from Izzi et. al. (2023) focus on one problematic aspect of the design of crystalline PV modules: the encapsulation. In particular, the encapsulation avoids high-value recycling or the remanufacturing of modules, which could close loops and extend the lifetime of the products. This work provides a study on new encapsulant materials suitable for the PV modules eco-design in order to evaluate their physical and optical parameters and sustain a future better recycling scheme and improve the circularity of PV value chain. The current encapsulation method using ethylene vinyl acetate (EVA) as the encapsulation material in terms of performance is not the optimal solution and requires an alternative. New encapsulation technologies thermoplastics (TPO) and elastomers (POE) are discussed and compared in terms of performance, sustainability and recyclability.

1.2.8.1 Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives.

Curtis et al. (2021) indicated as policy barriers in US the lack of information exchange between solar value chain actors. For example, no federal, state, or industry policies require or incentivize manufacturers to label PV modules to provide recyclers or landfill operators with the modules' chemical makeup. The lack of transparency between manufacturers and EoL PV module stakeholders compounds highly variable EoL management costs by requiring testing to determine if the module exceeds toxicity thresholds to ensure compliance with EoL management requirements. In addition, costs related to disassembly, collection, sorting, handling, transportation, and operations are often not well documented in analyses to date, which further complicates cost estimate calculations.

Furthermore, Curtis et al. (2021) consider that increased and publicly available information and information exchange between manufacturers and recyclers, as well as between end users and landfill owners and operators, can reduce costs, liability uncertainties and increase good faith relationships between solar industry stakeholders.

1.2.8.2 Analysis of material recovery from photovoltaic panels

The analysis of the EoL of silicon PV panels carried out by JRC (European Commission, 2016) has identified some criticalities in the recycling treatments. First of all, the uncertainty of the composition of the panels affects the efficiency of the treatments. The content of valuable substances (as critical, scarce and precious metals) is a driver for the selection of recycling treatments. The aim of the recycling is indeed to maximise the recovery of the most relevant fractions. On the other hand, the presence of hazardous substances influences the type of treatment and the quality and quantity of recycled materials. In the JRC study there was a general lack of information on the composition of the silicon PV panels. This was due to the age of panels currently reaching their EoL and the different technologies used in their manufacture. Some experimental tests on the composition of the panels have been performed within the FRELP project (and used as input for the JRC analysis). However, the provision by the manufacturers of detailed information on the composition of the panels would help further optimise the recycling efficiency.

Another key aspect in the recycling was the content of some specific halogenated plastics (especially for chlorinated and fluorinated plastics used in the back-sheet). According to the analysis in the FRELP project, PV without halogenated plastics can be treated in a pyrolysis plant, while PV with halogenated plastics have to be treated in specialised incineration plants. This latter would cause higher impacts compared to the pyrolysis scenario due to additional transport as well as the production of hazardous air pollutants and waste in the incineration plant.

1.2.8.3 Addressing uncertain antimony content in solar glass for recycling.

According to this report from the European Solar PV Industry Alliance (ESIA) (2023), while float glass, commonly used in PV solar glass in Europe, can be easily recycled within the EU due to its consistent composition, recycling imported patterned glass — through the import of modules — with variable antimony content is challenging and economically inefficient. Antimony containing glass can lead to undesirable interactions with the manufacturing process, impacting quality and emissions.

According to this ESIA report, to address these challenges, the EU should consider making it mandatory within the upcoming Ecodesign Regulation for PV modules, for manufacturers to disclose the composition and manufacturing process of solar glass, including additives like antimony compounds. This information should be included in the European Product Registry for Energy Labelling (EPREL), Digital Product Passport, or through other accessible means. Implementing such a measure will provide recyclers with the information needed to process solar glass effectively and economically, encouraging glass recycling within the EU and contributing to a more sustainable circular economy.

1.2.8.4 Product design and recyclability: How statistical entropy can form a bridge between these concepts - A case study of a smartphone

This study from Roithner et al. (2022) presents a recyclability assessment method for products that incorporates fundamental product information on material composition and product structure in to calculate the statistical entropy of the product, which is a well-established metric for the evaluation of material distributions. A case study is presented in which a modelled smartphone is investigated. The results show that statistical entropy is a valid measure to assess the recyclability of products at the stage of design and thus helping to identify weaknesses in product design. This metric is intended to address product designers and manufacturers to enable improvements in product design and comparisons between different products.

1.3 Comparative analysis

EDITOR NOTES: In the final report of this Interim report, expected to be published in November 2024, we intend to include a comparative analysis, on the reviewed literature. A matrix showing the common/different aspects or angles that the different studies have: one for the scoring methods and one for the articles dealing with scientific articles.
The intention is also to describe how each of the findings / recommendations from the literature review have been taken into account for the definition of recyclability parameters presented below.

2 Scoring system method

2.1 General approach to developing the methodology

The method described below is based on a general approach for developing a scoring system, already applied for the preparation of similar scoring systems in the context of the EU legislation (i.e. the repair scoring system for smartphone and tablets (Spiliotopoulos et al., 2022) included into the EU Delegated Regulation (EU) 2023/1669 of 16 June 2023 with regard to the energy labelling of smartphones and slate tablets) [10].

The key steps for the development of this recyclability scoring system are described in Figure 6:

I) Definition of key design for recyclability parameters;

II) Definition of priority materials and components;

III) Definition of scoring criteria;

IV) Definition of weighting and aggregation criteria;

The result is a methodology that allows the calculation of a "recyclability score" based on different scoring parameters applicable to priority parts, materials or applicable to the entire product.

Figure 6: Flowchart for the development of the scoring methodology

The general list of parameters is further adapted to the different sub-product categories within the PV products group: "PV modules" and "inverters". Within the "PV modules" product group, further adaptations of the scoring criteria have been introduced to reflect the diversity of design (e.g. with frame or frameless, crystalline vs. thin film, mono-facial vs bifacials).

In the following tasks of the study (end of 2024 and beginning of 2025), the proposed recyclability method will be complemented by a testing phase, aiming at the calibration and validation of the scoring systems. Eight different PV panel models and eight inverter device models that are representative of the market at the time of the study, will be tested by CENER at their testing facilities in Sarriguren (Spain). The study team will carry out a dismantling test and review product documentation that may be used in order to assign scores according to the methodology.

The aim of this testing stage will be also to verify whether the scoring system methodology is suitable for the intended use. Based on the test results, the study team aims to:

1. Verify the technical reproducibility of the scoring parameters (includes providing indication for verification tolerances).

[10] Commission Delegated Regulation (EU) 2023/1669 of 16 June 2023 supplementing Regulation (EU) 2017/1369 of the European Parliament and of the Council with regard to the energy labelling of smartphones and slate tablets (Text with EEA relevance)

2. Identify the most important methodological challenges encountered by the technicians in the application of the methodology and derive indications for the improvement of the methods or for the application of market surveillance.
3. Investigate how PV module and PV inverter models already placed on the market are positioned in the proposed scoring range in order to determine whether adjustments are necessary and to allow for a fair and future-proof scoring system.

2.2 Definition of recyclability parameters

As for the flowchart above (Figure 6), the first step is the definition of recyclability parameters. In order to develop a proposal, recyclability parameters and approaches already implemented in EU and Member States legislation, in European Standards and Ecolabels, have been reviewed, as also described in chapter 1.1.

According to the new Ecodesign for Sustainable Products Regulation (Regulation (EU) 2024/178) the following list of design for recycling parameters can be considered (Annex A (d) of the Regulation):

- use of easily recyclable materials;
- safe, easy and non-destructive access to recyclable components and materials or components and materials containing hazardous substances;
- material composition and homogeneity;
- possibility for high-purity sorting;
- number of materials and components used;
- use of standard components;
- use of component and material coding standards for the identification of components and materials;
- number and complexity of processes and tools needed;
- ease of non-destructive disassembly and re-assembly;
- conditions for access to product data;
- conditions for access to or use of hardware and software needed;

According to the CEN/CENELEC standard EN45555 "General methods for assessing the recyclability and recoverability of energy-related products", the following aspects are relevant for establishing recyclability criteria at product level:

- Identification of regulated substances, mixtures and components that have to be removed during depollution:
    - Assess the ability to identify the parts of the product containing substances, mixtures and components that shall be removed during depollution. This identification can be facilitated by e.g. sufficient marking for sorting provided by the manufacturer and visible on the product.
- Product design and structure:
    - Assess the ability to access and remove (e.g. depending on joining techniques used) the parts that require selective treatment according to the reference EoL treatment scenario. See e.g. WEEE Directive 2012/19/EU, Article 15.
    - Assess the ability to undo joints (including screws, glue, snaps, etc.), to separate and to sort materials compatible with recycling processes according to the reference EoL treatment scenario.
    - In case of non-separable material combinations, assess the use of materials which are compatible with existing recycling processes.
    - Assess the ability to access and remove parts containing CRMs from the product according to the reference EoL treatment scenario.
    - Assess the ability to access and remove parts that reduce the recyclability according to the reference EoL treatment scenario (e.g. plastic using certain fillers or certain flame retardants).

Based on the literature review and considering the inputs received by the stakeholders during the 1st stakeholder consultation, the following categories of recyclability parameters are proposed:

- **Service-related parameters (section 2.2.1)** are related to the availability of dismantling-related information (e.g., dismantling diagrams, marking, coding, software) (see details in section 2.2.1.3) and the availability of material related information (e.g. bill of materials (BoM), weight ranges, blending). Norgren et al. (2020)

highlight that identifying module composition and construction may permit higher tolerance for variable module designs that are otherwise suboptimal from a recycling perspective, because the recycling process can be designed to accommodate known variability. Known composition could also facilitate batch processing of categorized groups, enable isolation of problematic or incompatible chemical compositions, and avoid contamination of recycling products. Because PV modules may outlive their manufacturers, it would be helpful for labelling to be durable (on the scale of decades) and for any linked databases of construction or composition to remain accessible after a manufacturer goes out of business.

- **Dismantling related parameters (section 2.2.2):** these parameters can be considered as a proxy for the effort/time needed in the dismantling process to reach priority parts and materials. Scoring criteria should still award designs that facilitate the recovery of intact valuable target components (priority parts). The ability to separate components and remove fasteners to reach the priority parts of materials can be assessed based on the same type of parameters that are used in the assessment of reparability, i.e. a combination of dismantling parameters such as the number of steps needed, the tools needed and the type of fasteners/joint methods and possibly also their location. These parameters can be a proxy for the duration and complexity of the dismantling process. Regarding the Tools parameter, in the case of reparability scoring (i.e. a disassembly process), those range from basic tools (available even at user-level) to proprietary tools. In the case of recyclability, the dismantling process is expected to be performed by a professional, and therefore, even though product design allowing the use of basic tools for dismantling might still reduce the effort and time needed, this aspect is expected to be less critical compared to the case of reparability. On the other hand, proprietary tools are intrinsically less versatile, thus potentially complicating the work of recyclers, that have to treat different product models of PV modules. Regarding the Fasteners parameter, the reparability scoring considers the critical difference between reusable and removable fasteners. In the case of recyclability, the reusability of fasteners is not expected to influence the recyclability of the product that has reached its end of life, even though reusable fasteners might still accompany a part which has the potential to be reused.

- **Material related parameters (section 2.2.3):** these parameters cover the assessment of the material composition of the PV products. Scoring criteria can cover the presence/avoidance of certain substances of concern that can hinder the recycling process; selection of materials, material purity, blending and use of coatings are design aspects that can affect the quality and easiness of the materials recovery process and should be considered in this category of scoring criteria.

