ISSN 1831-9424

European Commission

Harmonised rules for the calculation of the carbon footprint of photovoltaic modules in the context of the EU Ecodesign Directive

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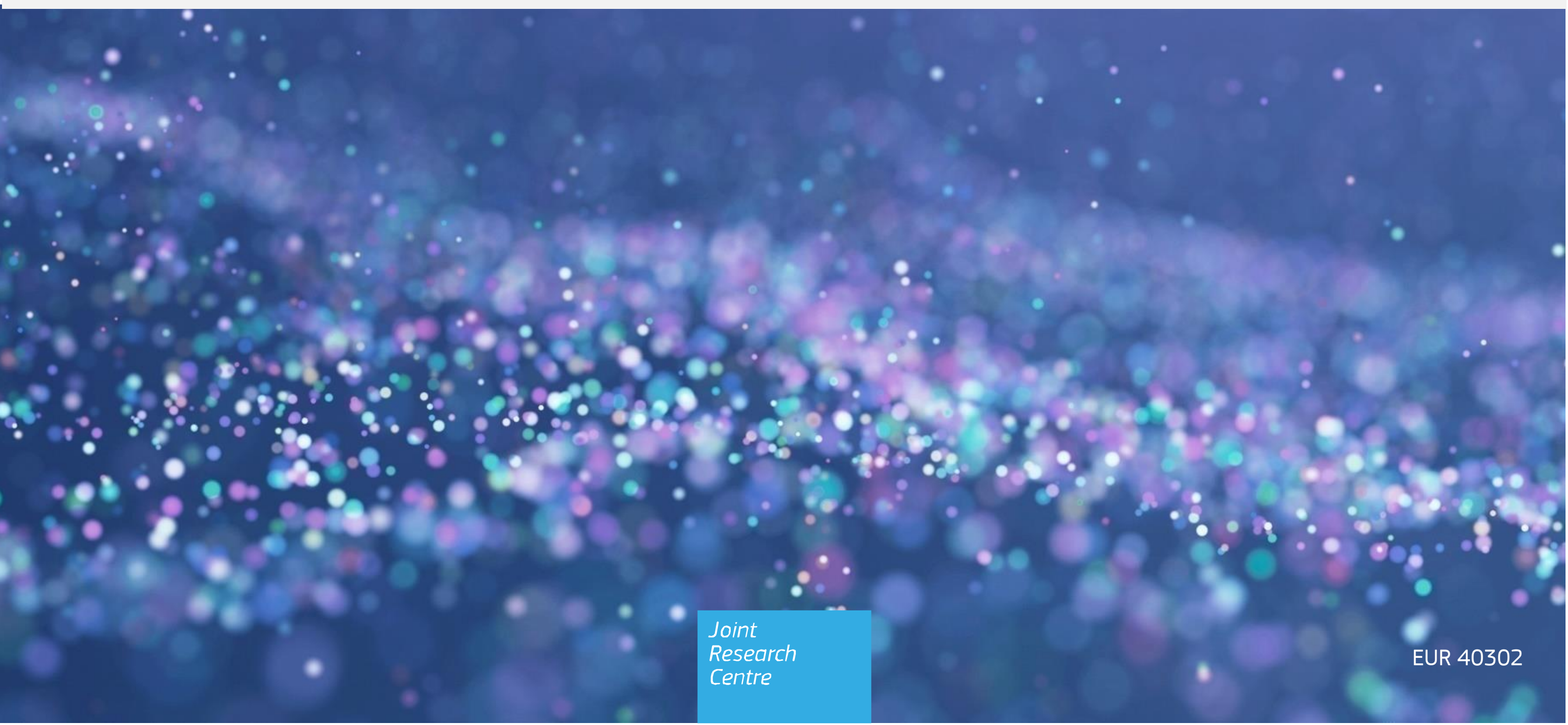
2025



Joint Research Centre

EUR 40302

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC141275

EUR 40302

PDF ISBN 978-92-68-26842-1 ISSN 1831-9424 doi:10.2760/4062978 KJ-01-25-254-EN-N

Luxembourg: Publications Office of the European Union, 2025

How to cite this report: European Commission: Joint Research Centre, Ardente, F., Eynard, U., Leccisi, E., Mathieux, F. and Wolf, K., *Harmonised rules for the calculation of the carbon footprint of photovoltaic modules in the context of the EU Ecodesign Directive,* Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/4062978, JRC141275.

Contents

Abstract

The decarbonisation of EU energy systems is critical to reach climate objectives in 2030 and 2050 as announced in the European Green Deal and, in this context, photovoltaics (PV) is called to have a prominent contribution, according to the REPowerEU plan.

In this direction, it is crucial to ensure that newly installed PV panel capacities in the EU are affordable and competitive, but also that they are manufactured in a sustainable manner.

The aim of this Science for Policy Report is to outline a set of harmonized rules for accounting the carbon footprint of PV panels, designed to be applicable in the regulatory context and in particular for the potential development of Ecodesign requirements (as in line with Directive 2009/125/EC for the Ecodesign of energy related products).

The harmonized rules proposed in the present report are based on the Environmental Footprint method developed by the European Commission (EC Recommendations 2279/2021)[1] and the Product Environmental Footprint Category Rules (PEFCR) for PV[2]. In particular, the PEFCR for PV have been used as pillar for building these harmonized rules with adaptations due to the application in a regulatory context.

The method has been the outcome of a consensus building process based on various positions from different stakeholders received at different stages.

[1] Available at : https://eur-lex.europa.eu/eli/reco/2021/2279/oj/eng

[2] PV PEFCR (Note that the time validity is 2021). Available at: https://wayback.archive-it.org/org-1495/20221006222253mp_/https:ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_feb2020_2.pdf

Acknowledgments

We would like to thank Susanna Andreasi Bassi, Jens F. Peters, Daniele Candelaresi, Nicola Ferrara from JRC unit D.3, for their support on discussing and reviewing some of the methodological aspects in the report. We would like to thank also Ewan Dunlop and Nigel Taylor from JRC C2 for providing technical information on PV technologies.

We would like to thank Marc-Andree Wolf of maki Consulting who has provided support on data and modelling.

We are grateful to thank Davide Polverini and Inés Pina Garcia- Galán from DG GROW and Mauro Cordella and Alicia Boyano Larriba from DG ENV for their support and inputs on the report and guidance on the policy developments and the regulatory aspects of this study.

Finally we acknowledge the detailed feedback received from several stakeholders, which helped us to improve the method for the accounting of carbon footprint of PV panels.

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Executive Summary

This Science for Policy Report illustrates a proposal of harmonized rules for accounting the carbon footprint of photovoltaic (PV) panels, which have been conceived to be applicable to regulatory contexts - in particular for the development of **Ecodesign requirements** as in line with Directive 2009/125/EC for the Ecodesign of energy related products.

The work has been performed by JRC for supporting DG GROW in the definition of a **carbon footprint method for Ecodesign implementing measures for PV panels**. External collaborators have been involved in this process, especially for what concern the LCA modelling of PV scenarios. Also, JRC colleagues involved in the preparatory study on PV panels[3] have been consulted to provide information related to the analysis of PV technology types and formulation of energy yield needed for calculating the carbon footprint.

The method proposed in the present report is based on the Environmental Footprint method developed by the European Commission (EC Recommendations 2279/2021)[4] and the Product Environmental Footprint Category Rules (PEFCR) for PV[5] have been used as pillar for building these harmonized rules with adaptations due to the application in a regulatory context.

The method has been the outcome of a **consensus building process** based on various positions from different stakeholders received at different stages. The first stakeholder consultation at the "*Consultation Forum Meeting on potential Ecodesign and Energy labelling requirements for photovoltaic modules, inverters and systems*" was held on June 27th 2022 and the second at the "*Technical stakeholder meeting on PV module carbon footprint calculation rules and related conformity assessment procedure"* on March 30th 2023, in which a total number of 80 written comments were received by 6 commenting stakeholders, including public and private entities. Differences and analogies with the PV PEFCR are presented and discussed in this report. In particular, compared to PEFCR, adaptations to the method regarded: the system boundary; the use of company-specific activity data and non-mandatory company-specific activity data; the inclusion of bifacial PV panels and innovative silicon-based multi-junction PV modules; the review of data quality rating of default secondary datasets; the modelling of recycling content and materials recycling; the electricity modelling.

Findings presented in this work are intended to inform the technical and political debate on the carbon footprint PV panels and to provide a scientific method that can be applied for supporting entry market Ecodesign requirements. This represents one of the first attempt (together with requirements in the EU Regulation on Batteries[6]) to introduce a mandatory **carbon footprint requirement for products in a regulatory context**.

This report discusses also how to model PV technologies and their life-cycle inventories under analysis (mono-crystalline silicon, multi-crystalline silicon, cadmium telluride), including the default secondary datasets and the associated activity data to be used. The inventories are detailed in an excel file that JRC has developed[7], based on the original input from the PV PEFCR. Moreover, this

[3] https://publications.jrc.ec.europa.eu/repository/handle/JRC122431

[4] https://eur-lex.europa.eu/eli/reco/2021/2279/oj/eng

[5] PV PEFCR (Note that the time validity is 2021) available at: https://wayback.archive-it.org/org-1495/20221006222253mp_/https:/ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_feb2020_2.pdf

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02023R1542-20230728

[7] https://ec.europa.eu/docsroom/documents/46532

report describes the support by JRC for a dedicated tool, currently under development by the EC, for facilitating the calculation of the carbon footprint of PV modules according to the harmonized methodological rules.

Results reported in this report show the carbon footprint of PV panels among different scenarios. The range of carbon footprint outcomes, spanning from the most favourable (10.8 $gCO_{2\ eq}$ per kWh) to the least favourable scenarios (44 $gCO_{2\ eq}$ per kWh)..

The primary contributors to the carbon footprint of mono- and multi-crystalline silicon PV panels include:

— **electricity for manufacturing the silicon,**

— **silicon content**

— **aluminium frame,**

— **glass.**

The product **lifetime** plays a significant role in terms of the carbon footprint per kilowatt-hour.

Future research could also focus on extending current rules to other relevant impact categories beyond carbon footprint - including for example resource use (fossils), resource use (minerals and metals) acidification and particulate matter. Finally, the proposed method should be adapted and extended to innovative PV technologies (e.g. single-junction perovskite panels) that will be potentially scaled up from laboratory to commercial scale as well as on existing PV panel technologies with technological improvements in their manufacturing (e.g. updated life cycle inventories).

1. Introduction

The European Union (EU) is fostering grid decarbonisation by requiring 1 TW of installed solar photovoltaics (PV), up from ~130 GW in 2021 (European Commission, 2022).

Also, the rapid deployment of renewable energy and PV is at the core of the REPowerEU plan – the EU initiative to put an end to its dependency from fossil fuels. By the end of 2023, the EU reached 271GW of solar PV installed generation capacity, having added more than 50 GW that year. It delivered around 5% of total EU electricity generation. The REPowerEU plan strategy aims to bring online over 320 GW of solar photovoltaic by 2025 (more than doubling compared to 2020) and almost 600 GW by 2030.

Facing the climate change challenge requires societies and economies to transform, thus phasing out unsustainable practices of production and consumption. Photovoltaic systems are considered a green or low-carbon technology, but their manufacturing is an energy intensive process and cause impacts on the environment. Consequently, PV systems and modules cannot be designed without considering also environmental criteria and estimating their impacts with the aim of reducing them as much as possible. With the aim of maximising the emission reduction, PV modules and inverters must not only have a high conversion efficiency and long lifetime, but materials and components should have been sourced, manufactured, used and disposed of, in an environmentally sensible manner.

Given that solar energy is going to play a relevant role among the energy sources of the future, it is timely to consider and to steer this production as much as possible towards a sustainable technology.

Globally, many national decarbonisation goals, have been declared; for example, the United States aspires to decarbonize the electricity grid by 2035 (White House, 2021). France and Korea have already identified solutions to start cutting emissions from PV, by including greenhouse gas (GHG) emissions targets in their national tenders. (Commission de régulation de l'énergie, 2021 & Korean Ministry of Environment, 2021).

Then, it is of paramount importance to estimate the carbon footprint of the PV sector, assessing and quantifying the material and energy flows of PV manufacturing.

With the aim of improving the sustainability of PV, not only voluntary goals have to be taken along, but compulsory regulations could potentially set requirements for the next PV modules generations to come to the market. It will then be necessary to set the rules for the clear quantification of the emissions.

The quantification of the carbon footprint of a product (PCF) is one of the first steps to complete in order to maximise the GHG emissions reduction. A number of companies in the photovoltaic sector are aiming to reduce significantly GHG emissions along their value chain and closely aligning towards the United Nation's sustainable development goals (SDGs) (Energy Global, 2022).