2.2.1 Service related parameters

2.2.1.1 #1 Technology identification

This qualitative parameter aims to assess the presence of a clear and durable identification of the model and type of technology placed or accessible on the product itself. This information can be printed on durable stickers, embossed, or engraved on the product itself or accessible from the product by electronic means in the form of bar codes, radio-frequency identification (RFID) or product passport based on blockchain technologies.

In the case of PV modules, identifying composition and construction may permit higher tolerance at the recycling plants for variable module designs that are otherwise suboptimal from a recycling perspective. The recycling process can be designed to accommodate and react to this known variability. The distinction of PV technologies is not always possible by optical inspection, especially in the case of thin film PV modules (as indicated in the EN 50625-2-4:2017 – Annex AA), where it is mentioned that there are no distinction criteria between silicon and non-silicon based thin film PV modules on an optical inspection basis.

As also suggested by Norgren et al. (2020), due to the fact that modules may outlive their manufacturers, it would be important to have durable labelling (on the scale of decades) and, if necessary, associated information should be provided in a database that would remain accessible after a manufacturer goes out of business. A specific marking / coding should be standardized for the technology identification. In the specific case of thin-film solar modules the following acronyms could be used: A-Si for amorphous silicon, OPV for the organic photovoltaic, CdTe for cadmium telluride, CGIS for copper indium gallium selenide and Si for the standard crystalline silicon technology.

Depending on the type of labelling method selected, the label composition, placement, and application method could have some minor negative recycling implications, but the label's information benefits should offset these potential implications.

Moreover, product labelling is already implemented for PV products where labelling is mandatory according to the Low Voltage Directive (2014/35/EU)[11] (see Figure 7).

- The EN IEC 61730 specifies the information that must be included both in the marking (on the nameplate of the product in clear and indelible way) and in the documentation that must accompany the module according to the Low Voltage Directive. The requested marking on the nameplate includes:name, registered trade name or registered trademark of the manufacturer,
- type or product number designation,
- serial number,
- date and place of manufacture; alternatively, serial number assuring traceability of date and place of manufacture,
- maximum system voltage,
- class of protection against electrical shock,
- voltage at open circuits including manufacturing tolerance,
- current at short circuit,
- PV module max power,
- For bifacial models, a clear indication of which side is designed as the front side, or if both are designed for prolonged exposure to direct sunlight,
- For flexible modules, the maximum radius of curvature,
- Positive and negative design load ratings in pascal (Pa).

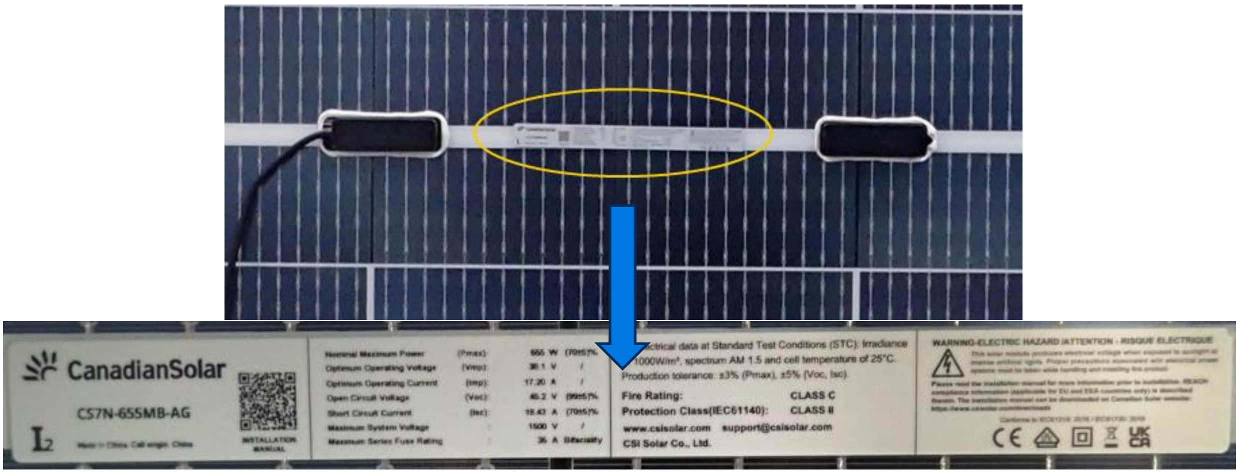


Figure 7: Product Labelling for PV modules according to the Low Voltage Directive (2014/35/EU)

[11] Directive 2014/35/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits (recast) Text with EEA relevance

2.2.1.2 #2 Information on the presence (or absence) of substance of concern

This scoring parameter aims to award points based on the availability of clear and durable information on the presence (or absence) of substances of concern. It is important to note that PV modules are exempted by RoHS Directive[12] and can contain substances that are restricted in other Electric and Electronic Equipment (EEE).

The new ESPR provides a wide definition of substances of concern in the Ecodesign context: According to Article 2(27) 'substance of concern' means a substance that:

a) *meets the criteria laid down in Article 57 of Regulation (EC) No 1907/2006 and is identified in accordance with Article 59(1) of that Regulation* (this section of the definition refers to substances identified as substances of very high concern (SVHC) in accordance with Article 59 of REACH);

b) is classified in Part 3 of Annex VI to Regulation (EC) No 1272/2008 in one of the following hazard classes or hazard categories (this section of the definition refers to substances with harmonized classification) *in one of the selected hazard classes or categories under the CLP Regulation: carcinogenicity categories 1 and 2, germ cell mutagenicity categories 1 and 2, reproductive toxicity categories 1 and 2, endocrine disruption for human health categories 1 and 2, endocrine disruption for the environment categories 1 and 2, persistent, mobile and toxic or very persistent, very mobile properties, persistent, bioaccumulative and toxic or very persistent, very bioaccumulative properties, respiratory sensitisation category 1, skin sensitisation category 1, chronic hazard to the aquatic environment categories 1 to 4, hazardous to the ozone layer, specific target organ toxicity repeated exposure categories 1 and 2, specific target organ toxicity single exposure categories 1 and 2;*

c) *is regulated under Regulation (EU) 2019/1021* (this section of the definition refers to persistent organic pollutants regulated under the POPs legislation); or

d) *negatively affects the reuse and recycling of materials in the product in which it is present*;

As for the criterion above, this information can be added to the product data plate, embossed or engraved on the product itself or accessible from the product by electronic means in the form of bar codes, radio-frequency identification (RFID) or product passport based on blockchain technologies. Product information can warn about both the presence of substances that can potentially be of risks to the health of recycling operators and for substances that would potentially hinder the recycling process. Recycling operators could use this information to implement the necessary depollution and risk mitigation strategies at the recycling plants. In this regard, a recent example comes from the Commission Regulation (EU) 2019/2021 of 1 October 2019 laying down ecodesign requirements for electronic displays pursuant to Directive 2009/125/EC, where the 'Cadmium inside' or the 'Cadmium free' logo shall be provided by manufacturers based on the concentration values of Cadmium (Cd) in homogeneous materials of the display (Figure 8). The logo is typically added to the product data plate as for other logos as the CE Marking or the WEEE logo.

[12] Directive 2011/65/EU — restriction of the use of certain hazardous substances in electrical and electronic equipment

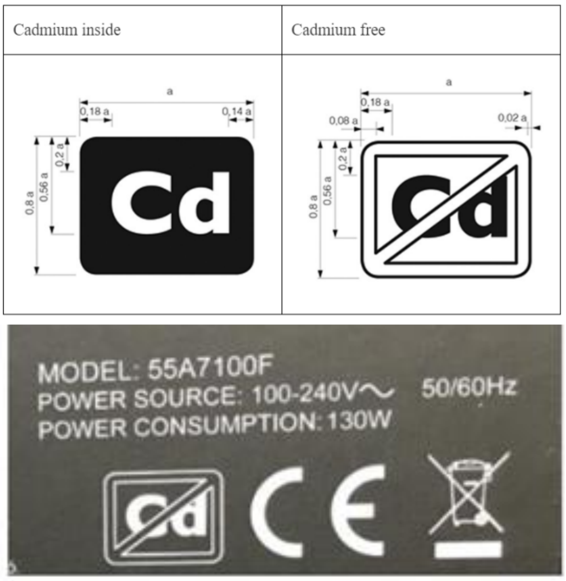


Figure 8: Above. Cadmium Logo according to the information requirement under the Commission Regulation (EU) 2019/2021. Below an example of product data plate with relevant recycling information, including the Cd logo-

2.2.1.3 #3 Access to dismantling and / or disassembly information

This scoring criterion evaluates the free availability of instructions for performing the dismantling or, whenever it is possible, the disassembly of the product. “Disassembly” means a process whereby a product is taken apart in such a way that it could subsequently be reassembled and made operational; “dismantling” is a similar process aiming to take apart the product but not requires that the process is reversible and the integrity of the equipment and the parts. In the context of PV modules, taking apart components is in most cases an irreversible process.

The dismantling instructions should be freely available on third party database / website. This would ensure that this information will be available for future use. The instruction should also include:

- the unequivocal product identification,
- the dismantling map or exploded view,
- the detailed step-by-step instructions on the dismantling of priority parts, including information on the unfastening operations, type of tools needed,
- diagnostic fault and error information (including manufacturer-specific codes, where applicable) component and diagnosis information (such as minimum and maximum theoretical values for measurements);[13]
- type of recycling technology needed to carry our specific recycling steps.

De Fazio et al. (2021) provide a relevant example of disassembly map. The provision of information is necessary to support the dismantling operations and should recollect all the information mentioned in the other parameters (e.g. dismantling depth, type of tools needed, removability of fasteners).

The availability of information can be defined in terms of:

- comprehensiveness of the information;
- availability to various target groups;
- duration of that availability;
- price at which access to information is provided.

2.2.1.4 #4 Information on composition (including critical and strategic raw materials)

For this parameter, two sub-parameters are proposed:

[13] The availability of this information can ensure that valuable and still functioning and valuable components can be separated and prepared for reuse.

- #4.1 Disclosure of material composition
- # 4.2 Disclosure of presence and location of Critical, Strategic and Environmental Relevant materials

#4.1 Disclosure of material composition

Knowing the material composition of a product, can facilitate batch processing of categorized groups, enable isolation of problematic or incompatible chemical compositions, and avoid contamination of recycling products. At the same time recyclers can have valuable information regarding the expected yield of the recycling process. Information about composition should be freely available on third party database / website. Different levels of ambitions could be awarded based on the percentage of product mass disclosed (e.g. 70% - 90% - 95% - 99%). A similar scoring criterion is provided by the NSF/ANSI 457 standard where the manufacturer shall demonstrate to have in place a system for recording information, calculating percentages of data acquired.

#4.2 Disclosure of presence and location of Critical, Strategic and Environmental Relevant materials

Critical, Strategic and Environmental Relevant materials could be less relevant in terms of mass and not fully captured by criterion #4.1. For this reason, criterion 4.1 on mass-based composition is proposed to be complemented by a criterion on the quantity and location of a specific list of Critical, Strategic and Environmental Relevant Raw Materials. The lists of materials have to be defined at product group level (see Table 5).

Table 5: Critical, Strategic and Environmental Relevant Raw Materials relevant for the two product groups.

PV Modules	PV Inverters
Cadmium	Aluminium
Silicon metal	Gold
Silver	Lead
Aluminium	Copper
Copper	Silicon carbide
Indium	Silver
Gallium	Indium
Germanium	Gallium
Tellurium	Tantalum
Lead	Nickel
Antimony	Palladium
Tin	Tin
	Cobalt
	Zinc

2.2.2 Dismantling Related Parameters

Taking apart PV products can facilitate the recycling of different priority materials present in different components by avoiding that all the parts are shredded together resulting into a higher risk of downcycling of the recovered material fractions.

Dismantling related criteria are also suggested by the EN45555:2019. This standard suggests general design related criteria in relation to the assessment of the ability to access and remove parts:

- The ability to undo joints (including screws, glue, snaps, etc.), to separate and to sort materials compatible with recycling processes.
- Ability to access and remove (e.g. depending on joining techniques used) the parts that require selective treatment (e.g. WEEE Directive 2012/19/EU, Article 15).
- Ability to access and remove parts containing CRMs.
- Ability to access and remove parts that reduce the recyclability (e.g. plastic using certain fillers or certain flame retardants).

As in the following sections is detailed, dismantling related information can be: the number of steps to dismantle a target component, the type of tools needed, and the type of fastening techniques applied can be proxies of the complexity of the dismantling process. The application of dismantling related parameters relies on the manufacturers declaration of the dismantling steps needed, including tools needed and applied fasteners (see criterion #3 above).

2.2.2.1 #5 Number of steps for the dismantling of priority parts (dismantling depth at part level).

This scoring criterion award points based on the number of dismantling steps (N) to reach and remove specific priority parts. For the calculation of dismantling steps, the following rules are proposed:

- the dismantling depth count is completed when the target part is separated and individually accessible.
- where multiple tools need to be used simultaneously, the use of each tool counts as a separate step.
- operations like applying thermal or chemical treatments to the product in order to facilitate the dismantling are also counted as steps.
- The Dismantling Depth score (DDi) for each priority part shall be calculated based on the number of steps required to remove that part from the product. The counting of the steps for each part starts from the fully assembled product.

2.2.2.2 #6 Type of tools to dismantle priority parts

This scoring criterion award points based on the complexity of tools needed to reach and remove specific priority parts.

In this case, the assessment starts from the previous priority part in disassembly sequence already removed. Where different types of tools are needed for the disassembly of a priority part, the type of tool with the lowest score shall be considered for the scoring.

In this context

- 'basic tools' means list of tools specifically defined for the product groups under assessment, considering the preliminary list in Table A.3 of the standard EN45554:2020;
- 'commercially available tool' means a tool that is available for purchase by the general public and is neither a basic tool nor a proprietary tool;
- 'proprietary tool' means a tool that is not available for purchase by the general public or for which any applicable patents are not available to license under fair, reasonable and non-discriminatory terms.

2.2.2.3 #7 Removability of fasteners to dismantle priority parts, reversibility of sealants and encapsulants

According to the Commission Delegated Regulation (EU) 2023/1669, a 'fastener' means a hardware device or substance that mechanically, magnetically or by other means connects or fixes two or more objects, parts or pieces. Under the same regulation, a hardware device which in addition serves an electrical function shall also be considered a fastener.

This scoring parameter aims to award points based on the removability of fasteners and the reversibility of adhesives, sealants and encapsulant used in the product and how they affect the dismantling of priority parts. In the context of this study, reversible adhesives, sealants and encapsulants can *'debond on-command'* potentially aiding / facilitating recyclability. The key aspect for a reversible conditions include easy to activate 'reversibility' on practical timescales (seconds to minutes ideally) by thermal or chemical treatment/process, low/no toxicity, and no detrimental effect on the bonded/de-bonded substrates (e.g. the resulting debonded components are not contaminated by the adhesive).

In the case of inverters, the use of removable fasteners (e.g. screws or clips) can facilitate the access for the recycling operators to the most valuable component and materials (sub criterion 7.1).

In PV modules, the use of thermal reversible encapsulants, able to be easily separated after a heating process (e.g. between 50 and 200 ◦C) can facilitate product dismantling and material liberation (sub criteria 7.2 and 7.3). Moreover, the application of edge sealing techniques instead of permanent sealants on the surface of the priority parts can facilitate its dismantling at the end of life (sub-criterion 7.4).

 # 7.1 Type of fasteners to dismantle priority part (X) (inverters)

Taking apart components for recycling can have different levels of complexity and circularity based on the type of fastening (or joining) technique applied:

- “removable fastener” means a fastener that is not a reusable fastener[14], but whose removal does not damage the product, or leave residue, which precludes reassembly (e.g. a screw is typically designed in a way that allows fastening and unfastening);
- “non-removable fasteners” means a permanent fastening (joining) techniques that makes the separation of the target part from the rest of the product not feasible or only feasible by damaging the part itself or the entire product.

This scoring criterion aims to distinguish between the use of removable and not removable fasteners for each priority part of the product. The assessment of the type of fasteners is based on the dismantling process to remove the specific priority part, starting from the previous priority part in dismantling sequence already removed. In case different types of fasteners are encountered in the disassembly of a priority part, the worst score shall be considered.

#7.2 Removability of the encapsulant after heating process (mono-facial PV modules)

The encapsulant has an important role in the design for durability of PV modules. Encapsulants shields the solar cells from moisture, oxygen, dirt, and various pollutants that may lead to damage to solar cells. Nevertheless, encapsulant removal at the end of life poses a challenge to many PV modules recycling processes. Some of the available recycling processes use high temperatures (180 Celsius or more) to soften or volatilize the encapsulant layer allowing the separation of the glass layer from the PV cell.

Several design options exist for modifying PV encapsulants and facilitate the recycling process (Bilbao et al. 2021), including:

- Adding release layers (the non-adhesive sheet in Figure 9)
- Using encapsulant materials with improved release performance at the typical recycling temperatures (e.g. 200 Celsius).
- Not using encapsulant.

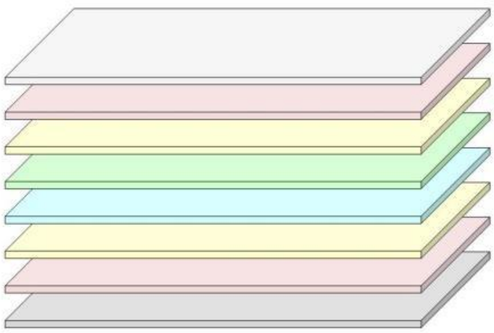


Figure 9: example of PV panel design with release layer. Source: Bilbao et al. 2021.

The aim of this parameter is to measure the reversibility of the encapsulant bond at conditions simulating a thermal-based recycling process (e.g. hot-knife) by a peel-off test applied to the interface encapsulant-glass. The peel-off test measures the encapsulant-glass adhesion force F (N/cm) at ambient temperature (at 23 ºC ± 2ºC). A new peel-off test method is proposed (to be further specified in next stage of the study) at higher temperatures, starting around 50 ºC (cross-linking temperature of the EVA) up to 200 ºC (hot-knife usual temperature), providing a method for measuring the adhesion force at beginning and at the end of a heating process, which exact optimum temperatures range will be defined by the test validation stage. The higher is the drop in adhesion force with heating, the higher is the score for this parameter.

	¨Traditional” peel off test	“Recyclability” peel off test
Objective of the test	Qualify insulation between different layers or rigid-flexible or flexible-flexible constructions of the PV module stack. Determines the adhesive strength between	Quantify the adhesive strength between polymeric materials bonded on a front sheet at the delamination temperature, and the adhesion strength diminution

[14] ‘reusable fastener’ means a fastener that can be completely reused in the reassembly for the same purpose and that does no damage either to the product or to the fastener itself during the disassembly or reassembly process in a way that makes their multiple reuse impossible;

	polymeric materials bonded on a front sheet and back-sheet.	
Interval of temperature	23ºC ± 2ºC	50ºC – 200ºC
Threshold in terms of adhesion force	75-125 N/cm for EVA-Glass $\frac{Force\ after\ aging}{Force\ before\ aging} > 0.5$	Decrease in the adhesion force with the increase in temperature. At 50ºC, the force should be 35 N/cm for EVA-Glass junction

$\Delta F_{peel\text{-}off} = F_1 - F_0$

Where F1 and F0 represent the measured Force at the initially proposed range of temperatures for the peel-off test, which are:

- T_0 = 100 °C
- T_1 = 140 °C

The interval of temperatures proposed aims to avoid trade-offs with durability/reliability and ensure that modules that are well designed to withstand high temperature (up to 100 °C) are not penalised by this recyclability parameter. At the same time this temperature is representative of existing thermal based recycling treatments such as hot-knife or similar dismantling process needing pre-heating of the PV panel.

It is important to consider that the standard values for the peel-off adherence between the glass and the encapsulant is in the range of 75-125 N/cm. Therefore, in order to have an easier dismantling, an adhesion force is expected to drop to values lower than 75 N/cm.

#7.3 Removability of the encapsulant after heating process (bi-facial PV modules)

In the case of bifacial devices, the adhesion force cannot be tested by a peel-off test. In this scenario the approach proposed is to expose the panel to heating process (see Figure 10 below) and measure at which temperature the panel can be dismantled by mean of metallic cord in a standardised conditions / setting (testing conditions to be further specified in the next stage of the study). Also in this case, the aim is to test the module at a temperature range that is closer to the conditions of a recycling plant.

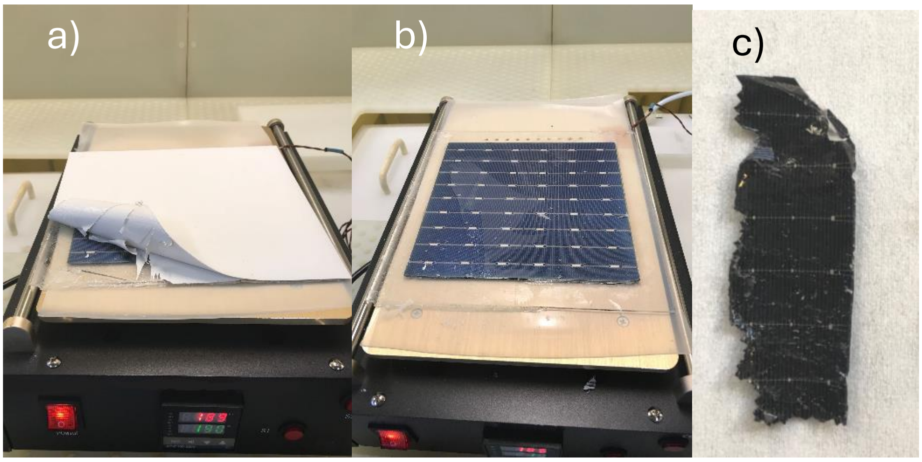


Figure 10: Dismantling tests for bifacial modules: a) backsheet removal, b) module without backsheet, c) cell and EVA strips. Dismantling technique available at CENER.

#7.4 Removability of the frame (only applicable to PV modules with frame)

Frame removal is the first step when recycling modules which have Al frames. Most module manufacturers use high performance silicone adhesive or double-sided adhesive tape as a frame sealant. These sealant materials, difficult to remove during module disassembly, increase the risk of module component damage, reducing its recycling value.

According to Bilbao et a. (2021) O-ring and U-profile techniques are alternative, easy-to-remove edge-sealing solutions that are suitable for PV modules. This sub-criterion aims to penalise the use of adhesives for fixing the frame on the surface of the module and award the presence of alternative edge sealing techniques, as the use of O-ring or U-profile (see Figure 11).

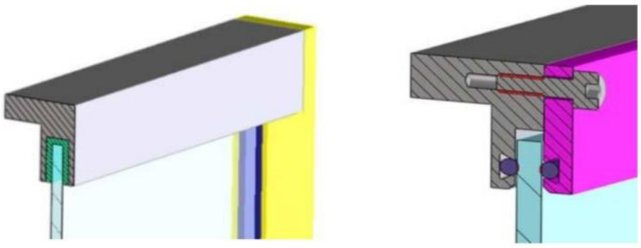


Figure 11: U profile and O-ring edge-sealing techniques applied to PV modules. Source: Bilbao et al. 2021.