CFP applied to PV is generally expressed as '$gCO_{2\ eq}$/kWh', i.e. grams of carbon dioxide equivalent per kilowatt-hour of electricity generated. Alternatively, it may be expressed in '$kgCO_{2\ eq}$/kWc'. Commission de Régulation de l'Energie Carbon dioxide is one of the most significant GHG and is produced, for example, when fossil fuels are burnt. GHGs other than carbon dioxide, such as methane, are quantified as equivalent amounts of carbon dioxide. This is done by calculating their global warming potential relative to carbon dioxide over a specified timescale, usually 100 years.

In many cases, emissions of “low-carbon” or “clean” electricity generation technologies do not arise directly from the operation and use of the generators, but they may be dominated by indirect emissions, such as those produced during construction of the plant or the production of fuels (where applicable). For solar PV energy, the geographical location-specific energy resource also has an important influence on the impacts (e.g. specific irradiation). This is because higher electricity outputs may cause lower footprints, as total emissions are spread over a greater amount of electricity (Polverini et al., 2023).

Ecodesign (European Union, 2009) and Energy Labelling (European Union, 2017) are European Union (EU) legislative acts that aim to contribute to a clean and less costly energy transition for business, citizens and governments and overall improve the EU’s energy efficiency and support the wider ‘European Green Deal’ objectives (European Commission, 2019), including the Circular Economy agenda. They create business opportunities and increase resilience by setting harmonised rules for energy-related products on aspects such as energy consumption, water consumption, emission levels and material efficiency. These measures also foster demand for and supply of more sustainable products whilst reducing energy user expenditure significantly: estimates indicate that savings in 2021 exceeded EUR 120 billion and could reach the double in 2022 (European Commission, 2021). Furthermore, these policies will help achieve the EU’s target of reducing GHG by at least 55% by 2030 (European Commission, 2020), compared to 1990 levels.

Within this policy framework, the European Commission established a third Ecodesign Working Plan (European Commission, 2016), identifying PV modules and inverters as one of the non-regulated product groups with the largest potential for environmental savings and indicating the need for investigating in more detail the possible environmental improvements.

Findings presented in this work are intended to inform the technical and political debate on the carbon footprint PV panels for supporting entry market Ecodesign requirements. This represents one of the first attempt (together with requirements in the EU Regulation on Batteries) to introduce mandatory carbon footprint requirement in a regulatory context.

The aim of this report is to discuss harmonised rules for the calculation of the carbon footprint of photovoltaic modules and potentially applicable in the context of the EU Ecodesign Directive. Overall, these rules have been elaborated based on the Environmental Footprint method, with a special focus on the accounting of the carbon footprint occurring during the PV manufacturing as choices of materials and components in terms of their amount/mass, origin, their quality affect the overall carbon intensity of the module. Updated life cycle inventories based on PVPS International Energy Agency have also considered for what concerns the electricity consumption for the silicon.

It is essential to clarify that the publication of this report does not imply that Ecodesign requirements for PV modules and inverters will be adopted, nor does it suggest that the proposed methodology will be incorporated into any future legislation. Policy discussions regarding the possible introduction of Ecodesign requirements for PV modules and inverters are still ongoing. This report is meant to inform the decision-making process, showing possible carbon footprint values associated to practical cases of country specific and/or worldwide manufacturing value chains.

The report is organised in eight sections. Specifically, Section 2 describes the background concepts underpinning the harmonised rules for the calculation of the carbon footprint of photovoltaic panels; Section 3 illustrates suggestions for future improvements including discussion on certain open methodological aspects. It includes also discussions on adaptations and alignments with the Product Environmental Footprint Category Rules (PEFCR) of PV[8]; Section 4 shows the life-cycle inventories of the PV technologies under analysis (mono-crystalline silicon, multi-crystalline silicon, cadmium telluride), including default secondary datasets provided and the associated activity data; Section 5 shows the analysis of some reference scenarios - including different geographical countries, different silicon mass, different panel lifetime, different recycled content, different electricity yields - providing carbon footprint results and their interpretation; Section 6 is focused on the stakeholder consultations; Section 7 describes the support provided to the realisation of a dedicated IT online tool for calculating the carbon footprint of PV panels, based on the method previously introduced. Finally, Section 8 presents the conclusions of the report.

1.1 Environmental Footprint (EF) method developed by the European Commission (EC Recommendations 2279/2021)

The Environmental Footprint method have been built after a long-standing process, which involved LCA practitioners and hundreds of companies in different sectors, and tested on a number of different products, including PV, over 4 years of pilot phase. The EF methods are also reflecting the newest advancements in line with progresses of the LCA scientific community (including taking into considerations recommendations Life Cycle Initiative). Specifically, the EF method is also in line with the latest updates of IPCC 2021 on characterization factors for Global Warming Potential. The prominent role of the EF method has been recognized in several other policies including the Farm to Fork Strategy (F2F), the Taxonomy Regulation, EU Ecolabel and Green Public Procurement (GPP), the Green Claims Directive for quantifying environmental life-cycle perspective, ensuring comparability through different products and using a consistent database. This role of the EF is expected to increase in the future, in order to grant more methodological coherence within different EU instruments. New examples of implementations of the EF method in recent policies include also the Ecodesign Directive (through the revised Methodology for Ecodesign of Energy related Products (MEErP) and related tool) and the Ecodesign for Sustainable Product Regulation (ESPR) proposal.

The EC Recommendations 2279/2021 states "*If a PEFCR exists, this should be used for calculating the environmental footprint of a product belonging to that product category*".

Generally, Product Environmental Footprint Category Rules (PEFCRs) provide specific guidance for calculating products' life cycle potential environmental impacts. In other words, they complement general methodological guidance by providing further specification at the level of a specific product category, contributing to increased relevance, reproducibility and consistency of the results.

1.2 Preparatory study for solar photovoltaic modules, inverters and systems

Following the inclusion of PV products in an Ecodesign working plan, the European Commission launched in 2017 the Preparatory study on sustainable product policy instruments to assess the feasibility of applying Ecodesign, Energy Label, Ecolabel and Green Public Procurement instruments to solar photovoltaic modules, inverters and systems. The four policy instruments assessed by the

[8] PEFCR_PV_electricity_feb2020_2.pdf - Note that the time validity is 2021

study are either mandatory - in the case of Ecodesign and the Energy label – or voluntary in nature - in the case of the EU Ecolabel and Green Public Procurement criteria.

The main objective of the study was to provide technical support for the development of a preparatory study to assess the feasibility of Ecodesign and/or Energy labelling requirements, as well as the potential for Ecolabel and Green Public Procurement criteria, for the PV panels, inverters and systems product group.

In 2020 it was published the report on the "Preparatory study for solar photovoltaic modules, inverters and systems" (Dodd et al. 2020). One of the main indications provided by this report was that the carbon footprint of the manufacturing phase of photovoltaic modules is among the most salient aspects of this product group (Dodd et al. 2020).

Indeed, for all photovoltaic modules, the carbon footprint is largely determined at the design stage. First, the manufacturer's choice of materials and components in terms of their amount/mass, origin, their quality affect the overall carbon intensity of the module. Second, a comparison of the output of the module (e.g. kWh produced), which is also largely dependent on its design, with the carbon intensity of these material inputs then determines the carbon footprint. Apart from these design factors, the carbon intensity of the energy mix used during the manufacturing process also influences the carbon footprint, as also confirmed by many studies (Leccisi et al., 2016, Fthenakis and Leccisi, 2021, Muller et al. 2021). The preparatory study (Dodd, 2020) therefore showed that there is significant improvement potential that could be attained by means of such design choices.

The policy relevance at EU level of potential carbon footprint requirements for PV modules has been also announced in the EU Solar Energy Strategy (European Commission, 2020): '*the Commission is also assessing options covering [..] the carbon footprint of PV modules.' and 'these measures are also expected to foster innovation and provide a common reference for potential buyers to compare different products*'.

2. Background concepts underpinning the harmonised rules for the calculation of the carbon footprint of photovoltaic panels

As described in Polverini et al., 2024, there are plethora of methods, guidance documents and standards that can be applied to calculate the carbon footprint. As an example, they are listed in Table 1**.**

Among all the methods and standard mentioned above, there is a need of harmonizing the carbon footprint specifically of PV products at the European level.

Table 1 Non-exhaustive list of standards, documents and guidelines that can be used for calculating the carbon footprint of photovoltaics.

Standards and other guidelines/ reference documents	**Description**	**Method**
ISO 14067: 2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification	Requirements and guidelines for quantification of CFP	ISO 14067:2018.
GHG Protocol Product Standard	Product Life Cycle Accounting and Reporting Standard to evaluate the full life cycle GHG emissions of a product	GHG Protocol Product Standard
EU Member states PCR (Italy, France, Norway, Finland, Netherlands)	Databases and Product Category Rules for construction products/services where PV modules and inverters are part of new and renovated buildings	EN 15804
European PEFCR Guide for PV modules	Guidance for calculating and reporting products' life cycle environmental impacts	PEF method
Italy's LCA legislation Promotion of the Green Economy	Legislation fully based on the Environmental Footprint methods. Voluntary "Made Green in Italy" label	PEF method
NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and PV Inverters	Standard to establish product sustainability performance criteria and corporate performance metrics exemplifying sustainability leadership in the market. Basis of conformity assessment, such as third-party certification.	NSF ANSI 457 -2019
France's public tenders for utility scale PV plants	Public tenders include carbon footprint requirements to prioritize projects with low-carbon manufacturing processes.	ADEME guidelines
Korean carbon footprint assessment regulation for PV modules	Carbon footprint assessment method and requirements to prioritize projects with low-carbon manufacturing processes	French Methodology CRE3 LCA according to ISO 14040
Electronic Product Environmental Assessment Tool (EPEAT)	Carbon footprint ranking system for evaluating, comparing and selecting products	ISO standards 14040-4 2, 3, IEA PVPS 12 'Methodology Guidelines for LCA on PV'

Source: JRC elaboration (Adapted from Polverini et al., 2023)

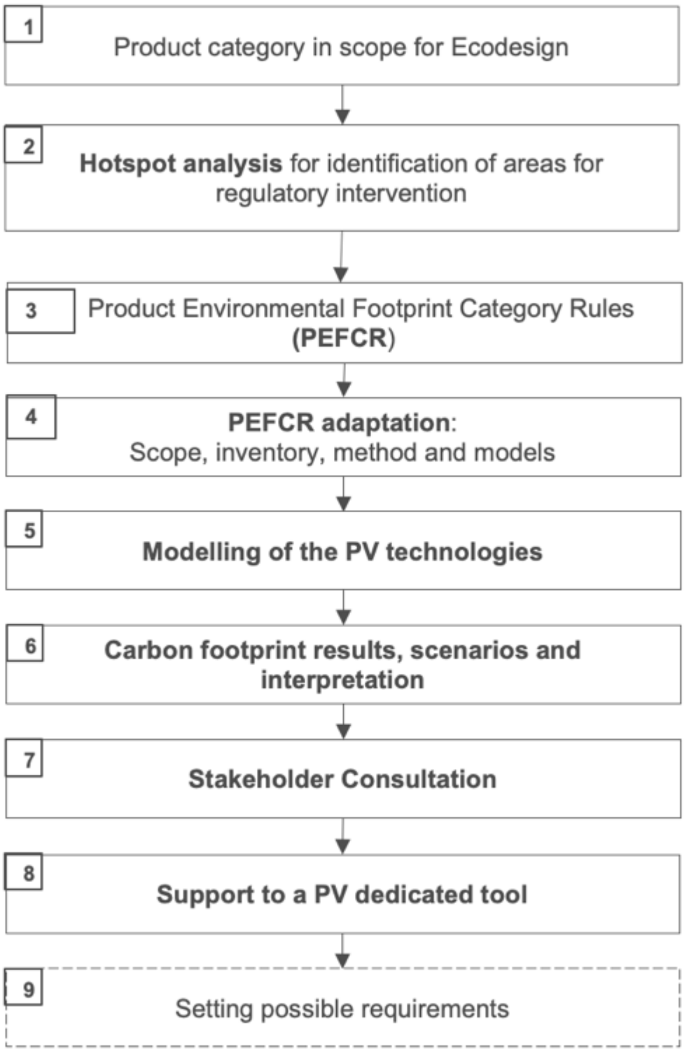
As detailed in Polverini et al., 2023 the method presented in this report uses as pillar the PEFCR of PV module and define the harmonised calculation rules for the carbon footprint evaluation under a regulatory context.

It focuses on products that are under the scope of the Ecodesign Directive (European Union, 2009).

These rules are applied to PV modules, with the objective to be conceptually applicable to different technologies and product groups.

Figure 1 shows a flow chart of the method summary for regulatory intervention, depicting the main phases of the definition of the harmonised rules for the calculation of the carbon footprint of photovoltaic modules. Each step is described and detailed in this report sections.

Figure 1 Flow chart of the method summary for regulatory intervention.



Source: JRC elaboration: Adapted from Polverini et al., 2023)

3. Suggestion for potential improvements of the harmonised rules for the calculation of the carbon footprint of photovoltaic modules

In this section suggestions for future improvements of the harmonised rules for the calculation of the PV carbon footprint are presented. Alignments and differences compared to the PV PEFCR, discussed in Section 4, are discussed. Also, potential technical improvements compared to the Annex A (attached to this report and shared with stakeholders during the consultation held on March 2023) with a policy proposal draft of the harmonized rules are illustrates and explained.