2.2.3 Material based parameters

2.2.3.1 #8 Concentration of substances of concern, including substances affecting the recycling process

This parameter aims to assess the concentration of substances of concern, including specific substances affecting the recycling process, in specific homogenous parts of the product. Reducing the presence of these substances is likely to enhance the possibilities and economic profitability of recycling of PV products and decrease the negative impacts on the health of workers in recycling plants.

The list of substances covered by this criterion should be defined at product group level. In the case where these substances are listed under RoHS the scoring criteria should consider the relevant maximum concentration values defined in Annex II of Directive 2011/65/EU (RoHS Directive) and their applicability / exemption for the product group in scope. For other materials identified as barriers to recycling, the scoring criteria should take into the requirements from recyclers and the availability on the market of products fulfilling these requirements.

The verification of these criterion can be carried out by analytical techniques as standard X-Ray Fluorescence. Specific substances of concern affecting the recyclability of PV have been identified:

Fluorine in backsheets: One important issue relates to backsheets containing fluorinated polymers, which produce hazardous fluorine (F) gases under thermal processing and thus increase thermal recycling costs or restrict treatment options. If thermal processing is not used, backsheet composition has less effect on recyclability. If fluoropolymers must be used in backsheets for a particular module design, lower F content is preferable for three reasons. First, air emissions from thermal processing can be controlled at lower cost owing to lower use of reagent to neutralize F. Second, the resulting gases will be less corrosive. Finally, Cu smelters will pay more for recovered materials with lower levels of F contamination. Bifacial PV modules eliminate the backsheet in favour of a second layer of glass which likely bypass the F issue.

Antimony in glass: According to ESIA (2023), the variable antimony content in patterned glass adds a substantial cost to the recycling process, as measuring it is essential to meet quality requirements for end-users of the glass cullet. Reducing these costs is crucial to enhance the reusability of solar glass cullet.

In addition to the toxicity of antimony, and the health risks it poses for the workers in glass factories, the differing compositions of patterned glass compared to low iron patterned glass or conventional float glass, make European float line and patterned line operators reluctant to accept recycled cullet from external sources. When reintroduced in the manufacturing process of float glass, the antimony reacts with the tin in float bath and the antimony in the glass is reduced causing a colouration on the surface, making it unusable. Furthermore, unwanted contamination could severely impact the yield and lifetime of glass melting furnaces, leading to a negative impact of the CO_2 footprint, which contradicts the carbon reduction objectives of the flat glass sector and the European Union's 2050 climate-neutral goal.

Consequently, float line operators are reluctant in accepting cullet from external sources. Patterned glass manufacturers might have more options to blend the antimony containing glass, provided there are no further impurities present (Fe, organics stones, ceramics etc.). Antimony-containing glass could in principle be recycled to produce new solar glass (antimony-containing) via the rolled process. However, the challenge is that the composition of the glass produced outside the EU remains unknown and the EU currently does not have the capacity to consume all the potentially available supply. Very low concentrations of antimony could theoretically be reintroduced in European glass production lines. However, the lack of knowledge about the amount of antimony in solar glass produced in countries/regions like China, Malaysia, Vietnam, India, Middle East, and Northern Africa inhibits solar glass recycling.

Standard X-ray fluorescence (XRF) measurements usually have a detection limit of 0.0002 wt% of impurities and contaminants of antimony can be around 0.0004 wt% if no antimony trioxide have been added on purpose. According to ESIA, typical antimony levels when the substance have been added intentionally are in the range 0.1 wt% up to 0.25 wt%.

Brominated flame retardants in plastic components: Presence of halogenated flame retardants represents a major issue in the recycling of plastics of electric and electronic equipment. According to Annex VII of the WEEE Directive, plastics containing BFRs have to be removed from any separately collected WEEE. Usually, they can be separated by recyclers and end up in incineration. Several BFRs are already restricted, and it is possible that more will be banned in the future. If these substances are used in materials today, it is likely that they will not meet the requirements to be recycled and reused in new products in the future (legacy substances).

2.2.3.2 #9 Selection of materials based on their recyclability complexity

According to Berwald et at. (2021), the following materials should be avoided in EEE design for recycling:

- **Thermosets and composites:** Thermosets and composites cannot currently be recycled with existing technologies. When they are necessary (e.g., for functional reasons), materials outside the density range of commonly recycled plastics (0.85–1.25 g/cm3) should be preferred to avoid mixing of recyclable and not recyclable plastic in sorting processes by density.
- **Avoid the use of foam:** Foam can lead to issues during the recycling process. When foam is necessary (e.g., for functionality), thermoplastic foam should be preferred to foam from elastomers or thermosets.
- **Minimise the use of magnets:** Magnets end up in the ferrous material stream, leading to a pollution of the stream. For this purpose, the use of magnets should be reduced to a minimum when the functionality is required and no alternatives are currently available (e.g., neodymium magnets in mobile phones).

This proposed scoring criterion awards points based on the intrinsic recyclability of the materials used in the product and/or specific parts. This approach is based on a classification of materials based on their intrinsic recyclability complexity. A similar approach has been used by the French methodology for the calculation of the recyclability of electric and electronic equipment (EEE), where materials are classified in three different categories (green, orange, red) based on their recyclability:

- **green list:** substances that are the easiest to be recycled (metals and metal alloys such as copper, aluminium, steel, silver)
- **orange list:** substances that are the easy to be recycled but for which the fulfilment of specific design conditions should be verified (e.g. plastics as ABS, PE and PP not filled with BFR; glass without intentionally added antimony).
- **red list:** substances that are of more complex to recycle: thermoset and composites, rubbers, silicones, elastomers, foams, BFR-filled plastics, magnets)

2.2.3.3 #10 Combination of materials used / homogeneity

This scoring criterion award points based on the way different materials are combined in single parts and aims to award design based on homogeneous or separable materials versus the use of “disruptive”[15] l or innovative inkages (non-separable material combinations). The assessment has to be carried out at priority part level.

According to Berwald et at. (2021), the following disruptive linkages should be penalized:

[15] As for the French recyclability score, disruptive linkages are gluing, overmoulding, co-injection, crimping, heat or ultrasonically insertion.

- **Moulding different material types together by multiple-K processes**[16] (different plastic materials injected into the same mould, over-moulding, or in-mould decoration). It is very challenging to separate different materials that have been joined by multiple-K processes. They will usually end up as residue or (depending on the density) pollute other plastic streams. If the material types are the same and only differ in colour and additives (e.g., moulding red PP containing antioxidants on black PP containing talc) multiple-K processes are not an issue. An in-mould assembly by multiple-K processes that does not result in a chemical bonding of the materials is acceptable since the materials will be separated during shredding.

- **Connections that enclose a material permanently**. Avoid methods such as moulding-in inserts into plastics, rivets, staples, press-fits, bolts, bolt and nuts, brazing, welding, and clinching. The mentioned processes are typical for tightly enclosing materials and should be avoided, if possible. Enclosing a material permanently makes separation more challenging and can pollute the recyclers' waste stream.

- **Use of coatings on plastics.** All forms of coatings pollute the material stream or make the recycling process more challenging. Coatings change the density of the plastic, which can cause the plastic to end up in the wrong material stream. Printing numbers or lines for level-indication are not considered problematic and are usually better than using a sticker for the same purpose. Other options are screen-printing, in-mould texturing or laser engraving. When a coating is still needed, a density difference <1% of the material's weight is acceptable. Multilayer lacquering should always be avoided.

- **Plating, galvanizing, and vacuum-metallization as a coating on plastics.** The mentioned techniques connect plastics with metals, a combination that cannot be separated in the recycling process.

- **Fixing ferrous metals to non-ferrous metals in either parts or fasteners.** For example, do not use a screw (ferrous metal) to attach a part to aluminium (non-ferrous). If a product that contains joined ferrous and non-ferrous materials goes into shredding, it is very likely that either the ferrous or the non-ferrous stream will be polluted. The materials are shredded into small pieces and either the screw will go with the host part to the non-ferrous stream, or the non-ferrous part will follow the screw into the ferrous stream.

2.2.3.4 #11 Number of materials (excluded parameter)

According to Bilbao et al. (2021), decreasing the number and complexity of module materials can presents some trade-offs related to recyclability and its economics. Two trends in PV module designs exemplify trade-offs with regard to reducing the number and complexity of materials.

Frameless modules are one trend. PV modules are typically designed with frames, but they can be designed without frames. Framing helps protect the module during transportation, installation, and EOL removal while easing the installation process and providing torsional rigidity throughout the life cycle. Frameless modules are more prone to breakage, although certain transportation strategies and, for instance, reusable corner protectors can reduce breakage. On the other hand, frameless modules simplify recycling. De-framing a module adds a recycling step and increases the potential for glass and cell breakage. However, the frames are relatively easy to recover, and the aluminium can add more an important value in recycling revenue.

Similarly, glass/glass module designs present other trade-offs. Glass/glass designs increase the potential glass cullet revenue per module and eliminate use of a backsheet, which is often fluorinated. However, if different grades of glass are used for the front and rear, the recycling process can mix these grades, thereby degrading the quality and market value of the recycled glass.

Given these complexities, a criterion based solely on the number of materials oversimplifies the issue and can lead to misleading conclusions. While reducing materials may streamline recycling, it also impacts the economics and environmental trade-offs of module design. Omitting certain materials might simplify recycling but could reduce the module's structural integrity or economic value at EOL, affecting overall sustainability.

[16] Multi-material injection moulding is the process of moulding two or more different materials into one plastic part, at the same time. It is sometimes called Multi-Shot Moulding. There are various other techniques such as over-moulding that are commonly referred to as Multi-Material (K) Moulding techniques or MMM for short.

Moreover, there is no clear correlation between the number of materials and recyclability. Designs with fewer materials, like frameless modules, may be easier to disassemble, but increased breakage offsets these benefits. In contrast, framed modules with more materials may offer higher recovery value, improving recycling economics.

Therefore, "Number of Materials" does not provide enough insight to justify its inclusion. The focus should be on material quality, recyclability, lifecycle benefits, and economic viability, rather than just the number of materials.

Regarding PV inverters, as most the EEE are composed by a long list of materials. Nevertheless, the recycling of materials currently focus on the most precious elements like gold, silver and copper and it is based on pyrometallurgic processes that focus on the separation of these materials from all the rest of materials based on their physical properties. In this context, the number of materials, it is not considered by itself to be a proxy of the recycling complexity.

2.2.4 Summary of the scoring parameters

Table 6: Summary of the selected general parameters, their applicability, scoring principles, recyclabiliy benefits and verification complexity.

Type of parameters	N	Parameter	Product specific parameter	Applicability	Principle	Benefit in terms of recyclability	Verification
Service-Related Parameters	1	Technology identification	NA	PV Modules	Scoring criterion based on the presence of a clear and durable identification of the type of technology.	The distinction of PV technologies is not always possible by optical inspection,	MSA to verify the availability and accuracy of the information.
	2	Information on the presence (or absence) of substances of concern	NA	PV Modules PV Inverters	Scoring criterion based on the presence of clear and durable information of presence (or absence) of substances of concern	Easy identification of substances hindering recycling or needing some special care An example comes from mandatory Cadmium logo in EU Ecodesign Regulation for Electronic Displays (EU 2019/2021) (see below).	MSA to verify the availability and accuracy of the information.
	3	Dismantling information and condition for access	NA	PV Modules PV Inverters	Scoring criterion based on the availability of dismantling information (e.g. a dismantling map or exploded view, including detailed step-by-step dismantling and recycling instructions for priority parts and including information supporting the operations).	The manufacturer can facilitate the dismantling and further recycling by providing recommendations (e.g. specific suggestions on how to separate priority parts in an effective way and which recycling techniques are recommended).	MSA to verify the availability and accuracy of the information.

Type of parameters	N	Parameter	Product specific parameter	Applicability	Principle	Benefit in terms of recyclability	Verification
	4	Information on composition (including critical and strategic raw materials): #4.1 Disclosure of material composition	NA	PV Modules PV Inverters	Scoring criterion based on the disclosure of the material composition of the product. Different levels of ambitions could be awarded (e.g. 70% - 90% - 99% - 99.9% of product mass can be disclosed).	The recyclers can have valuable information regarding the expected yield of the recycling process.	Environmental Product Declarations could be used as proof of compliance.
		Information on composition (including critical and strategic raw materials): # 4.2 Disclosure of presence and location of Critical, Strategic and Environmental Relevant materials	NA	PV Modules PV Inverters	Scoring criterion based on the disclosure of the quantity and location of a specific list of Critical, Strategic and Environmental Relevant Raw Materials	The recyclers can have valuable information regarding the expected yield of the recycling process.	
Dismantling Related Parameters	5	Number of steps for the dismantling of priority parts (dismantling depth)	NA	PV Modules PV Inverters	Number of dismantling steps (N) to reach and remove specific priority parts.		

Type of parameters	N	Parameter	Product specific parameter	Applicability	Principle	Benefit in terms of recyclability	Verification
	6	Types of tools to dismantle priority parts	NA	PV Modules PV Inverters	Level of complexity in terms of tools needed for dismantling a priority part (from lower to higher complexity): No tools; Basic tools (e.g. screwdrivers); Commercially available tools; Proprietary tools.	Taking apart PV products can facilitate the recycling of different priority materials present in different components. The number of steps to dismantle a target component, the tool needed, the removability of fasteners and reversibility of sealants or encapsulants, can be a proxy of the complexity of the dismantling process. Easy	Manufacturer to declare the dismantling process and the associated steps, tools needed and types of fasteners. MSA to verify the availability and accuracy of the information.
	7	Removability of fasteners to dismantle priority parts, reversibility of sealants and encapsulants	7.1. Type of fasteners to dismantle priority part (X)	PV Inverters	Type of fastening technique used: the use of removable[17] fasteners (e.g. screw) instead of non-removable fastening techniques (not reversible adhesives) the separation of priority parts		
			7.2 Removability of the encapsulant after heating process: peel of test	PV Modules (monofacial)	The aim of this parameter is to measure the reversibility of the encapsulant bond at conditions simulating a thermal-based recycling process (e.g. hot-knife) by a peel-off test applied to the interface encapsulant-glass. The peel-off test aim collect data on the variation of the encapsulant-glass adhesion force at different temperatures (at beginning and at the end of the heating process). Higher is		Laboratory test (peel-off). Temperature and Adhesion force are the main parameters measured.

[17] 'Removable fastener' means a fastener that is not a reusable fastener, but whose removal **does not damage the product, or leave residues**

Type of parameters	N	Parameter	Product specific parameter	Applicability	Principle	Benefit in terms of recyclability	Verification
					the drop in adhesion force with heating, higher is the score for this parameter.		
			7.3 Removability of the encapsulant from the glass after heating process: metal cord test	PV Modules (bifacial)	The principle is to expose the PV panel to heating process and measure at which temperature the panel can be dismantled by means of metallic cord in a standardized condition/settings.		Dismantling test by metal cord in a laboratory condition. Temperature and applied force are the main parameters measured.
			7.4 Removability of the frame	PV Modules (with frame)	Design strategies that reversibility of the sealant and encapsulants (e.g by. the use of release layers, thermo-softening techniques). Several sub-criteria proposed.		Visual inspection of the product during the dismantling.
Material based parameters	8	Level of concentration of hazardous substances and other substances affecting the recycling process		PV Modules PV Inverters	Scoring based on different concentration levels of substances (e.g. Antimony or F-containing materials, brominated flame retardants). Scores from maximum in case of total avoidance to lower scores based on the level of presence.	Avoid / reduce cost and risks linked to depollution activities.	Bill of materials / Declarations of manufacturers Analytic techniques as X-ray fluorescence (XRF) Standard X-ray fluorescence (XRF) measurements usually have a detection limit of 0.0002 wt% of impurities

Type of parameters	N	Parameter	Product specific parameter	Applicability	Principle	Benefit in terms of recyclability	Verification
							and contaminants of antimony.
	9	Selection of materials based on recyclability complexity		PV Modules PV Inverters	Score based on positive design for recyclability / easiness to be recycled.	Materials that by themselves are easy to recycle and reduce costs at the end of the life. An example comes from the French Decree on recyclability[18] that provides a table of materials rated based on their intrinsic recyclability.	Bill of materials / Declarations of manufacturers. Verification of the availability and accuracy of this information.
	10	Combination of materials used / homogeneity		PV Modules PV Inverters	This scoring criterion award points based on the way different materials are combined in single parts and aims to award design based on homogeneous or separable materials versus the use of disruptive linkages (non-separable material combinations).	The combination of different materials in a single component means more difficulty in material separation at the recycling stage	Manufacturer to declare the material composition. Verification of the availability and accuracy of this information.

[18] https://www.ecologic-france.com/outils/centre-de-ressources/media/recyclabilite-eee-note-technique-eng.html

2.3 Definition of priority materials and components

Several principles can guide the prioritization of materials for recyclability. The recyclability index aims to address existing design advantages or barriers, facilitating improvements in recycling processes. For instance, aluminium in the PV module frame, or in the PV inverter casing may have a low priority, because it is already easily recoverable from modules. In contrast, silicon and glass may score higher, due to the potential of design for recyclability solutions to overcome current recycling challenges. In order to manage complexity and uncertainty, a total of four key criteria have been selected to be followed with equal weighting:

- **Mass content relevance**

  This approach assigns higher relevance to materials that are more abundant in the product, be it PV modules or PV inverters.

- **Environmental relevance**

  Under this approach higher relevance is assigned to materials whose recyclability is more beneficial from the environmental point of view. The methodology followed applied to calculate the environmental relevance has been using life cycle assessment methods. The Ecoinvent database has been used for background data and life cycle impact assessment, and the Environmental Footprint 3.0[19] method has been used to evaluate the materials present in PV modules and inverters. The impacts have been normalized with the normalization factors

- **Criticality and strategic relevance**

  Materials classified under the EU CRM list 2023 receive higher relevance. The agreed CRM act sets time limits on permitting for projects involving mining, recycling, and processing of the 16 raw materials considered "strategic" for the EU's green and digital transition. Criticality has been expressed in a 1 to 4 scale, being 1 not critical and 4 CRM.

  1. not critical
  2. somewhat relevant
  3. strategic raw material
  4. critical raw material

- **Economic / Demand**

  This approach prioritizes materials with higher value or demand in the commodity market, offering the greatest economic incentive for the recycling process. It is of outmost importance to have a secondary raw materials market ready for when the recycled materials arrive. Values here have been extracted from Trading Economics or Price Metal websites[20].

2.3.1 PV modules

Starting with the **mass content aspect**, glass is the most relevant material in terms of weighting PV modules, accounting for approximately two/thirds of the total weight of Crystalline Si modules. Mass metals such as copper (in wires) and aluminium (in frames) are also important. Other materials like silver, tin, cadmium, tellurium, indium, germanium are far below 1% in terms of weigh composition. An example of the material composition for a PV module is given in Table 7.

[19] The Environmental Footprint (EF) is an LCA-based method that allows the quantification of the environmental impacts and the comparison of products belonging to the same product category in case Product Environmental Footprint Category Rules are available. The Environmental Footprint (EF) method considers 16 environmental impact indicators, which can be aggregated into a single weighted score.

[20] https://price.metal.com/ and https://tradingeconomics.com/commodity/

Table 7. Left: Data for a 22,29 kg PV module. Right: Break-down of the solar cell off the PV module. Source: recycler in Spain, CERFO.

Material/parts		**Concentration (%)**
Glass		73,19
		10,17
Polymers	EVA (ethylvinylacetate)	3,55
	Tedlar (polyvinylfluoride)	
Solar cell		3,43
Adhesive		1,14
Copper		0,56
Junction box		1,31

SOLAR CELL

Material	**Concentration (%)**
Silver	0,69
Aluminium	9,00
Lead	0,04
Tin	0,06
Silicon	90,00
Copper	0,01

Regarding the **environmental aspect**, precious metals (e.g. silver and gold) are among the materials in PV modules and inverters with highest extraction and manufacturing impacts, and for which recycling would be more environmentally beneficial. Also, recycling of glass is environmentally relevant because the use of glass cullet in glass manufacturing requires less energy to melt compared to carbonated raw materials and avoids the impacts from the extraction of raw materials.

The environmental impacts listed in Table 8 below, have been calculated as follows:

1. **Impact Calculation:** First, the normalized impacts of materials commonly present in a PV modules were calculated using Simapro software and selecting the Environmental Footprint method. The Environmental Footprint (EF) method considers 16 midpoint impact indicators, which can be normalized (see Annex). The initial analysis shows that silver has the highest cumulative impacts among all materials typically found in a PV module.
2. **Impact Categories:** The most relevant impact categories were then identified, showing that Resource use (minerals and metals) is the most significant environmental category, followed by Freshwater eutrophication and Ecotoxicity in freshwater.
3. **Normalization** of Resource use (minerals and metals) values, using the factors given by the Joint Research Centre in 2023[21].

Onto **criticality**, silicon is classified both critical and strategic and should be scored highest due to the fact that EU accounted for only 0.6% of global crystalline silicon cell production in 2021 (Carrara et al., 2023). Aluminium is classified as critical and not strategic; Copper is strategic but not critical. Silver is not in the list, but PV module production is one of the most relevant sectors consuming silver. According to Carrara et al., 2023, germanium is used in minimal quantities, making dependence on it marginal for energy market modules. Few EU companies still produce small quantities of high-purity gallium, germanium, boron, and indium, but their numbers have been declining over the past decade. 68% of refined silver metal comes from domestic production within the EU, primarily from Germany, Italy, France, and Belgium, with Switzerland, the US, and the UK providing most imports (20%).

Regarding the **economic value (in EUR/kg)**, silver is on the other hand, the most expensive material in solar cells, being more than 1500 times more valuable per kilogram compared to other materials.

Based on the above criteria, the material prioritization in Table 8 was derived, where environmental impacts are normalized values for Resource use, minerals and metals. See the Annex for a detailed explanation of the multicriteria decision methods and the normalization factors used.

[21] https://publications.jrc.ec.europa.eu/repository/handle/JRC130796

Table 8. Material prioritization PV modules silicon based, based on four aspects. Own elaboration.

Material	Mass-content (%)	Environmental impacts (kg Sb_{eq})	Criticality / EU strategy	Economic / demand (EUR/kg)
Weighting score	25%	25%	25%	25%
Glass (material)*	73,20%	1,14E-04	2	0,62
Silicon*	3,10%	9,17E-04	4	15,86
Copper	0,60%	1,14E-01	3	9,78
Aluminium	10,50%	1,06E-03	3	2,52
Silver	0,02%	1,24E+01	3	953,59
Ethyl vinyl acetate	6,50%	4,07E-04	1	1,85
Tedlar (PVF)/ Polydivinyl fluoride (PVDF)	3,60%	2,69E-03	1	9
Tin	0,002%	4,23E-01	2	32,67
Lead	0,001%	2,07E-02	2	2,19

There is a series of materials that can be present in traces in PV modules, however no complete datasets for mass-content, nor criticality or economic value were found. These are boron, gallium, indium and selenium.

Material prioritization for silicon-based PV modules is evaluated based on the four aspects, each aspect being given an equal weighting score of 25%. A simplified multicriteria decision method is applied with equal weighting (25% each) for the four aspects. The results are presented below in Table 9.