3.1 Product category in scope for regulatory intervention

As shown in Figure 1, the first step of the harmonized rule is the definition of the product category in scope for regulatory intervention. In this case, it consists of a complete photovoltaic panel that includes the aluminium frame and glass layers. Differently compared to PV PEFCR, the mechanical and electrical balance of system are excluded from the scope mainly because these represent different products systems compared to the PV module.

In terms of PV module technological coverage, the following technologies can be included:

- mono-crystalline silicon PV modules
- multi-crystalline PV modules,
- cadmium telluride (CdTe) PV modules
- silicon based PV modules with extra-layers (e.g. silicon perovskite tandem PV modules))

CIGS (copper, indium, gallium, (di) selenide) and micro-silicon PV panels were included in the PEFCR, however now they do not have currently a relevant market share and therefore they have been excluded from the scope of this analysis (Fraunhofer 2024).

Mono-crystalline silicon PV category includes different technological types such as passivated Emitter and Rear Cell (PERC), tunnel oxide passivated contact (TOPCon), interdigitated back contact (IBC) and heterojunction (HJT) PV modules (IEA PVPS Task 12, 2024).

Silicon-based PV modules with extra-layers (e.g. silicon perovskite tandem PV modules) are not listed in the PEFCR, but they could enter in the market in the not-to-distant future (Leccisi et al., 2021) and then they could be added to the scope with the aim of covering innovative types of PV panels I.

3.2 Hotspot analysis for identification of potential areas for regulatory intervention

The second step of the harmonized rules, as illustrated in Figure 1, is the hotspot analysis.

The calculation of the carbon footprint of photovoltaic modules is based on the bill of material, the energy, and auxiliary materials used to produce the specific product. The hotspot analysis highlights that, in particular for both mono- and multi-silicon PV panels, the electricity for manufacturing the silicon, aluminium frame, glass, and silicon have to be accurately identified as they are the primary contributors to the carbon footprint of a photovoltaic panel. These key findings are confirmed and explained in Section 5 of this report as well as the influence of electricity contribution that varies depending on the electricity mix of the country that manufactures the panel. Moreover, the product's lifespan plays a significant role in terms of the carbon footprint per kilowatt-hour produced.

3.3 Product Environmental Footprint Category Rules (PEFCR) "Photovoltaic modules used in photovoltaic power systems for electricity generation"

The step 3 of Figure 1 consists of the 'Product Environmental Footprint category rules' (PEFCR) (Product Environmental Footprint Category Rules, 2020) of PV power systems for electricity generation, which was developed in the framework of the Product Environmental Footprint (PEF) pilot phase.

It establishes the methodology to calculate environmental impacts for the main PV technologies and for a representative (virtual) product.

PEFCRs reflect the international agreements and technical/scientific progress in the area of life cycle assessment.

The Technical secretariat who developed the PEFCR has been composed of manufacturers of PV modules, energy research centres, LCA consultants, and PV industry associations who were part of stakeholder consultations, overall representing more than 50% of the EU market player for this product group at the time of the study. Also, the PV PEFCR has been prepared taking into account relevant schemes at the time of the study, including several established international standards and guidelines such as IEA PVPS Task 12 Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity (2015b); Product Category Rules within the International EPD System IES (PCR CPC 171 & 173 2013); Product Category Rules within the European Standards on Environmental Product Declaration of construction works (EN 15804 2013) (IEA PVPS Task 12). Specifically, the PV PEFCR has been developed with reference to products sold in the European Union + EFTA. The product category corresponds to the production of photovoltaic modules used in photovoltaic power systems for electricity generation and the product analysed is a photovoltaic module. "Photovoltaic module" is used as general term for panels (framed modules) and laminates (unframed modules).

The PV PEFCR includes five subcategories representing the following PV technologies:

- Cadmium-Telluride photovoltaic modules (CdTe)
- Copper-Indium-Gallium-Selenide photovoltaic modules (CIS / CIGS)
- Micromorphous Silicon photovoltaic modules (micro-Si)
- Multicrystalline Silicon photovoltaic modules (multi-Si)
- Monocrystalline Silicon photovoltaic modules (mono-Si)

PECFCR is a useful tool for having consistent comparisons between different PV manufacturing technologies and various products. However, given that PV technology has developed fast in a relatively short time, many different technologies for panel production exist today. They differ in material consumption/efficiency, power conversion efficiency (PCE), life expectancy, degradation ratio and costs but also in their environmental performance.

In the PV PEFCR, the FU is 1 kWh (kilowatt hour) of DC electricity generated by a photovoltaic module. The product system of the electricity production with a photovoltaic module consists of five life cycle stages:

- raw material acquisition and pre-processing,
- distribution and storage,
- production of the main product,
- use and
- end of life.

The manufacturing of PV modules shall cover raw material extraction to wafer, cell and module production in case of crystalline silicon modules, the supply chain of semiconductors (e.g. micromorphous silicon, cadmium sulphide, cadmium telluride, gallium and other materials used in thin film technologies) in case of thin film PV modules and the supply chain of carrier and connection materials (such as glass, silver, junction box and frame in case of PV panels). In the PV PEFCR, the product system also includes the mounting system required to fix the PV modules on a slanted roof because its demand depends on the conversion efficiency of the module. The electric installation is also taken into account. The inverter and the AC cabling is not be part of the product system. The transport of the PV modules, the mounting system and the electric installation to the place of installation of the PV system is included in a separate life cycle stage. The production of the main product shall comprise the assembly of the PV system. The use phase includes electricity production and the maintenance efforts (cleaning). The end of life covers the transport of the PV modules to a recycling facility or to a landfill, the dismantling of the modules and the recycling / landfilling process itself.

These rules help to place the focus on those aspects and parameters that matter the most, and hence contribute to increased relevance, reproducibility and consistency of the results.

The Climate Change impact category is expressed in $kgCO_{2eq}$/kWh. PV PEFCR also discusses that the 'climate change' impact (i.e. the impact assessment method used to quantify the carbon footprint) is one of the most relevant impact category for the manufacturing phase. The contribution analysis of carbon footprint impacts of PV panels as well as the major contributors to the total score depend on the underlying assumptions and the technology types. Moreover, according to the PV PEFCR, the most relevant processes (cumulatively contributing at least 80% to the characterised results) for the representative product (PV technology mix) of in the climate change impact category includes electricity, aluminium, solar glass, and steel.

3.4 PEFCR adaptation

According to the step 4 in Figure 1 the PV PEFCR can be adapted according to the policy purpose of setting Ecodesign requirements. Specifically, each section of the PEFCR have been checked and modified according to the scope of Ecodesign requirement on carbon footprint of PV modules.

All the adaptations should be reported in a public version of a supporting study.

A summary of technical aspects that have been considered for the adaptation of the PV PEFCR for the purpose of the harmonized rules for calculating carbon footprint is shown in Table 2.

Table 2 Main aspects considered for adapting the PV PEFCR for the purpose of using it for harmonized rules for calculating carbon footprint.

PEFCR sections	Aspects to be considered
Scope	The technologies under analysis have been updated based on current market share: CIGS and micro-Si can be deleted Silicon based technologies with additional layers can be added Innovative PV technologies should be considered
	System boundaries have been adapted to the regulatory context: Balance of system components can be excluded from the analysis, including only the PV panel (including glass and aluminum frame if present)
	Functional unit is aligned to that of PV PEFCR for comparability of the results. It consists of 1 kWh (kilowatt hour) of DC electricity generated during a photovoltaic module's service life.
	The reference flow is the amount of product needed to fulfil the defined function and shall be measured in m^2 of photovoltaic module. All quantitative input and output data collected by the manufacturer to quantify the carbon footprint shall be calculated in relation to this reference flow.
	Impact assessment method for calculating results (based on EF method) have been updated based on the latest one available
	Application of Circular Footprint Formula (CFF) and default values of CFF: The proportion of material in the input to the production that has been recycled from a previous system (R1) can be set equal to 0 by default for all materials and can be changed by the declarant in case of different values The proportion of the material in the product that will be recycled (or reused) in a subsequent system (R2) can be updated according to the current state of the art and fix by default for all materials
Life Cycle Inventory	EF datasets and their universally unique identifier (uuids) have been updated
	Company-specific data for mandatory processes shall be used
	Company-specific data for non mandatory processes may be used when the declarant has access to specific information
	if the applicant has access to company-specific data for other processes along the supply chain (e.g. electricity mix), the applicant may use such data
Data Quality Rating	Time representativeness, geographical representativeness and technological representativeness of default secondary datasets shall be evaluated for using them Precision has been deleted
Data Need Matrix	Data Need Matrix has been deleted
Life Cycle Stages and Distribution	The distance and mass transported shall be characterised with company-specific activity data.

Source: JRC elaboration

3.4.1 Functional unit and reference flow

In the harmonized rules for calculating the carbon footprint of PV, the functional unit is defined as one kWh (kilowatt-hour) of the total DC electric energy generated over a photovoltaic module's service life, measured in kWh, and that is aligned with the PV PEFCR.

The selected functional unit (i.e. kWh) allows to consider the effect of the lifetime of the photovoltaic module, its power conversion efficiency, its degradation ratio as well as the level of irradiation of the place of installation.

Moreover, it allows the potential comparison with electricity generated by other electricity generation technologies.

The reference flow is the amount of product needed to fulfil the defined function and shall be measured in m^2 of photovoltaic module. All quantitative input and output data collected by the manufacturer to quantify the carbon footprint shall be calculated in relation to this reference flow.

The reference flow (m^2) is linked to the functional unit (kWh) by the "DC total energy yield over the service life", calculated according to the Annex III of the policy proposal that is reported in the Annex B attached to this report.

3.4.2 System boundary

Considering the scope of the analysis detailed in Section 3.1, the following life cycle stages and processes of the PV modules need to be included in the system boundary:

- Raw materials acquisition, pre-processing and manufacturing of photovoltaic modules.
- mining and pre-processing, up to the manufacturing of silicon ingot, wafers and. photovoltaic cells;
  - the supply chain of semiconductors (cadmium sulphide, cadmium telluride, and other materials used in thin film technologies) in case of thin film modules; and
- the supply chain of carrier and connection materials (such as glass, silver, junction box and frame) in case of all modules.
  - cell and module production in case of crystalline silicon modules;
- assembly of photovoltaic cells; and
- assembly of modules with the frame and the electric/electronic components. However, in the case of photovoltaic modules that do not require a frame for the installation and are supplied without one, the frame shall not be accounted in the carbon footprint calculation.

The distribution should cover:

- the transportation of PV modules from the manufacturing plants to the point of placing the PV panel on the market (to be identified and justified by the manufacturer).

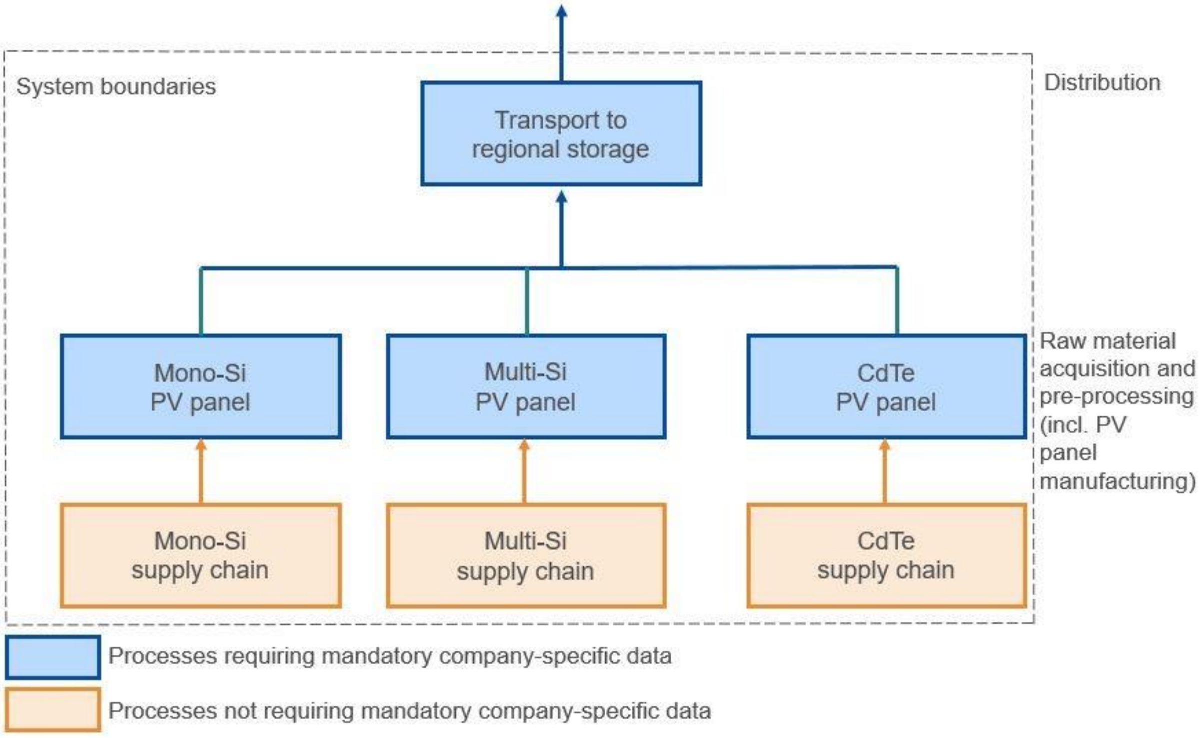
Compared to PEFCR, the distribution rationale may be revised and specifically it may include also the distribution within Europe and the activity data may be company-specific, while default secondary datasets are provided.

The following processes may be excluded from the life cycle calculation in alignment with the product in scope:

- Manufacturing of equipment (capital goods) for modules assembly and recycling.
- All processes belonging to the subsequent life cycle stages (i.e., distribution to the final consumer, assembly of the system, use and disposal, dismantling and recycling of the photovoltaic modules) due to the adapted scope for the Ecodesign requirement on carbon footprint of PV modules.
- Benefits and burdens of recycled materials in input and of manufacturing wastes of specific materials are considered in the application of the CFF to the module production – as detailed in Section 3.4.8.

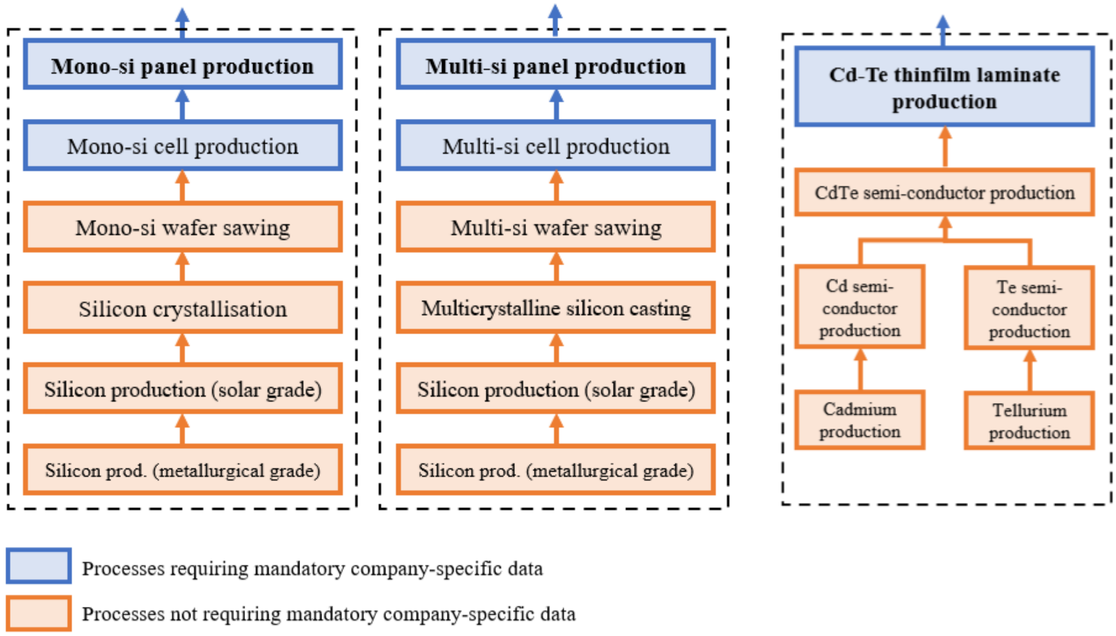
A common schematic of the process supply chain of mono-Si, multi-Si, and CdTe PV modules is shown in Figure 2 and Figure 3.

Figure 2 System diagram for the PV technologies included in scope (Adapted from PV PEFCR).



Source: JRC elaboration (adapted from PV PEFCR)

Figure 3 Flow diagram of the supply chain for the PV technologies included in scope. (Adapted from PV PEFCR).



Source: JRC elaboration (adapted from PV PEFCR)

3.4.3 Impact assessment

The impact assessment shall be done by applying the Environmental Footprint ('EF') impact assessment method available in the Life Cycle Data Network "LCDN" on the European Platform on LCA for the impact category "climate change" and be reported in grams $CO_{2\text{-eq}}$/kWh.

3.4.4 Use of company-specific activity data

— Mandatory company-specific activity data

Company-specific activity data are required in particular for the manufacturing of PV modules and may also be used to model the semiconductor material supply chain.

As listed in Figure 2 and Figure 3, for mono-crystalline and multi-crystalline silicon PV modules, mandatory company-specific activity data are required for cell and panel production, while for thin film CdTe PV modules, company-specific activity data are required for laminate PV production.

As stated in the PV PEFCR, several companies producing crystalline silicon cells or modules are vertically integrated and have control over wafer production, silicon crystallization and partly also solar grade silicon production.

The following paragraphs describe a technical approach that may be used as a guide for potential improvements on the use of company-specific activity data.

The manufacturer shall use company-specific activity data for the processes listed in Table 3.

Also, the activity data to be collected and the default secondary datasets to be used for each process are listed in the Excel spreadsheet with PV life-cycle Inventories "CF_Annex_PV_modules-Life_cycle_inventory" described in Section 4.1.

The data quality of the default secondary datasets used to model the product shall be reassessed, based on the rules in Section 3.4.6, by the manufacturer to ensure a certain level of representativeness:

If the default secondary dataset is representative of the process (i.e. TeR≤2 and GeR≤3), the default secondary dataset shall be used in combination with company-specific activity data.

If the default secondary dataset is not representative (TeR>2 or GeR>3) of the process, the manufacturer shall adapt the dataset to the manufacturing context (i.e.g. to what concerns electricity consumption) and recalculate the DQR following the rules in Section 3.4.6.

If the recalculated DQR is higher than 1.6, the manufacturer shall use a secondary dataset respecting the following hierarchy:

- A secondary dataset respecting the following hierarchy:
  - the most representative EF-compliant dataset commissioned by the European Commission available in LCDN. If the EF-compliant dataset is a partially disaggregated, the electricity dataset or datasets connected to the core process one level down the supply chain at -1 level may be changed for the representative average electricity consumption mix of the country where the process is occurring, modelled in accordance with section 3.4.10. Such choice shall be duly justified in the carbon footprint study;
  - a representative ILCD entry-level compliant dataset
- a company-specific dataset with a DQR equal to or lower than 1.6.

If a default secondary dataset is not available, such as but not limited to innovative materials, the manufacturer may use a proxy dataset (selected from the Excel spreadsheet with life-cycle inventories "CF_Annex_PV_modules-Life_cycle_inventory) discussed in Section 4.1, if after reassessing its quality (TeR, GeR) the recalculated DQR of the dataset is ≤1.6, according to the rules in Section 3.4.6.

If the recalculated DQR of the proxy dataset is higher than 1.6, the manufacturer shall choose one of the following options:

- A secondary dataset respecting the following hierarchy:
  - the most representative EF-compliant dataset commissioned by the European Commission available in LCDN. If the EF-compliant dataset is a partially disaggregated, the electricity dataset or datasets connected to the core process one level down the supply chain at -1 level may be changed for the representative average electricity consumption mix of the country where the process is occurring, modelled in accordance with section 3.4.10. Such choice shall be duly justified in the carbon footprint study;
  - a representative ILCD entry-level compliant dataset
- a company-specific dataset with a DQR equal to or lower than 1.6.

Table 3 List of processes for which the use of company-specific activity data is mandatory.

Technology	Life cycle stage	Process
Cadmium-Telluride PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic laminate, CdTe, at plant
	Distribution	Photovoltaic laminate, CdTe, at regional storage
Multicrystalline Silicon PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic cell, multi-Si, at plant
	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic panel, multi-Si, at plant
	Distribution	Photovoltaic panel, multi-Si, at regional storage
Monocrystalline Silicon PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic cell, mono-Si, at plant
	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic panel, mono-Si, at plant
	Distribution	Photovoltaic panel, mono-Si, at regional storage

Source: JRC elaboration (adapted from PV PEFCR)

3.4.4.1 Bifacial PV panels

The harmonized rules for calculating carbon footprint of PV panels have also the aim of proving guidance for innovative and emerging PV technologies (e.g. bifacial, innovative silicon-based multi-junction PV modules), which was not taken into the account in the PV PEFCR but are important to consider for updating PV technological aspects.

In particular, bifacial PV receives sunlight to DC electricity on both the front and back of the PV modules and usually generates more energy than mono-facial ones.

The manufacturer shall use company-specific activity data for modelling the glass used in the front and rear sides of bifacial PV panels, including the additional amount needed for the rear glass.

The manufacturer shall follow the rules described for the default secondary datasets to be used for modelling the glass of bifacial PV panels.

In case of bifacial PV panels, some materials (e.g. backsheet in polyvinylfluoride - PVF) may not be needed anymore in the product. In that case, the manufacturer of bifacial PV panels may disregard the corresponding material or component in the modelling of the carbon footprint.

3.4.4.2 Innovative silicon-based single- and multi-junction PV modules

The photovoltaic energy conversion efficiency of solar cells and solar panels based on silicon is fundamentally limited to 29.4 percent. This limitation can be overcome by coating the solar cells with additional materials to create a “multi-junction” solar cell. In such a geometry, multiple light absorption layers are stacked on top of each other, so that each layer effectively absorbs a specific part of the sunlight's color spectrum. This multi-layer concept can strongly enhance the cell efficiency. An example of multi-junction architecture could be a silicon perovskite tandem PV module, which reached a laboratory energy conversion efficiency of 33.7% in 2024[9].

An example of innovative silicon-based single-junction PV module consists of heterojunction (HJT) PV modules that differs from standard solar cells due to different materials used for the n-type and p-type layers of the absorbing layer.

Specifically, HJT PV technology combines crystalline silicon (c-Si) wafer-based PV technology with thin-film technology (i.e. amorphous silicon) and indium tin oxide (ITO) is one of the applied materials for the transparent conductive oxide (TCO) layer of the heterojunction solar cell.

The absorber layer of the HJT PV module encloses a c-Si wafer-based layer placed between two thin intrinsic amorphous silicon layers with doped amorphous silicon layers placed on top. The number of TCO layers varies depending on the HJT cell being mono-facial or bifacial PV, with the rear layer being a metal layer acting as the conductor for mono-facial heterojunction cells.

In this context, the manufacturer shall use company-specific activity data for the modelling of any extra-layers (e.g. amorphous silicon) that may be added to the silicon-based PV cell.

The manufacturer shall follow the rules described for the default secondary datasets to be used for modelling those extra-layers.

As for bifacial PV, these innovative silicon-based single-junction PV modules were not in the scope of PV PEFCR, but they are relevant for assessing PV technologies with improved power conversion efficiencies.

3.4.5 Non-mandatory company-specific activity data

Below it is described a technical approach that may be used as a guide for the use of non-mandatory company-specific activity data. These refer to all processes that are not included in the list of processes for which company-specific activity data are mandatory. Differently, from PV PEFCR the data need matrix shall not be applied for these data because it has been replaced with specific requirements as described in this chapter.

Case 1: The manufacturer has access to (company) specific information

If the manufacturer has access to company-specific information - including activity data of the processes - the data quality of the default secondary datasets used to model the product should be reassessed by the manufacturer to ensure a certain level of representativeness based on the rules set out in Section 3.4.6, to combine them with the specific company activity data.

If the default secondary dataset is representative for the manufacturer (i.e. TeR≤2 and GeR≤3), the default secondary dataset may be used in combination with company-specific activity data.

If the default secondary dataset is not representative (TeR>2 or GeR>3) of the process, the manufacturer may adapt the dataset to the manufacturing context (i.e. to what concerns electricity consumption) and recalculate the DQR following the rules in Section 3.4.6.

If the recalculated DQR is higher than 1.6, one of the following options shall be chosen:

[9] Photovoltaics-Report (14).pdf

— A secondary dataset respecting the following hierarchy:

  - o the most representative EF-compliant dataset commissioned by the European Commission available in LCDN. If the EF-compliant dataset is a partially disaggregated, the electricity dataset or datasets connected to the core process one level down the supply chain at -1 level may be changed for the representative average electricity consumption mix of the country where the process is occurring, modelled in accordance with section 3.4.10. Such choice shall be duly justified in the carbon footprint study;
  - o a representative ILCD entry-level compliant dataset

— a company-specific dataset with a DQR equal to or lower than 1.6.

<u>Case 2: The manufacturer does not have access to (company) specific information.</u>

If the manufacturer does not have access to company-specific information, the default secondary datasets and default activity data listed in the Excel spreadsheet with life-cycle inventory of PV technologies named "*CF_Annex_PV_modules-Life_cycle_inventory*" shall be used.