Table 9. Rank for materials in PV modules prioritised with weighted scores for the four aspects/criteria.

Material	Mass-content	Env. impacts	Criticality / EU strategy	Economic / demand	Weighted Relevance score
Silver	3,28E-04	1,00	0,75	1,00	2,75
Glass (material)*	1,00	9,19E-06	0,50	6,50E-04	1,50
Silicon*	0,04	7,40E-05	1,00	0,02	1,06
Aluminium	0,14	8,55E-05	0,75	2,64E-03	0,90
Copper	0,01	9,19E-03	0,75	0,01	0,78
Tin	2,73E-05	3,41E-02	0,50	0,03	0,57
Lead	1,37E-05	1,67E-03	0,50	2,30E-03	0,50
Ethyl vinyl acetate (EVA)	0,09	3,28E-05	0,25	1,94E-03	0,34
Tedlar (PVF)/Polydivinyl fluoride (PVDF)	0,05	2,17E-04	0,25	0,01	0,31

The selection of priority parts in PV modules was guided by an analysis of the materials used, focusing on their mass content, environmental impact, criticality within the EU strategy, and economic demand. Table 9 provides a weighted relevance score for these materials, which was instrumental in identifying the most critical components for recyclability assessment. Hence, **based on the prioritised target materials, parts of the PV modules can be prioritized based on the presence of these target materials**. Below is a detailed explanation of the rationale behind prioritizing the five specific parts of PV modules.

1. Solar Cell

- Materials Present: Silver, silicon, tin, lead

- Rationale:
  - High Weighted Scores: Silver (2.75) and silicon (1.06) are the top two materials with the highest relevance scores, emphasizing their critical role in PV modules. Silver's score reflects its high economic value and significant environmental impact, while silicon is crucial due to its role as a semiconductor material in solar cells.
  - Functional Importance: Solar cells are the core component of PV modules, responsible for converting sunlight into electricity. The presence of silver, silicon, and other relevant materials like tin and lead further justifies their prioritization for recyclability.
  - Strategic Relevance: The EU's focus on securing supply chains for critical materials like silver and silicon underscores the importance of solar cells as a priority part in recycling strategies.

2. Glass

- Material Present: Glass
- Rationale:
  - High Weighted Score: Glass (1.50) ranks second in the weighted relevance score due to its mass content and moderate criticality in the EU strategy. While it has a lower environmental impact, its sheer volume in PV modules makes it a significant target for recycling.
  - Protection Function: Glass serves as the protective layer for solar cells, ensuring durability and efficiency. Given its mass content and importance in the module's structure, it is essential to prioritize glass in the recyclability assessment.
  - Economic Impact: Although glass has a lower economic value compared to metals, its importance in the overall structure and functionality of PV modules makes it a priority for recycling.

3. Frame

- Material Present: Aluminium
- Rationale:
  - High Weighted Score: Aluminium (0.90) is the fourth-ranked material, recognized for its criticality and economic demand within the EU. As a light and durable material, it is widely used in the frame of PV modules.
  - Structural Importance: The aluminium frame provides structural integrity and protection for the PV module, making it a vital component in ensuring the longevity and effectiveness of the solar panel.
  - Recyclability Potential: The abundance and recyclability of aluminium make it a significant focus for material recovery efforts, aligning with EU strategies for sustainable resource management.

4. Cables

- Material Present: Copper
- Rationale:
  - High Weighted Score: Copper (0.78) is ranked fifth due to its high relevance in economic demand and criticality. As a key material for electrical conductivity, copper is essential in the functioning of PV module cables.
  - Electrical Function: Cables in PV modules are crucial for transmitting the electricity generated by the solar cells. The presence of copper, a high-priority material, underscores the need to prioritize cables in recyclability efforts.
  - Strategic Importance: The EU's emphasis on securing copper supplies, combined with its role in the energy transition, highlights the importance of recycling copper-containing components like cables.

5. Junction Box

- Material Present: Copper

- Rationale:
  - High Weighted Score: Similar to cables, the junction box contains significant amounts of copper, further supported by its weighted score (0.78).
  - Electrical and Safety Function: The junction box is crucial for the safety and efficiency of PV modules, housing the electrical connections and protecting against potential faults. Its role in ensuring reliable power output makes it a priority component.
  - Recyclability and Resource Recovery: Given the presence of copper and the strategic importance of this material, the junction box is a critical part to target in recycling initiatives.

The recyclability assessment will be limited to these prioritized parts. Furthermore, weighting can be assigned to parts containing prioritized materials based on their material composition relevance.

Table 10: Prioritised parts for the PV modules

Priority parts for PV modules
1. Solar Cell (silver, silicon, tin, lead)
2. Glass
3. Frame (aluminium)
4. Cables (copper)
5. Junction box (copper)

2.3.2 PV Inverters

The WEEE Directive lists materials and components for selective treatment in Annex VII. Several of these components are potentially present in inverters and their easy removal for “selective treatment” at the beginning of the recycling process is a priority. The easy dismantling should be prioritised for these parts:

- **external electric cables**
- **printed circuit boards** (**greater than 10 cm^2**),
- when present, **plastic containing brominated flame retardants**
- when present, **liquid crystal displays above 100 cm^2**

Starting with the **mass content** aspect, PV inverters comprise various materials, with significant components including aluminium (19%), copper (28%), and steel (21%). Minor yet crucial elements such as gold, silver, nickel, tin, and palladium, although present in smaller quantities, hold high value and importance due to their critical applications and economic significance (Baudais et al., 2023).

Onto the **environmental aspect**, materials like gold, palladium, and silver exhibit substantial environmental impacts due to their energy-intensive extraction and refining processes. Recycling these materials can lead to significant environmental benefits, reducing the need for primary extraction and associated impacts. Aluminium and copper also demonstrate considerable environmental relevance, with recycling contributing significantly to CO_2 emissions reduction.

The environmental impacts listed in below, have been calculated as it follows:

1. Normalized Impacts: Using Simapro and the Environmental Footprint method, the normalized impacts of materials in PV inverters were assessed across 16 environmental categories. Gold exhibits the highest cumulative impacts, followed by silver and palladium (see Annex, Figure 14).
2. Impact Categories: The most relevant impact categories for PV inverters include resource use (minerals and metals), climate change, and resource use (fossils).
3. Normalization of Resource use (minerals and metals) values, using the factors given by the Joint Research Centre in 2023[21].

Looking at the **criticality aspect**, materials such as aluminium, copper, nickel, silicon, and palladium are classified as critical or strategic raw materials, making their recycling and reuse essential to reduce dependency on imports and enhance supply security. The EU places high priority on these materials due to their strategic applications in technology and industry.

Regarding **economic value**, gold and palladium are highly valuable, with gold being particularly expensive and used in small quantities in PV inverters. Despite their low mass content, the economic demand for these metals drives their prioritization in recycling efforts. Copper and aluminium, while more abundant, also hold significant economic value due to their extensive use in electrical and electronic components.

Based on these considerations, the values for the different materials in Table 11 were derived, where environmental impacts are normalized values for Resource use, minerals and metals. See the Annex for a detailed explanation of the multicriteria decision methods and the normalization factors used.

Table 11. Material prioritization PV inverters based on four aspects. Own elaboration

Material	Mass-content (%)	Environmental impacts (kg Sb_{eq})	Criticality / EU strategy	Economic / demand (EUR/kg)
Weighting score	25%	25%	25%	25%
Aluminium (CRM)	19%	1,06E-03	4	2,52
Copper (SRM)	28%	1,13E-01	3	9,78
Nickel (SRM)	0,42%	3,42E-02	3	17,28
Silicon (SRM)	9%	2,49E-03	3	1,68
Tin	0,42%	4,23E-01	2	32,67
Gold	0,31%	1,02E+03	2	69574,22
Silver	1%	1,24E+01	3	953,59
Lead	0,2%	2,07E-02	1	2,19
Palladium (CRM)	0,0%	1,31E+01	4	30527,13
Steel	21%	3,18E-05	1	3,40
Cobalt	0,002%	2,49E-01	1	27,15
Zinc	0,002%	2,38E-02	1	2,85
Specific plastic polymers:	11%			
- Glass-reinforced epoxy laminate material	1%	3,47E-03	1	2,80
Ferrite	2%	1,16E-04	1	0,02

There is a series of materials that can be present in traces in PV inverters, however no complete datasets for mass-content, nor criticality or economic value were found. These are tantalum, bismuth, arsenic, antimony, and hafnium.

Material prioritization for PV inverters is evaluated based on the four aspects, each aspect being given an equal weighting score of 25%. A simplified multicriteria decision method is applied with equal weighting (25% each) for the four aspects. The results are presented below in Table 12.

Table 12. Rank for materials in PV inverters prioritised with weighted scores

Metal/Material	Mass-content	Env. impacts	Criticality / EU strategy	Economic / demand	Weighted score
Gold	2,82E-03	2,50E-01	0,13	2,50E-01	0,63
Copper (SRM)	0,25	2,77E-05	0,19	3,51E-05	0,44
Aluminium (CRM)	0,17	2,60E-07	0,25	9,05E-06	0,42
Palladium	0,00	3,22E-03	0,25	1,10E-01	0,36
Silicon	0,08	6,11E-07	0,19	6,04E-06	0,27

Steel	0,19	7,82E-09	0,06	1,22E-05	0,25
Silver	0,01	3,04E-03	0,19	3,43E-03	0,20
Nickel (SRM)	0,00	8,40E-06	0,19	6,21E-05	0,19
Tin	0,00	1,04E-04	0,13	1,17E-04	0,13
Ferrite	0,02	2,85E-08	0,06	8,61E-08	0,08
Glass-reinforced epoxy (FR4)	0,01	3,47E-03	0,06	1,1E-05	0,07
Lead	0,00	5,09E-06	0,06	7,88E-06	0,06
Cobalt	0,00	6,11E-05	0,06	9,76E-05	0,06
Zinc	0,00	5,84E-06	0,06	1,03E-05	0,06

Here gold, copper, aluminium, palladium, and silicon are in the top 5 with a higher score. Once the prioritized target materials are defined, **parts of the PV inverters can be prioritized based on the presence of these target materials**. In view of the above materials ranking and having also into account the WEEE list of materials and components of the inverter for selective treatment, a list of prioritised parts containing those materials is presented here, and summarized in Table 13.

1. Printed Circuit Board (PCB)

- Materials Present: Gold, silver, copper, tin, lead
- Rationale:
  - High Weighted Scores: Gold (0.63), copper (0.44), and silver (0.20) are among the top materials with the highest weighted scores. These metals are crucial due to their high economic value, environmental impact, and criticality.
  - Functionality: PCBs are integral to the operation of PV inverters, connecting and supporting various electronic components. The presence of multiple high-priority materials (gold, silver, copper) makes PCBs a key target for recyclability assessment.
  - WEEE Directive Alignment: PCBs are listed in the WEEE Directive for selective treatment, highlighting their importance in recycling processes.

2. Heat Sink

- Materials Present: Copper, aluminium
- Rationale:
  - High Weighted Scores: Copper (0.44) and aluminium (0.42) are ranked second and third, respectively. Their high thermal conductivity makes them essential for dissipating heat in PV inverters.
  - Criticality and Demand: Aluminium, being a Critical Raw Material (CRM), and copper, designated as a Strategic Raw Material (SRM), are both highly demanded in the EU's strategy, underscoring their economic and strategic importance.
  - Environmental Impact: Although aluminium has a relatively low environmental impact score, its prevalence and criticality in electronic components make it a priority.

3. Casing

- Material Present: Aluminium
- Rationale:
  - High Weighted Score: Aluminium (0.42) is not only critical due to its CRM status but also widely used in the casing of PV inverters due to its light weight and durability.
  - Economic and Strategic Importance: Aluminium's use in the casing supports the structural integrity and longevity of PV inverters. Given its economic significance, aluminium is a top candidate for targeted recycling efforts.

4. Cables

- Material Present: Copper
- Rationale:
  - High Weighted Score: Copper (0.44) again ranks highly due to its essential role in electrical conductivity, making it a vital material in PV inverter cables.
  - Functionality: The copper in cables is crucial for the efficient transmission of electrical signals and power within the inverter. This importance, combined with copper's economic and strategic relevance, justifies the prioritization of cables for recycling.

5. DC Link Capacitors

- Materials Present: Palladium, tantalum
- Rationale:
  - High Weighted Score: Palladium (0.36) is included in the list due to its significance in the electronic industry and high value, despite its small mass content.
  - Criticality: Palladium is considered a CRM, crucial for the EU's technological advancements, and its presence in capacitors highlights the need to prioritize these components in recycling.
  - Specialized Use: DC link capacitors, containing palladium and tantalum, are specialized components that play a key role in stabilizing voltage within inverters, making them essential for effective recycling.

The recyclability assessment will be limited to these prioritized parts. Furthermore, weighting can be assigned to parts containing prioritized materials based on their material composition relevance.

Table 13: Prioritised parts for the PV inverters

Priority parts for PV inverters
1. Printed Circuit Board (PCB) (gold, silver, copper, tin, lead)
2. Heat sink (copper, aluminium)
3. Casing (aluminium)
4. Cables (copper)
5. DC link Capacitors (palladium, tantalum)

2.4 Scoring Criteria

The scoring criteria proposed are in a 1 to 5 numerical rating scale. This is a straightforward numeric scale where one point is assigned to the lowest option (least recyclable) and five points represent the highest or best option (most recyclable).

The number of scoring options can vary across the different parameters, based on the number of scoring options available. The following rules apply as for Table 14:

Table 14: scoring options and associated numerical scores

	Numerical score (1 to 5) Less recyclable <--> More recyclable				
5 scoring options	1	2	3	4	5
4 scoring options	1	2	--	4	5
3 scoring options	1	--	3	--	5
2 scoring options	1	--	--	--	5

As described in previous sections of the study, this recyclability score is expected to be used in the Ecodesign Directive / Energy Labelling regulatory context. It is, therefore, meant to complement a set of minimum recyclability requirements (e.g. information requirements) by awarding higher scores to devices with improved design for recyclability compared to the minimum requirements. In this context, all the scoring criteria will need to be fine-tuned considering the final draft version of the requirements for PV products. Moreover, the lowest option (1 point) will still need to comply with the ecodesign requirements.

Scoring is based on a combination of part- and product-level assessment. Points are assigned at product level for parameters (specifically #1, #2, #3, #4). Points are assigned at priority part level for the other parameters (specifically #5, #6, #7, #8, #9, #10). The scoring criteria for each scoring parameters are summarized in Table 15.

Table 15: Scoring criteria for the proposed parameters.

Type of Parameter	**N◦**	**Parameters**	**Product specific parameters (if applicable)**	**Applicability**	**Scoring Criteria**	**Points**
Service Related Parameters	1	Technology identification		PV modules	No technology identification available/accessible on the product itself.	1
					Technology identification available/accessible on the product itself.	5
	2	Information on the presence (or absence) of substance of concern		PV modules and PV inverters	No information specifying the presence/absence of substances of concern on the product itself.	1
					Information specifying the presence/absence of substances of concern on the product itself.	5
	3	Availability of dismantling instructions		PV modules and PV inverters	Dismantling instructions not freely available on a third-party database / website.	1
					Dismantling instructions freely available on a third-party database / website.	5
	4	Information on composition (including	4.1 Disclosure of material composition	PV modules and PV inverters	Disclosure of material composition (≤70% of product mass) freely	1

		critical and strategic raw materials)			available on a third-party database / website.	
					Disclosure of material composition (> 70% of product mass) freely available on a third-party database freely available on a third-party database / website.	2
					Disclosure of material composition (> 90% of product mass) freely available on a third-party database / website.	3
					Disclosure of material composition (> 95% of product mass) freely available on a third-party database / website.	4
					Disclosure of material composition (> 99% of product mass) freely available on a third-party database / website.	5
			4.2 Disclosure of presence and location of Critical, Strategic and Environmental Relevant materials	PV modules and PV inverters	Presence and location of CRM, Strategic and Environmental Relevant materials not disclosed	1
					Presence and location of CRM, Strategic and Environmental Relevant materials only partially disclosed	3
					Presence and location of CRM, Strategic and Environmental Relevant materials fully disclosed and available on a third-party database / website.	5
Dismantling related parameters	5	Number of steps for the dismantling of priority part (X)		PV modules and PV inverters	DDi > A steps	1
					A steps ≥ DDi > B steps	2
					B steps ≥ DDi > C steps	3
					C steps ≥ DDi > D steps	4
					DD ≤ D steps	5
	6	Type of tools to dismantle priority part (X)		PV modules and PV PV inverters	Proprietary tools	1
					Commercially available tools	2
					Basic tools	4
					No tools	5
	7	Removability of fasteners, reversible sealants and	7.1 Type of fasteners to dismantle priority part (X)	PV Inverters	Not-removable fasteners	1
					Removable fasteners	5

		encapsulant layers	7.2 Removability of the encapsulant after heating process: peel-off test	Mono-facial PV modules	"Non-reversible encapsulant": the product / components are damaged during the testing peel-off process (the peel off test is not passed)	1
					Difficult to remove encapsulant[22]: based on the measurement of the drop of the adhesion force between 100 at 140 °C	3
					Easy to remove encapsulant[22]: based on the measurement of the drop of the adhesion force between 100 at 140 °C	5
			7.3 Removability of the encapsulant from the glass after heating process: metal cord test	Bifacial PV modules	"Non-removable encapsulant": the product / components are damaged during the dismantling process.	1
					Difficult to remove encapsulant: the dismantling with the cord is feasible but only at a temperature equal or higher than 140 Celsius	3
					Easy to remove encapsulant: the dismantling with the cord is feasible but only at a temperature higher than 150 Celsius	5
			7.4 Removability of the frame	PV modules with frame	Presence of adhesive on the glass / frame interface	1
					Use of edge sealing techniques (e.g. O-ring or U-profile design)	5
Material based parameters	8	Concentration of substances of concern, including substances affecting the recycling process in Priority Part (X)	Applicable to the following parts / substances in PV panels 1) Antimony in Glass; 2) Fluorine in backsheet 3) Brominated flame retardants in plastic	PV modules PV inverters	Substance concentration by weight (%) in homogeneous material > A%	1
					Substance concentration by weight (%) in homogeneous material ≤ A% and > B%	2
					Substance concentration by weight (%) in homogeneous material ≤ B% and > C%	3
					Substance concentration by weight (%) in homogeneous material ≤ C% and > D%	4
					Substance concentration by weight (%) in homogeneous material ≤ D%	5

[22] The difference between 'easy' and 'difficult' will be clarified in the next version of the report, e.g. by determining the value of the force needed for a sample of PV modules.

			componen ts			
	9	Selection of materials based on their recyclability complexity in Priority Part (X)		PV modules and PV inverters	Use of materials with low recyclability (red list)	1
					Use of materials with conditional recyclability (orange list)	3
					Use of materials with high recyclability (green list)	5
	10	Combination of materials used / homogeneity in Priority Part (X)		PV modules and PV inverters	Use of combined materials that are not separable.	1
					Use of combined materials that are separable (allow easy liberation)	3
					Use of homogenous material in a specific part	5

2.5 Weighting and aggregation

The final step of the methodology entails the definition of weighting factors that allow the evaluation of the relevance of each rated criterion / priority parts and allow tailoring the scoring system in order to reflect the specificities of the product group.

Weighting factors can be introduced at two different levels:

- Weight of the different priority parts (based on the relevance of the parts as described in section 2.3)
- Weight of the different parameters (described in section 2.2)

Weighting factors for the scoring parameters will be provided after the consultation with the stakeholders on the list of scoring parameters. A description of an aggregation mechanism, which consists of mathematically combining the scores achieved for each parameter and priority part, is provided in section 2.5.1 below.

2.5.1 Scoring Aggregation

The final score (defined as Recyclability Index) can be calculated using the formulas below (1) and (2). Whenever necessary, partial scores ($S_{j,i}$) are first calculated at priority part / material level and then aggregated at parameter level (S_j) using the weighting factors of priority parts / materials. Finally, the parameter scores are aggregated in a Recyclability Index, based on the combination of different parameters and corresponding weighting factors.

The “Recyclability Index” is calculated according to the following general formula:

$$R = \sum_{j=1}^{10} \boldsymbol{S_j} \cdot \mathbf{W_j} \qquad (1)$$

Where the scoring parameters requires that the scores are calculated at specific part / materials level, the following formula is applied:

$$S_j = \sum_{i=1}^{N} S_{j,i} \cdot \omega_i \qquad (2)$$

Where:

R is the overall recyclability index
S is the score (per part/material or parameter)
ω is the priority part weighting factor
W is the parameter weighting factor

i is a specific priority part/material,
N is the number of priority parts/materials
j is a specific parameter

The scoring and aggregation formulas are adjusted to PV panels (Table 16) and PV inverters (Table 17) in order to consider product specific parameters and the applicability to specific design options. An example is the scoring criterion #7.4 that is only applicable to PV modules with frame. In case of frameless PV modules, users of this scoring system can simply skip this parameter. Regarding criteria #7.2 and #7.3 these have to be considered alternative options, since criterion #7.2 applies in case of monofacial modules and criterion #7.3 in case of bifacial PV modules.

Table 16: Scoring aggregation and calculation of the recyclability index for PV modules

Parameter	**Score for priority part/material i [1-5]**	**Weight for priority part/material i [%]**	**Parameter Score [1-5]**	**Parameter Weight [%]**	**Final Score [1-5]**
#1 Technology Identification			S_1	W_1	
#2 Information on the presence (or absence) of substance of concern			S_2	W_2	
#3 Availability of dismantling instructions			S_3	W_3	
#4.1 Disclosure of material composition			$S_{4.1}$	$W_{4.1}$	
#4.2 Disclosure of presence and location of Critical, Strategic and Environmental Relevant materials			$S_{4.2}$	$W_{4.2}$	
#5 Dismantling depth	$S_{5,i}$	$\omega_{5,i}$	$S_1 = \sum_{i=1}^{N} S_{5,i} \cdot \omega_i$	W_5	Recyclability Index $R = \sum_{j=1}^{10} \boldsymbol{S_j} \cdot \mathbf{W_j}$
#6 Tools (type)	$S_{6,i}$	$\omega_{6,i}$	$S_6 = \sum_{i=1}^{N} S_{6,i} \cdot \omega_i$	W_6	
Optional # 7.2 or #7.3 Removability of the encapsulant after heating process			$S_{7.2}$ or $S_{7.3}$	$W_{7.2}$ or $W_{7.3}$	
Optional #7.4 Removability of the frame (only applicable to PV modules with frame)			$S_{7.4}$	$W_{7.4}$	
#8 Substances of concern	$S_{8,i}$	$\omega_{8,i}$	$S_8 = \sum_{i=1}^{N} S_{,i} \cdot \omega_i$	W_8	
#9 Selection of materials based on their recyclability complexity	$S_{9,i}$	$\omega_{9,i}$	$S_9 = \sum_{i=1}^{N} S_{,i} \cdot \omega_i$	W_9	