3.4.6 Data quality rating (DQR) of default secondary datasets

With the aim of ensuring an accurate representation of each PV process manufacturing and its components/stages, the default secondary datasets provided in the Excel spreadsheet with life-cycle inventories should be evaluated based in specific criteria described below, which is an adaptations of the Data Quality Rating (DQR) used in PV PEFCR.

Specifically, a DQR should be calculated for the default secondary datasets used for PV modelling according to the following procedure, which has been adapted for being more accurate for policy purpose:

Assign the DQR criteria for each of the default secondary datasets to ensure an accurate representation of the context:

— Technological Representativeness (TeR),

— Geographical Representativeness (GeR).

The values of each criterion shall be assigned based on Table 4.

Calculate the DQR score of the declared value as the sum of the values of the two DQR criteria divided by two (TeR + GeR)/2.

The DQR score and the values of the single DQR criteria (TeR and GeR) for each of the default secondary datasets shall be provided in the public version of the supporting study.

Table 4 Evaluation of the DQR criteria.

Quality rating	TeR dataset	GeR dataset
1	The technology modelled and the pathway of production* in the PV carbon footprint declaration is exactly the same as the one in the scope of the default secondary dataset.	The process modelled in the PV carbon footprint declaration takes place in the country for which the dataset is valid.
2	The technology modelled in the PV carbon footprint declaration is included in the scope of the default secondary dataset, with some yet limited differences in the pathway of production*.	The process modelled in the PV carbon footprint declaration takes place in the region (e.g., Europe, Asia, North America, Africa) for which the dataset is valid.
.3	The technology modelled in the PV carbon footprint declaration is included in the scope of the default secondary dataset with substantial but not critical differences in the pathway of production*.	The process modelled in the PV carbon footprint declaration takes place in one of the geographical regions where the dataset is valid (e.g., global – GLO, ROW).
4	The technology modelled in the PV carbon footprint declaration is similar (i..e, technological proxy) to those included in the scope of the dataset	The process modelled in the PV carbon footprint declaration takes place in a country that is not included in the geographical region(s) for which the dataset is valid, but it is estimated that there are sufficient similarities based on expert judgement
5	The technology modelled in the PV carbon footprint declaration is different from those included in the scope of the dataset	In all the other cases not listed on 1-4

Source: JRC elaboration

*The pathway of production for the modelled technologies shall be checked and evaluated against the default secondary dataset description and, if provided there, under consideration of process parameters and major process inputs (e.g. efficiencies, fuel types, temperature, pressure, scale).

Adjustments have been made in the data quality criteria definition compared to PV PEFCR. In particular, precision is not included for evaluating the representativeness in the mandatory company-specific processes because the activity data shall be provided by the declarant. For the non-mandatory company-specific processes, the activity data may be default values in case the declarant has no access to specific information. In this case, the source of default activity data is the PEFCR (and it is one source for all the stages). The data are already verified since they were in the PEFCR.

If the electricity is changed in the '–1 level' of a default secondary dataset, the GeR of the default secondary dataset shall be recalculated as follows:

$$GeR = GeR_{original} - (GeR_{original} - GeR_{modified, -1}) * Contribution_{original, -1}$$

where:

GeR is the GeR of the default secondary dataset after changing the dataset describing the electricity consumption in the −1 level, based on Table 4.
$GeR_{original}$ is the GeR of the default secondary dataset before changing the dataset describing the electricity consumption in the −1 level, based on Table 4.
$GeR_{modified,-1}$ is the GeR of the dataset describing the electricity consumption in the '-1 level' after the adjustment based on Table 4. GeRnew,-1 represents the geographical representativeness of the electricity production referring to where the process happens in reality.
$Contribution_{original,-1}$ is the contribution, expressed as a percentage, of the carbon footprint of the electricity consumption in the '-1 level' compared to the total carbon footprint of the secondary dataset.

3.4.7 Life cycle stages

Raw material acquisition, pre-processing and module manufacturing

This life cycle stage includes raw material acquisition and pre-processing, as well as the manufacturing of the photovoltaic modules. The supply chain of the modules shall include the production of the modules, the cells and wafers (if applicable) and the supply chain of the materials required in the module and in manufacturing (such as working materials and process gases, energy carriers), including raw material extraction and refining towards the directly employed material. The supply chain of the frame (if applicable), shall similarly include raw material extraction and refining.

Compared to PV PEFCR, the mounting system and the electric installation as well as their life stages are excluded as detailed in section 3.4.2.

The processes taking place in the life cycle stage raw material acquisition and pre-processing, the inputs and outputs as well as the default secondary datasets to be used are listed in the Excel file named "CF_Annex_PV_modules-Life_cycle_inventory", sheet "Raw-Materials&Pre-Processing" discussed in Section 4.

Transport of raw materials and intermediate products

Transport of raw materials and intermediate products to the production site shall be included in this life-cycle stage.

Table 5 shows the default transport distances by train and lorry (lorry >32 t, EURO 4) for some frequently used raw materials and intermediate products, as listed in PV PEFCR. These default values may also be used to estimate default transport distances for similar products required in the supply chain of PV modules. The default transport distances shown in Table 5 shall be used in case company-specific information is not available. For transports by lorry, a default utilization ratio of 64% shall be used if specific data are not available. This utilization ratio includes empty return trips.

For suppliers located outside Europe, the default transport scenario described in the Excel file with life-cycle inventories named "CF_Annex_PV_modules-Life_cycle_inventory" and discussed in Section 4, sheet Transport-Scenarios should be used. This scenario includes the transport of raw materials or intermediate products between the harbour or airport and the factories in and outside Europe, which is estimated to 1'000 km by lorry (>32 t, EURO 4). The intercontinental transport to Europe occurs either by transoceanic container ship (18,000 km) or by cargo airplane (10,000 km). If the location of the supplier is known, specific data may be used to calculate the transport distances and modelling the applicable transport modes to the production site.

Air cargo shipping of semi-finished products such as wafers and cells shall be included according to its share in supply logistics in a three year period.

Table 5 Default distances for transport of raw materials and intermediate products.

	Density [kg/m3]	Consumption in Europe	
Mineral products		km train	km lorry 32t
gravel/sand	2000	-	50
metals			
Steel/cast iron	7900	200	100
copper	8900	200	100
aluminium	2700	200	100
plastics			
PVC	1400	200	100
PE	950	200	100
PP	900	200	100
Wood products			
Particle board	680	200	50
Basic chemicals, inorganic (carrier substance to be considered additionally)			
Caustic soda	1045	600	
Soda (sodium carbonate)	2532	600	
Hydrochloric acid	909	200	
Sulphuric acid	1840	600	
Nitric acid	1383	600	
Phosphoric acid	1685	600	
Hydrofluoric acid	993	600	
Basic chemicals, organic			
ethylene		600	100
naphta		600	100
refrigerants		600	100
Organ. solvents		600	100
Gases (if not produced on the spot) if bought in cylinders: doubling of transport distances (due to tare weight)			
oxygen		100	50
nitrogen		100	50
hydrogen		100	50
helium		100	50
For all other materials		240	130

Source: JRC elaboration (adapted from PV PEFCR)

Packaging materials

The use and disposal of packaging materials shall be considered for the entire product system and modelled as part of the raw material acquisition stage. The raw material consumption of reusable packaging shall be calculated by dividing the actual weight of the packaging by the reuse rate. The reuse rate affects the quantity of transport that is needed per functional unit. The transport impact shall be calculated by dividing the one-way trip impact by the number of times this packaging is reused.

For reusable packaging, the default reuse rates provided below shall be used, unless data of better quality are available:

- Plastic pallets: 50 trips
- Wooden pallets: 25 trips

3.4.8 Modelling of recycled content and materials recycling

The recycled content of materials used in PV modules as well as their recycling potential at the end-of-life shall be modelled according to the following circular footprint formula (CFF):

$$(1 - R\_1) \cdot Ev + R\_1 \cdot (AE\_recycled + (1 - A) \cdot Ev \cdot QSin/Qp) + (1 - A) \cdot R2 \cdot (E\_recyclingEoL - Ev^{*} \cdot QSout/Qp)$$

A: allocation factor of burdens and credits between supplier and user of recycled materials.

R1: proportion of material in the input to the production that has been recycled from a previous system.

R2: proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant

Ev: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.

Erecycled (Erec): specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.

ErecyclingEoL (ErecEoL): specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.

E*v: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

Qsin: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.

QSout: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.

Qp: quality of the primary material, i.e. quality of the virgin material.

The default parameter values for applying the CFF and the default values for R1 and R2 are listed in the Excel spreadsheet "CF_Annex_PV_modules-Life_cycle_inventory" discussed in Section 4, sheet CFF-parameters. An exerpt is shown in Figure 4.

Adjustments have been made compared to PV PEFCR for policy purpose. In particular, in the harmonized rules for calculating carbon footprint of PV, if default values are provided for R2 and these are not possible to be changed. For all materials not listed in the sheet CFF-parameters, it is assumed that R2=0.

The default secondary datasets for modelling the CFF (for glass, copper, aluminium, aluminium alloys, steel) are listed in the same Excel spreadsheet "CF_Annex_PV_modules-Life_cycle_inventory", sheet "Raw-Materials&Pre-Processing".

If a default secondary dataset of a specific recycled material (i.e. silicon) is not available in the Excel list "CF_Annex_PV_modules-Life_cycle_inventory", sheet "Raw-Materials&Pre-Processing", the manufacturer shall develop an EF compliant dataset with a DQR ≤ 1.6 following the Guide for EF compliant datasets. This EF compliant dataset shall be implemented in the CFF to model the impact of the recycled content of such material based on the R1 value declared by the manufacturer.

The R1 values are by default equal to 0, unless differently declared and proved. Specifically, the applied R1 values shall be subject to verification and provided in the supporting study.

The following general guidelines shall be followed when using supply-chain specific R1 values:

- The supplier information (through e.g., statement of conformity or delivery note) shall be maintained during all stages of production and delivery at the converter.
- Once the material is delivered to the converter for production of the end products, the converter shall handle information through their regular administrative procedures.
- The converter for production of the end products claiming recycled content shall demonstrate through his management system the [%] of recycled input material into the respective end product(s).
- The latter demonstration shall be transferred upon request to the user of the end product.
- Company-owned traceability systems can be applied as long as they cover the general guidelines outlined above

Figure 4: CFF parameters.

Category	Material	Application	Parameters				
			A	R_1	R_2	$Q_{s, in}$ / Q_p	$Q_{s, out}$ / Q_p
Metals	Steel	photovoltaic panel	0.20	0	0	1.00	n.a.
	Aluminum	photovoltaic panel	0.20	0	0	1.00	1.00
	Aluminum alloys	AlMg3 - photovoltaic panel	0.20	0	0.92	1.00	n.a.
	Copper	photovoltaic panel	0.20	0	0.70	1.00	1.00
	Copper telluride	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Cadmium	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Silicon metal	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Gallium	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Lead	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Indium	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Silver	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Tellurium	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Tin	photovoltaic panel	0.20	0	0	n.a.	n.a.
	Zinc	photovoltaic panel	0.20	0	0	n.a.	n.a.
Glass	Glass	photovoltaic panel	0.20	0	0.09	n.a.	1.00
Others	Other materials	photovoltaic panel	0.50	0	0	n.a.	n.a.

Source: JRC elaboration (adapted from PV PEFCR)

<u>The CFF applied to manufacturing waste</u>

All manufacturing waste shall be considered in the modelling.

The total amount of manufacturing waste shall be consistent with the BoM (total input to the manufacturing process), the mass balance of the final product and the yield rates of the manufacturing processes.

Specifically, the waste of products used during the manufacturing stage shall be included in the overall modelling and reported at the life cycle stage where the waste occurs.

3.4.9 Distribution

The transportation of photovoltaic modules from factory to the market point shall be modelled within this life cycle stage. The distance and mass transported shall be characterised with company-specific activity data.

The transport from regional storage to the photovoltaic power system where the photovoltaic modules are installed is excluded from the system boundary. If photovoltaic modules are produced in several production sites, the share of each facility in the European supply mix shall be accounted for in the life cycle stage distribution.

The processes taking place in the life cycle stage distribution, the inputs and outputs as well as the default datasets are listed in the Excel spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory" and discussed in Section 4, sheet "Distribution".

3.4.10 Analysis of electricity modelling approaches

In this section there is an analysis of potential alternative modelling approaches for accounting the electricity demand for manufacturing PV panels.

Two alternative approaches are presented in the following sub-sections 3.4.10.1 and 3.4.10.2.

The first approach allows the use of contractual instruments within a set of minimum criteria (as described below) as well as the use of residual consumption mix. This first approach is elaborated based on PEF/PEFCR rules with additional clarifications and stricter requirements intended for policy purpose. Specifically, PEF Recommendations (Commission Recommendations (EU) 2021/2279 on the use of the Environmental Footprint methods to measure and communicate the life-cycle environmental performance of products and organisations) allows the use of contractual instruments under certain criteria based on GHG Protocol Guidelines. The first approach includes two stricter requirements compared to PEF related to the transparency of the tracking systems and it avoids double counting of claims.