Parameter	Score for priority part/material i [1-5]	Weight for priority part/material i [%]	Parameter Score [1-5]	Parameter Weight [%]	Final Score [1-5]
#10 Combination of materials used / homogeneity	$S_{10,i}$	$\omega_{10,i}$	$S_{10} = \sum_{i=1}^{N} S_{,i} \cdot \omega_i$	W_{10}	

Table 17: Scoring aggregation and calculation of the recyclability index for PV inverters

Parameter	Score for priority part/material i [1-5]	Weight for priority part/material i [%]	Parameter Score [1-5]	Parameter Weight [%]	Final Score [1-5]
#2 Information on the presence (or absence) of substance of concern			S_2	W_2	
#3 Availability of dismantling instructions			S_3	W_3	
#4.1 Disclosure of material composition			$S_{4.1}$	$W_{4.1}$	
#4.2 Disclosure of presence and location of Critical, Strategic and Environmental Relevant materials			$S_{4.2}$	$W_{4.2}$	
#5 Dismantling depth	$S_{5,i}$	$\omega_{5,i}$	$S_5 = \sum_{i=1}^{N} S_{5,i} \cdot \omega_i$	W_1	
#6 Tools (type)	$S_{6,i}$	$\omega_{6,i}$	$S_6 = \sum_{i=1}^{N} S_{6,i} \cdot \omega_i$	W_2	
#7.1 Fasteners (type)	$S_{7,i}$	$\omega_{7,i}$	$S_7 = \sum_{i=1}^{N} S_{7,i} \cdot \omega_i$	$W_{7.1}$	
#8 Substances of concern	$S_{8,i}$	$\omega_{8,i}$	$S_3 = \sum_{i=1}^{N} S_{8,i} \cdot \omega_i$	W_8	
#9 Selection of materials based on their recyclability complexity	$S_{9,i}$	$\omega_{9,i}$	$S_3 = \sum_{i=1}^{N} S_{9,i} \cdot \omega_i$	W_9	
#10 Combination of materials used / homogeneity	$S_{10,i}$	$\omega_{10,i}$	$S_3 = \sum_{i=1}^{N} S_{10,i} \cdot \omega_i$	W_{10}	

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Annex

Materials prioritization

Extra information about normalization and environmental categories relevance.

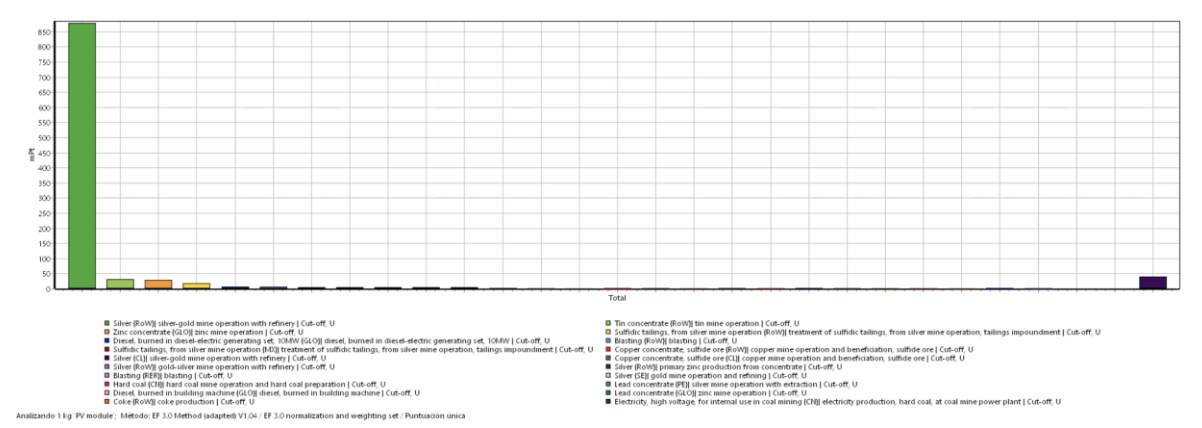

Figure 12. Normalized impacts for materials in PV modules. First is silver, then tin, then zinc.

Looking at which are the most relevant impact categories, a second figure below can be drawn, showing that "Resource use, minerals and metals" is the environmental category with highest score, followed by "Eutrophication, freshwater" and "Ecotoxicity freshwater".

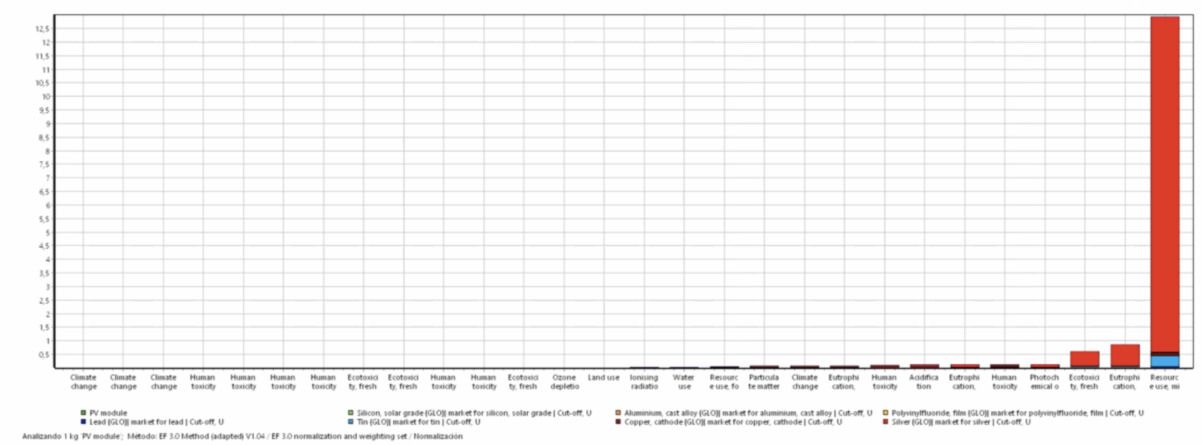

Figure 13. Normalized impacts for materials in PV modules using Simapro and Environmental Footprint EF 3.0 methodology.

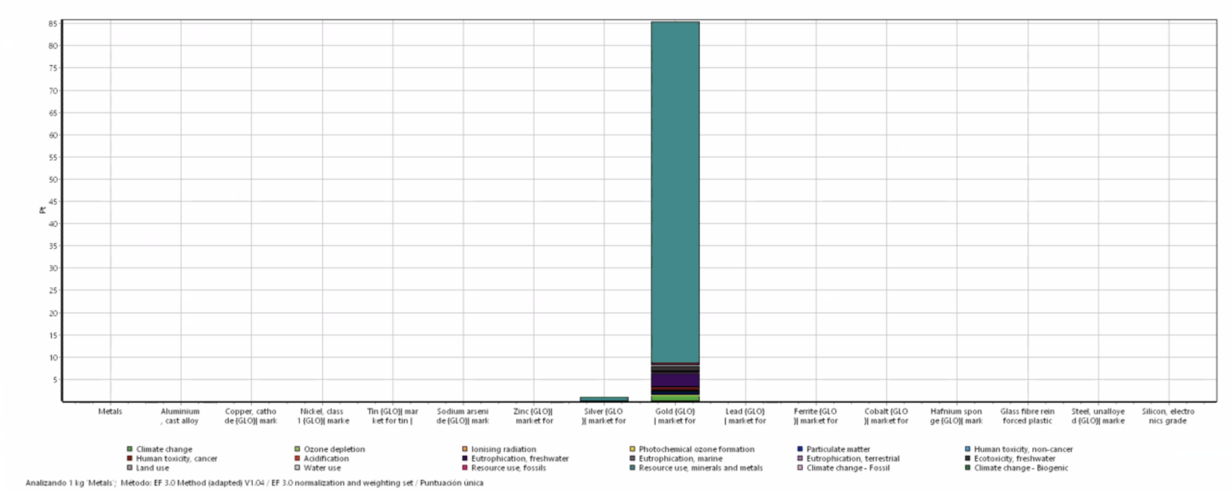

Figure 14. Normalized impacts for materials in PV inverters. First is gold, then silver, then the rest is 100,000 lower in score.

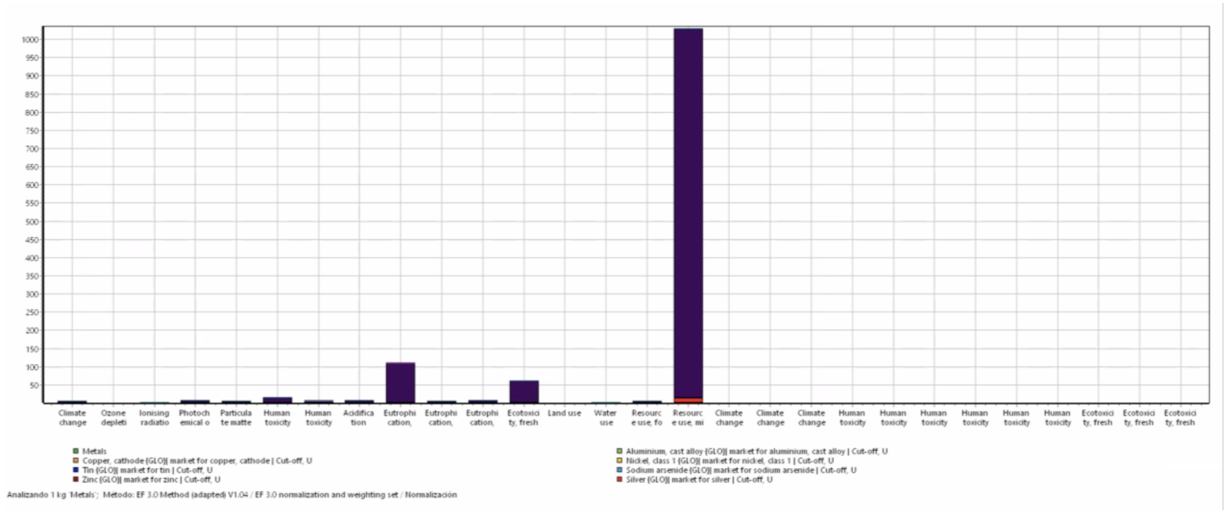

Figure 15. Normalized impacts for materials in PV inverters using Simapro and Environmental Footprint EF 3.0 methodology.

Multi-criteria decision methods

Here is the calculation procedure followed to prioritise materials in PV modules and PV inverters.

First, the objective is to prioritise the material with: 1) the highest mass content, 2) the highest environmental impact, 3) the lowest highest criticality and 4) the highest cost. Therefore, all four aspects here need to be maximized. That means that a linear normalization is needed; all values for each aspect are divided by the highest value in the series:

Linear normalization: $\frac{x_{ij}}{Max\ (x_{ij})}$

For example, in the Table 8, the values for the mass content would be all divided by the maximum of the series which corresponds to glass (73,2%), and same for the other three aspects.

On solving we will get a normalized decision matrix, next step is to assign the weightage to the criteria. In this case, we have allotted equal weight age to all criteria for me all the selecting criteria (25% each). important thing to note here is the sum of weight age is always 100%.

Then the weight assigned to each criterion (0,25) is multiplied with its normalized performance value. On solving we get the weighted normalized decision matrix. Finally, by adding all weighted normalized performance value of each alternative to get a performance score. For example, in Table 9, adding silver scores 3,28E-04 + 1,00 + 0,75 + 1,00 = 2,75, making silver the material with the highest score for PV modules.

Other calculations

- Fiberglass mass

FR4 fiberglass density is 1,85 g/cm^3

Typical thickness in PCBs is 1,57 mm[23]

[23] https://resources.altium.com/p/should-you-use-thick-or-thin-fr4-your-pcb-substrate