The second approach is based on the discussion with stakeholders and includes only the national average electricity consumption mix unless there is a direct electricity connected.

3.4.10.1 Electricity modelling approach

Specifically, in the first approach, the following electricity mix shall be used in hierarchical order:

1. On-site generated electricity modelled according to section 3.4.10.1.1 if it meets the conditions set in the same section.
2. Supplier-specific electricity product modelled according to section 3.4.10.1.2 if the contractual instrument meets the set of minimum criteria described in the same section.
3. Residual consumption mix modelled according to section 3.4.10.3 if the activity occurs in a grid/country where a contractual instrument respecting the criteria described in section 3.4.10.1.2 exists. The residual consumption mix shall be used even if the declarant itself did not claim any supplier-specific electricity product. The residual consumption mix characterizes the unclaimed, untracked or publicly shared electricity and prevents double counting with the use of supplier-specific electricity product in the point (2) of the hierarchy.
4. Average consumption mix modelled according to section 3.4.10.1.4 if the activity occurs in a grid/country where no contractual instruments meeting the criteria described in section 3.4.10.1.2 exist (i.e., no residual consumption mix is available). The average consumption mix reflects the total electricity mix including claimed or tracked electricity.

The use of carbon intensity factors values provided by a grid operator or certificate-issuing entity is not permitted.

The way the electricity is modelled shall be reported in the supporting study.

3.4.10.1.1 On-site generated electricity

The on-site generated electricity shall be claimed if the electricity is supplied to the plant from a production asset within the premises of the energy-consuming plant and if the production asset is connected to the energy-using plant by means of a direct and dedicated connection.

If the energy-consuming plant is also connected to the electricity grid and electricity is sourced from the grid in addition to on-site generation (e.g., during times of low on-site generation), all energy sourced from the grid shall be accounted and modelled following the points (2), (3), or (4) of the hierarchy described in section 3.4.10.1. The maximum amount of electricity that may be claimed in a year is the difference between the yearly total amount of energy produced and the yearly amount of energy injected in the grid. The manufacturer shall provide evidences in the supporting study of the values of on-site generated electricity considered in the calculation.

If contractual instruments of any type, related to the on-site generated electricity, have been sold to a third party, then the on-site generated electricity cannot be claimed. If such electricity is consumed in the plant, then it shall be modelled following the points (2), (3) or (4) of the hierarchy described in section 3.4.10.1.

No credit shall be modelled if the amount of electricity produced exceeds the amount consumed on-site within the defined system boundary and it is sold to, e.g., the electricity grid.

Datasets describing medium-voltage may be used for low-voltage, neglecting the conversion losses.

3.4.10.1.2 Supplier-specific electricity product

The environmental integrity of the use of supplier-specific electricity products depends on ensuring that the related contractual instruments (for tracking) are reliable and unique. Without this, the carbon footprint calculation lacks the accuracy and consistency needed to drive claims on the electricity procurement. Therefore, the contractual instrument shall be claimed if the respect of the following five minimum criteria is proved in the supporting study.

Datasets describing medium-voltage may be used for low-voltage, neglecting the conversion losses.

Criterion 1 – Convey attributes

To satisfy the criterion, the contractual instrument shall:

- Convey the energy source mix and complementary attributes of the product associated with the unit of electricity produced.
- Include an explanation of the calculation method used to determine the energy source mix of the product.

Criterion 2 – Be a unique claim

To satisfy the criterion, the contractual instrument shall:

- Have mechanisms in place that ensure it is the only instrument that carries the environmental attribute claim associated with that quantity of electricity generated.
- Have mechanisms in place to ensure the instrument can be claimed only once.
- Be tracked and redeemed, retired, or cancelled by or on behalf of the company (e.g., by an audit of contracts, third party certification), or handled automatically through other disclosure registries, systems, or mechanisms.
- Be associated with a quantity of generated electricity that is reported and considered for the determination of the country-specific residual consumption mix, and this unique residual consumption mix is disclosed publicly by a competent authority. Sometimes national laws and regulations may define a residual consumption mix for a geographical area that is different from the country. The manufacturer shall report the residual consumption mix and its source in the supporting study.
- Allow for the unambiguous identification of the technology type, age and location and capacity of the energy generation facility to which it refers.

- Refer to an energy generation facility that is located in a country with a tracking system in place that meets the minimum criteria for tracking systems.

Criterion 3 – Be issued from a tracking system that fulfils specific criteria

To satisfy the criterion, the contractual instrument shall be issued by a tracking system that fulfils the following criteria:

- Is based on objective, non-discriminatory, and transparent criteria for the issuing certificates.
- Is a unique entity per geographical area and per type of energy production and it shall be governmentally appointed.
- Relies on accurate, reliable, and fraud-resistant mechanisms for the issuance, transfer and cancellation of certificates.
- Is independent from the verifier.
- Entrusts the issuance of certificates, as well as the supervision of their transfer and cancellation of certificates, to a legal entity or entities who are independent from the production, trade of energy, and the corresponding certificates.
- Whose activities are governed by transparent rules and procedures.
- Whose decisions may be challenged and reviewed in the context of proceedings before an independent judiciary.
- Whose use is enforceable by national legislation for claims on the origin of consumed energy.
- Works in interaction with the authority publishing the residual consumption mix in a way that prevents double claims of renewable energy sources and other environmental attributes.

Criterion 4 – Be as close as possible to the period to which the contractual instrument is applied

To satisfy the criterion, the contractual instrument shall:

- Ensure that certificates are valid no longer than 12 months after the represented electricity was generated. Certificates shall be used (hence cancelled/redeemed/retired) within 18 months after the electricity was generated.

Criterion 5 – Be sourced from the same market in which the reporting entity's electricity-consuming operations are located and to which the instrument is applied

The electricity to which the contractual instruments refer to and the company claiming the contractual instrument shall be within the same market boundaries.

The "market boundary" refers to an area in which:

- There is a physical interconnection between the point of generation and the point of consumption of renewable electricity. When interconnection happens across different grids, there shall be an entity that coordinates and tracks the exchange between such grids.

- The countries' utilities/energy suppliers recognize each other's energy source tracking instruments and have a system in place to prevent double counting of claims

3.4.10.1.3 How to model the residual consumption mix

If a default secondary dataset modelling the residual consumption mix in a specific country (e.g., residual consumption mix in Estonia) is present in the Excel spreadsheet named ""CF_Annex_PV_modules-Life_cycle_inventory" discussed in Section 4, then this dataset shall be used. Otherwise, the manufacturer shall model its own residual consumption mix for the considered country using the following approach:

- Use the composition of the residual consumption mix (e.g., X% of MWh produced with hydro energy, Y% of MWh produced with coal power plant). The most recent composition shall be used (e.g. from the issuing body). Then the background processes per energy tyoe and country/region (e.g. production of 1MWh solar energy in the corresponding country/region) shall be combined.

If the residual consumption mix is modelled with own data, the source, the year, the geographical boundaries, the percentage from each electricity source, and the background datasets shall be provided in the supporting study.

3.4.10.1.4 How to model the average consumption mix

The average consumption mix shall be modelled using default secondary datasets listed in the Excel spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory", discussed in Section 4.

If in the spreadsheet "CF_Annex_PV_modules-Life_cycle_inventory" there is a dataset modelling the average consumption mix in the country, or in the region (EU) of interest, that dataset shall be used giving priority first to the country, and then to the region.

3.4.10.2 Alternative approach

Alternatively, the carbon footprint of the consumption of electricity may be calculated according to the following hierarchy:

- On-site generated electricity modelled according to section 3.4.10.1.1 if it meets the conditions set in the same section.
- Average consumption mix modelled according to section 3.4.10.1.4

4. Modelling of the PV technologies

The life cycle inventories of PV technologies under analysis (mono-crystalline silicon, multi-crystalline silicon, CdTe) are listed in an Excel spreadsheet10 linked to the Annex A, which was part of a policy proposal dated March 2023. In that Excel spreadsheet, for each PV stage (e.g. panel, cell, wafer) the default secondary datasets are provided with their associated uuid. In addition, for all the non-mandatory processes, the associated activity data are provided for each default secondary datasets. In terms of geographical locations, four areas are listed (i.e. European Union, US, China, APAC). Also, CFF parameters are provided in the tab “CFF parameters” with a dedicated Table.

In the following section 4.1, additional suggestions for complementing the life-cycle Inventory of PV technologies are discussed. Additions and adjustments in that Excel file with life-cycle inventories were needed to allow applicability to the harmonized rules for calculating carbon footprint of PV (including all the PEFCR adaptations described in Section 3).

4.1 Life cycle inventories of PV technologies

In this section, potential suggestions implemented in the excel spreadsheet with the life-cycle inventories of PV are discussed in comparison with the version shared with stakeholders on the consultation held in March 2023.

Below a summary of the major identified changes:

- Distribution
  - distribution from extra EU to EU to be implemented as company-specific information;
  - distribution from EU to EU to be implemented as company-specific information
- Elementary flows
  - Elementary flows to be added for all the processes according to the model of the representative product of the PEFCR PV
- UUID
  - UUIDs of EF 2.0 datasets to be replaced with UUIDs of EF3.1 datasets
- Update silicon production mix
  - electronic grade and electronic off grade silicon processes to be deleted because these technological processes are not yet used in the manufacturing of PV wafer;
  - solar grade silicon to be kept as it is still used in commercial production;
  - the geographical market share of silicon production mix (kg of each solar grade silicon) to be updated according to the values in Table 6.
- Electricity consumption
  - As shown in Table 7, In the mono-crystalline silicon PV, the activity data of electricity consumption (MJ per kg and MJ per m^2) to be updated according to the latest values listed in the IEA PVPS Task 12 2020 for the following processes:
    - Silicon, solar grade, modified Siemens process in EU, CN, US and APAC

[10] https://ec.europa.eu/docsroom/documents/46532

        - CZ single crystalline silicon, at plant in EU, CN, US and APAC
        - Wafer, mono-Si, at plant in EU, CN, US and APAC
    - Residual grid mix default datasets may be deleted and replaced with electricity consumption mix default datasets depending on the approaches adopted;
    - Default dataset of electricity consumption mix in DE to be replaced with the default dataset of electricity consumption mix in EU (average mix) in the solar grade production
    - Electricity consumption mix dataset for US to be replaced with RNA (Regional Nord America) because it was not present in the EF 3.1 database.
- Default activity data
    - Default activity data for mandatory processes to be deleted (e.g. panel and cell in mono-Si and multi-Si for EU, CN, US and APAC and laminate in CdTe for MY and US)
- Default values of Data Quality
    - Default values of DQR, GeR, TeR and P to be deleted

Table 6 shows the production mix of silicon that have been implemented for updating the scenarios of silicon production described in PV PEFCR. In particular, electronic grade and electronic off grade silicon processes are obsolete and not yet used in the manufacturing of PV wafer, according to data listed in the IEA PVPS Task 12 2020. Also, the geographical area has been updated with the aim of being more realistic as possible.

Table 6 Update of silicon production mixes (JRC elaboration: adapted from PEFCR PV and based on IEA PVPS Task 12 2020)

Items	EF datasets name	unit	amount	UUID EF dataset
Silicon, production mix, photovoltaics, at plant (EU)	Silicon, electronic grade, at plant (DE)*	kg	0	0e38bfe5-fa5b-3377-ad1f-c4682c194843
	Silicon, electronic grade, off-grade, at plant (DE)	kg	0	868aa61b-a71b-3819-b059-e19147908962
	Silicon, solar grade, modified Siemens process, at plant (EU)	kg	1.00E+00	78e55a85-2481-320f-b923-ba53fea5b217
	Silicon, production mix, photovoltaics, at plant (EU)	kg	1.00E+00	7cf88a38-da63-3a31-9a0d-233f0a1b13d1
Silicon, production mix, photovoltaics, at plant (CN)	Silicon, electronic grade, at plant (APAC)	kg	0	b9883a06-1487-39c8-a840-10619cf4c8fb
	Silicon, electronic grade, at plant (CN)	kg	0	83091162-30c3-36fb-83b1-5f7de4eb5a47
	Silicon, electronic grade, at plant (DE)	kg	0	0e38bfe5-fa5b-3377-ad1f-c4682c194843
	Silicon, electronic grade, at plant (US)	kg	0	7d01962d-8443-39d1-bf23-7935bda83fcd
	Silicon, electronic grade, off-grade, at plant (APAC)	kg	0	9f1ac96d-7b85-3521-b5f0-e97ab0522898
	Silicon, electronic grade, off-grade, at plant (CN)	kg	0	178ff0ec-d9b0-357f-9dc9-eef4509665ba
	Silicon, electronic grade, off-grade, at plant (DE)	kg	0	868aa61b-a71b-3819-b059-e19147908962
	Silicon, electronic grade, off-grade, at plant (US)	kg	0	c2a2c742-e991-3179-a7fb-0d91ba5e451b
	Silicon, solar grade, modified Siemens process, at plant (APAC)	kg	1.30E-02	e8889cc9-1305-38be-8bba-842a507ad4e2
	Silicon, solar grade, modified Siemens process, at plant (CN)	kg	9.87E-01	3ce0bf75-144f-3454-be68-7f2bbd9afbdd
	Silicon, solar grade, modified Siemens process, at plant (EU)	kg	0	78e55a85-2481-320f-b923-ba53fea5b217
	Silicon, solar grade, modified Siemens process, at plant (US)	kg	0	f23b1307-6416-3819-8818-7b28dcb24dd8
	Silicon, production mix, photovoltaics, at plant (CN)	kg	1.00E+00	88b711e1-8138-304e-a723-1afa259ac633
Silicon, production mix, photovoltaics, at plant (APAC)	Silicon, electronic grade, at plant (APAC)	kg	0	b9883a06-1487-39c8-a840-10619cf4c8fb
	Silicon, electronic grade, off-grade, at plant (APAC)	kg	0	9f1ac96d-7b85-3521-b5f0-e97ab0522898
	Silicon, solar grade, modified Siemens process, at plant (CN)	kg	9.87E-01	3ce0bf75-144f-3454-be68-7f2bbd9afbdd
	Silicon, solar grade, modified Siemens process, at plant (APAC)	kg	1.30E-02	e8889cc9-1305-38be-8bba-842a507ad4e2

Items	EF datasets name	unit	amount	UUID EF dataset
	Silicon, production mix, photovoltaics, at plant (APAC)	kg	1.00E+00	d373023c-aceb-311c-9bab-78f035750547
Silicon, production mix, photovoltaics, at plant (US)	Silicon, electronic grade, at plant (US)	kg	0	7d01962d-8443-39d1-bf23-7935bda83fcd
	Silicon, electronic grade, off-grade, at plant (US)	kg	0	c2a2c742-e991-3179-a7fb-0d91ba5e451b
	Silicon, solar grade, modified Siemens process, at plant (US)	kg	1.00E+00	f23b1307-6416-3819-8818-7b28dcb24dd8
	Silicon, production mix, photovoltaics, at plant (US)	kg	1.00E+00	e2b44dee-717e-3785-b3ac-6ba2bd173633

Source: JRC elaboration: adapted from PEFCR PV and based on IEA PVPS Task 12 2020

Table 7 shows the activity data of electricity consumption (MJ per kg and MJ per m^2) that have been implemented according to the values listed in the IEA PVPS Task 12 2020.

Table 7. Updated activity data for electricity to be implemented in the modelling and in the Excel file.

Process	Unit	Old data in the Excel (based on PV PEFCR)	New data as implemented in the modelling and in the Excel for EU, APAC, US and CN	New data potentially to be implemented in the Excel for EU, APAC, US and CN with an increase of 30% for being convervative
MG-Si	MJ/kg	39.6	39.6	n.a*.
SOG-Si	MJ/kg	129 (EU) and 396 (CN, US, APAC)	176.4	229.3
Cz ingot	MJ/kg	246.0	115.2	149.8
Wafer	MJ/m^2	92.5	17.1	22.3
Cell	MJ/m^2	51.8	63.7	n.a.*
Panel	MJ/m^2	13.4	50.4	n.a.*

Source: JRC elaboration

*n.a. in case the values have not been changed, or the values are related to company specific information

4.2 Additional potential materials needed for key and innovative PV technologies

Compared to conventional PV technologies, key and emerging PV panels (e.g. TOPCON, HJT, IBC, Silicon-perovskite tandem) may need additional materials and processing for manufacturing them, compared to what listed in the Excel spreadsheet with life-cycle inventories of PV technologies.

With the aim of addressing this, we conducted a preliminary screening of additional potential datasets needed for key and innovative PV technologies. Results of this analysis are summarized in Annex C.

In particular, for each mapped material it is associated the PV technology in which it may be used (such as PERC, TOPCON, CdTe, Silicon-perovskite tandem) and the reference source with the associated link.

Annex C also lists the amount of material (activity data) used for producing such PV panels (as retrieved from inventories in the references).

The "Recycling Silicon" table in Annex C is intended as a preliminary screening of key documents, projects and sources mapping recycled silicon processes, indicating the technologies used and the reference scale which they refer to.

5. Carbon footprint results and discussion

5.1 Carbon footprint results

In this section carbon footprint results, scenarios and interpretation are presented. In particular, carbon footprint results have been calculated according to the harmonized rules described in Section 3 of this report and the life-cycle inventories used are aligned to what described in Section 4 of this report.

The energy yield used for the calculation are illustrated in Annex III of the policy proposal and summarized in Annex B of this report.

The scenarios selected for the analysis were chosen based on their electricity grid mixes (fossil fuels based, renewable energies based, balanced presence of fossil fuels and renewable energies). Sensitivity analysis in terms of different parameters have been conducted (as described in Section 5.4) and specifically those are:

- Operational years
- Electricity yield
- Silicon content
- Conservative and updated activity data for key electricity processes
- Circular Footprint Formula parameters

In terms of results, the results across all scenarios for mono-crystalline silicon PV range from the worst-case scenario, which is 4.40 E-02 $kgCO_{2\ eq}$ per kWh, to the best-case scenario, which is 1.08E-02 $kgCO_{2\ eq}$ per kWh.

For multi-crystalline silicon PV panel, the results across all scenarios range from the worst-case scenario, which is 5.01E-02 $kgCO_{2\ eq}$ per kWh, to the best-case scenario, which is 1.78E-02 $kgCO_{2\ eq}$ per kWh.

In other words, the range of carbon footprint outcomes, spanning from the most favourable to the least favourable scenarios, is a factor of 4 for mono-crystalline silicon and a factor of 2.8 for multi-crystalline silicon PV panel.

In Table 8 and Table 9, the results are presented for mono-crystalline and multi-crystalline scenarios with variations in the grid carbon intensity. For mono-crystalline PV results reported in Table 8, information about the use of updated activity data for the electricity process of silicon and in terms of silicon production mix (including technological process and geographical location) are reported in the column named “activity data”. Within this column, “old data” represents the values of the PV PEFCR, while “new data” are the updated values based on Table 6 and Table 7.

The carbon footprint of CdTe PV panel calculated with the assumptions and the inventories described below would be 1.20E-02 $kgCO_{2\ eq}$ per kWh.

Table 8 Summary carbon footprint results of all mono-crystalline photovoltaic panel scenarios.

Sc. No.	PV scenario	Country	Operational year [yrs]	Electricity yield per m^2	Silicon [kg] per m^2	activity data	R1 Al	R1 Si	R2 Al	R2 Si	Climate Change – Global Warming Potential [$kg_{CO2\ eq.}$ per kWh]
1	PV produced in country 1	1	30	6,733 kWh	0.58	old data*	0	0	0.92	0	1.082E-02
2	PV produced in country 1 except wafer, crystalline in country 2	1	30	6,733 kWh	0.58	old data*	0	0	0.92	0	1.44E-02
3	PV produced in country 2 except wafer, crystal	2	30	6,733 kWh	0.58	old data*	0	0	0.92	0	1.77E-02
4	PV produced in country 2 with default silicon mix	2	30	6,733 kWh	0.58	old data*	0	0	0.92	0	1.82E-02
5	Country3, 6,733 kWh, Si0.58kg, 25%PV for all in supply chain	3	30	6,733 kWh	0.58	old data*	0	0	0.92	0	1.84E-02
6	Country3, 6,733 kWh, Si0.58kg, Country3 supply except MG from Country2	3	30	6,733 kWh	0.58	old data*	0	0	0.92	0	2.08E-02
7	Country4, 6,733 kWh, Si 0.58kg, Country4 supply with Country2 electricity)	4	30	6,733 kWh	0.58	old data*	0	0	0.92	0	2.10E-02
8	Country4, 6,733 kWh, Si 0.58kg, 25% PV for all processes	4	30	6,733 kWh	0.58	old data*	0	0	0.92	0	2.11E-02
9	Country4, 6,733 kWh, Si 0.58kg, R1 PEFCR	4	30	6,733 kWh	0.58	old data*	0.77	0	0.92	0	2.39E-02
10	Country4, 6,733 kWh, Si 0.58kg, 25% PV for panel and cell	4	30	6,733 kWh	0.58	old data*	0	0	0.92	0	2.40E-02

Sc. No.	PV scenario	Country	Operational year [yrs]	Electricity yield per m²	Silicon [kg] per m²	activity data	R1 Al	R1 Si	R2 Al	R2 Si	Climate Change – Global Warming Potential [$kg_{CO2\ eq.}$ per kWh]
11	Country4, 6,733 kWh, Si 0.58kg,	4	30	6,733 kWh	0.58	old data*	0	0	0.92	0	2.44E-02
12	Country4, 6,733 kWh, Si 0.58kg, 25 years	4	25	5686,71 kWh	0.58	old data*	0	0	0.92	0	2.93E-02
13	Country4, 6,733 kWh, Si 1.080kg	4	30	6,733 kWh	1.08	old data*	0	0	0.92	0	3.42E-02
14	Country4, 6,733 kWh, Si 0.58kg, 20 years	4	20	4610.03 kWh	0.58	old data*	0	0	0.92	0	3.65E-02
15	Country4, 6,733 kWh, Si 1,580kg,	4	30	6,733 kWh	1.58	old data*	0	0	0.92	0	4.40E-02
16	Country4, 6,733 kWh, Si 0.58kg,	4	30	6,733 kWh	0.58	New data*	0	0	0.92	0	1.87E-02
17	Country2 : 0_MonoSi,6,733 kWh, Si0.58kg	2	30	6,733 kWh	0.58	New data*	0	0	0.92	0	1.62E-02
18	Country4: 0_MonoSi, 6,733 kWh, Si 1,580kg	4	30	6,733 kWh	1.58	New data*	0	0	0.92	0	2.99E-02
19	Country 2: 0_MonoSi ,6,733 kWh, Si1,58kg,	2	30	6,733 kWh	1.58	New data*	0	0	0.92	0	2.53E-02
20	Country4: 6,733 kWh, Si 0.58kg, EF3.1, Country4 supply,SiR10.5, R20.50)	4	30	6,733 kWh	0.58	New data*	0	0.5	0.92	0.5	1.85E-02
21	Country4, 6,733 kWh, Si 0.58kg, EF3.1, Country4 supply,SiR10.5)	4	30	6,733 kWh	0.58	New data*	0	0.5	0.92	0	1.866E-02
22	Country4, 6,733 kWh, Si 0.58kg, SiR10.33)	4	30	6,733 kWh	0.58	New data*	0	0.33	0.92	0	1.869E-02

Sc. No.	PV scenario	Countr y	Operational year [yrs]	Electricity yield per m^2	Silicon [kg] per m^2	activity data	R1 Al	R1 Si	R2 Al	R2 Si	Climate Change – Global Warming Potential [$kg_{CO2\ eq.}$ per kWh]
23	PV produced in country 1	1	30	6,733 kWh	0.58	New data*	0	0	0.92	0	1.080E-02
24	PV produced in country 1	1	30	6,733 kWh	1.08	New data*	0	0	0.92	0	1.25E-02
25	Country 2: 0_MonoSi ,6,733 kWh, Si1,58kg,	2	30	6,733 kWh	1.08	New data*	0	0	0.92	0	2.08E-02
26	Country3, 6,733 kWh, Si0.58kg, Country3 supply except MG from Country2	3	30	6,733 kWh	0.58	New data*	0	0	0.92	0	1.86E-02
27	Country3, 6,733 kWh, Si0.58kg, Country3 supply except MG from Country2	3	30	6,733 kWh	1.08	New data*	0	0	0.92	0	2.33E-02
28	Country4, 6,733 kWh, Si 0.58kg, silicon mix as defined in PEFCR	4	30	6,733 kWh	0.58	NA	0	0	0.92	0	2.33E-02

Source: JRC elaboration

*detailed information about "old data" and "new data" are available in Table 6 and Table 7

Note: R1Al is recycled content of Aluminium;R2Al is recyclability of aluminium at the end of life; R1Si is recycled content of silicon; R2Si is recyclability of silicon at the end of life; R1 PEFCR scenario include recycled content of aluminium according to PEFCR; SiR1 0.5, R2 0.50 Recycled content of Silicon 50% in the input and recyclability at the end of life 50%; SiR10.33 Recycled content of Silicon 33% in the input

Table 9 Summary carbon footprint results of all multi-crystalline photovoltaic panels scenarios.

Sc. No.	PV scenario	Description	Silicon [kg} per m^2	Climate Change [kg $_{CO2\ eq.}$ per kWh]
1m	Country 1 Multi-Si (646g Si)	All manufacturing processes are located in country1, with 30 years operation.	0.646	1.78E-02
2m	Country2:Multi-Si (646g Si)	All manufacturing processes are located in country 2, with 30 years operation.	0.646	2.63E-02
3m	Country3: Multi-Si (646g Si 25%PV all)	All manufacturing processes are located in country3, with 25% electricity from PV in production, with 30 years operation.	0.646	2.65E-02
4m	Country4: Multi-Si (Si646g)	All manufacturing processes are located in Country4, with lower electricity consumed in production, with 30 years operation.	0.646	2.74E-02
5m	Country4: Multi-Si (Si646g,25%PV all processes)	All manufacturing processes are located in Country4, with 25% electricity from PV in production, with 30 years operation.	0.646	2.92E-02
6m	Country3: Multi-Si (646g Si) except MG)	All manufacturing processes are located in country3, with the exception of MG in country 2, with 30 years operation.	0.646	2.93E-02
7m	Country4: Multi-Si (Si646g, 25%PV for panel and cell)	All manufacturing processes are located in Country4, with 25% electricity from PV in panel an cell production, with 30 years operation.	0.646	3.27E-02
8m	Country4: Multi-Si (Si646g, R1PEFCR)	All manufacturing processes are located in Country4 with 30 years operation, with recycled aluminium 77% as input	0.646	3.29E-02
9m	Country4: Multi-Si (Si646g)	All manufacturing processes are located in Country4 with only 30 years operation	0.646	3.34E-02
10m	Country4: Multi-Si (Si833g)	All manufacturing processes are located in Country4 with only 30 years operation	0.833	3.74E-02
11m	Country4: Multi-Si (Si646g, 25Yrs)	All manufacturing processes are located in Country4 with only 25 years operation	0.646	4.01E-02
12m	Country4: Multi-Si (Si1020g)	All manufacturing processes are located in Country4 with only 30 years operation	1.020	4.14E-02
13m	Country4: Multi-Si (Si646g, 20Yrs)	All manufacturing processes are located in Country4 with only 20 years operation	0.646	5.01E-02
14m	Country 1: Multi-Si (646g Si)	All manufacturing processes are located in country1, with the exception of the casting and wafer procedures, which are based in country 2 with 30 years operation.	0.646	2.06E-02
15m	Country4, Si 646g with default countries mix silicon production	All manufacturing processes are located in Country4 except silicon production that some silicon produce in other countries e.g. Europe with only 30 years operation	0.646	3.16E-02

Source: JRC elaboration

5.2 Key findings

The main contributors to the carbon footprint of a photovoltaic panel, both mono- and multi-silicon PV, are:

- Electricity for manufacturing silicon,
- Silicon content.
- Glass content,
- Aluminium content,

The percentage of contribution from electricity varies, depending on the carbon footprint per kilowatt-hour of the electricity mix of the country that manufactures the panel.

For monocrystalline silicon PV panels, the product's lifespan plays a significant role in terms of the carbon footprint per kilowatt-hour. For instance, in the scenario of country 4, when the lifespan of the PV panel decreases from 30 years to 25 years, the carbon footprint increases by 20%. If the lifespan is further reduced to 20 years, the carbon footprint increases by 50%. In this context, it is relevant to ensure the verifiability of the lifetime and the degradation ratio provided by the PV panel producer (e.g. through a linked technical guaranty).

Furthermore, when the amount of silicon increases from 0.58 kg per square meter of ingot to 1.58 kg per square meter of ingot, the carbon footprint per kilowatt-hour increases by 80% for the country 4 scenario. It should be noted that the silicon content mainly depends on the silicon wafer thickness and on the kerf losses in the manufacturing processes. Both factors are constantly decrease over the year11 .The high amount of silicon (i.e. 1.58 kg/m^2) implemented in the modelling is a conservative default value that can be used by the declarant in absence of specific information on its specific silicon usage because it represents obsolete PV production processes. Currently, the silicon wafer thickness reported by industries is about 150 µm12 and the silicon content is below 0.5 kg/m^2[13].

The assumption on energy production is based on the formula provided in the Annex III of the policy proposal as described in Annex B of this report. Specifically, it has been used the following equation:

$$EEIM\_30y = EEIM \times (1 - DR \times (30 \times 0.5))$$

where:

- EEIM is the Energy Efficiency Index as the ratio of the DC energy yield delivered by one module (EYm(DC) over one year (considered the first year of installation) expressed in kWh, delivered by the module area (Am) in m^2.
- EEIM_30y the Energy Efficiency Index over 30 years of panel lifetime.
- DR. Linear annual degradation rate for mono- and multicrystalline silicon 0.7% per annum.

[11] Available at: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html
[12] Photovoltaics-Report (14).pdf
[13] Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems

Energy Efficiency Index for modules (EEIM) kWh*m-2 per year are calculated without considering age degradation and assuming operation at the default measurement temperature of 25 °C (i.e., the temperature-dependent, typically lower yield is not considered).

Monocrystalline N-type Silicon EEIM_30y: 6733.0 kWh*m^{-2} per 30-year lifetime

Multicrystalline EEIM_30y: 5917.4 kWh*m^{-2} per 30-year lifetime

CdTe EEIM_30y: 4820.0 kWh*m^{-2} per 30-year lifetime

5.3 Data gaps

Below is the list of the data gaps of this study, same as in PEFCR; these gaps are within the permitted cut-off criteria of the PEF method:

- Adhesive for metals
- Charcoal
- Chemicals inorganic
- Chemicals organic
- Disposal, building, electric wiring, to final disposal
- Disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill
- Disposal, waste, silicon wafer production, 0% water, to underground deposit
- Graphite, at plant
- Helium, at plant
- Metal working machine, unspecified, at plant
- Nitrogen trifluoride, at plant
- Petroleum coke, at refinery
- Solvents, organic, unspecified, at plant
- Water supply network

Table 10 lists where proxy datasets have been used as the required process or product was not available in the official EF compliant database EF 3.1 the same as in the PV PEFCR Version: 1.2 Date of publication: February 2020:

Table 10 Use of proxies.

Process or product needed in model	**Proxy data set used**
Solder production plant	Building, steel frame construction (1 m^3 gross volume = 125 kg), single route, at plant, steel frame construction, material quantities adjustable
Disposal, slag from MG silicon production, 0% water, to inert material landfill	Landfill of inert (construction materials) landfill including leachate treatment and with transport without collection and pre-treatment production mix (region specific sites), at landfill site
Disposal, sludge, pig iron production, 8.6% water, to residual material landfill	Landfill of inert (construction materials) landfill including leachate treatment and with transport without collection and pre-treatment production mix (region specific sites), at landfill site
Silicon tetrachloride, at plant	silicon tetrachloride
Aluminium, production mix, wrought alloy, at plant	Aluminium ingot mix (high purity) primary production, aluminium casting single route, at plant 2.7 g/cm3, >99% Al
Brass, at plant	Brass die-casting die casting, from copper and zinc, primary production single route, at plant 8.41- 8.86 g/cm3
Brick, at plant	Bricks vertically perforated (EN15804 A1-A3), production mix, at plant, technology mix, vertically perforated
Building, hall	Building, reinforced concrete frame construction (1 m^3 gross volume = 242 kg), single route, at plant, reinforced concrete frame production, material quantities adjustable
Diesel, burned in building machine	Diesel combustion in construction machine, diesel driven
Disposal, building, brick, to sorting plant	Landfill of inert (construction materials) landfill including leachate treatment and with transport without collection and pre-treatment production mix (region specific sites), at landfill site
Disposal, building, reinforced concrete, to sorting plant	Landfill of inert (construction materials) landfill including leachate treatment and with transport without collection and pre-treatment production mix (region specific sites), at landfill site
Disposal, building, reinforcement steel, to sorting plant	Landfill of inert (steel) landfill including leachate treatment and with transport without collection and pre-treatment production mix (region specific sites), at landfill site
Ethylvinylacetate, foil, at plant	Packaging film, High barrier PE/EVOH/PE raw material production, extrusion, blowing, flattening single route, at plant grammage: 0.066 kg/m^2 outer, 0.042 kg/m^2 inner; thickness: 135 μm (outer film: 90 μm, inner film: 45 μm)
Gallium, semiconductor-grade, at regional storage	Gallium technology mix production mix, at plant 5.9 g/cm3
Glass fibre reinforced plastic, polyamide, injection moulding, at plant	Glass fibres production mix at plant per kg glass fibres
Light fuel oil, burned in industrial furnace 1MW, non-modulating	Thermal energy from light fuel oil (LFO) technology mix regarding firing and flue gas cleaning production mix, at heat plant MJ, 100% efficiency

Process or product needed in model	**Proxy data set used**
Natural gas, burned in boiler condensing modulating >100kW	Thermal energy from light fuel oil (LFO) technology mix regarding firing and flue gas cleaning production mix, at heat plant MJ, 100% efficiency
Natural gas, burned in boiler modulating >100Kw	Thermal energy from light fuel oil (LFO) technology mix regarding firing and flue gas cleaning production mix, at heat plant MJ, 100% efficiency
Natural gas, burned in industrial furnace low-NOx >100kW	Thermal energy from light fuel oil (LFO) technology mix regarding firing and flue gas cleaning production mix, at heat plant MJ, 100% efficiency
Polyvinylbutyral foil, at plant	Polyvinyl Butyral Granulate (PVB), single route, at plant, polymerisation of polyvinyl alcohol, 142 g/mol per repeating unit
Polyvinylfluoride film, at plant/US	Polyvinyl fluoride polymerisation of vinyl fluoride production mix, at plant 1.77 g/cm3
Reinforcing steel, at plant	Reinforced steel (wire) EAF route production mix, at plant wire
Sheet rolling, steel	Steel hot dip galvanised steel sheet hot dip galvanization single route, at plant 1.5 mm sheet thickness, 0.02 mm zinc thickness
Silicone plant	(Proxy) Building Hall for Silicone plant
Solar collector factory	Building, steel frame construction (1 m^3 gross volume = 125 kg), single route, at plant, steel frame construction, material quantities adjustable
Solar collector factory	Building, reinforced concrete frame construction (1 m^3 gross volume = 242 kg), single route, at plant, reinforced concrete frame production, material quantities adjustable
Steel, low-alloyed, at plant	Steel hot dip galvanised steel sheet hot dip galvanization single route, at plant 1.5 mm sheet thickness, 0.02 mm zinc thickness
Treatment, PV cell production effluent, to wastewater treatment, class 3	Treatment of effluents from glass production wastewater treatment including sludge treatment production mix, at plant 1m3 of wastewater treated
Treatment, sewage, from residence to wastewater treatment, class 2	Treatment of residential wastewater, small plant wastewater treatment including sludge treatment production mix, at plant 1m3 of waste water treated
Treatment, sewage, unpolluted, from residence, to wastewater treatment, class 2	Treatment of residential wastewater, small plant wastewater treatment including sludge treatment production mix, at plant 1m3 of wastewater treated
Treatment, sewage, unpolluted, to wastewater treatment, class 3	Treatment of residential wastewater, small plant wastewater treatment including sludge treatment production mix, at plant 1m3 of wastewater treated

Source: JRC elaboration

5.4 Description of the scenarios under analysis and differences with PEFCR

Model configurations of PV associated with the results described in section 5.1 have several aspects that differ from the representative product (RP) that is described in the PV PEFCR. For example, the amount of silicon per area of ingot is higher in the PEFCR than the PV that is modelled in this scenario; more recent electricity mix have been considered; and the RP in the PEFCR is the average product unlike in this project, in which different specific products in different location have been assessed. The reason for such difference was to capture the carbon footprint of different product in the market, representing particular supply chains. Moreover, EF 2.0 datasets referenced in the PV PEFCR, which are no longer valid, have been replaced by EF 3.1 datasets. The silicon mix was also assumed as different, as explained in section 4.1 and section 5.4.3.

Scenario analysis for mono-Si

A three-step scenario analysis has been conducted. In the first step, the electricity consumption in the production of panel, cell, solar grade silicon, off grade silicon, electronic grade silicon, wafer data is derived from the Excel spreadsheet that was shared with the stakeholders during the consultation held in March 2023 and linked to the policy proposal attached to the Annex A ("Old data based on PV PEFCR" as explained and listed in Table 7). This initial scenario considers four countries where panel is manufactured, the utilization of green electricity for the production phase, alterations to the quantity of silicon per panel area, and the product's lifespan.

In the second step, some of the activity data have been updated to reflect the advancements in current technology. This includes the integration of the most recent data on electricity consumption in production and silicon usage. In the third and final step, the focus shifts towards anticipating future technological developments, such as enhancements in the silicon recycling process.

5.4.1 Amount of Silicon in panel

The amount of silicon usage in mono-crystalline PV panels is documented in Table 11 with an assumed range from the lower to a high content. As explained above, the current silicon usage reported by industries is below 0.5 kg/m^2 and then the high silicon content represents a conservative value that can be used by the declarant in absence of specific information.

Table 11 Amount of silicon per area.

Technology	**Si (min) [kg/m^2]**	**Si (mean) [kg/m^2]**	**Si (max) [kg/m^2]**
Mono	0.588	1.08	1.58
Multi	0.646	0.833	1.02

Source: JRC elaboration

5.4.2 Electricity in production

The new data of electricity usage is based on the report "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems" in December 2020 (Report IEA-PVPS T12-19:2020) that published by the International Energy Agency (IEA), as documented in Table 7, were used to model the different scenarios for the mono-crystalline Si PV panels. For multi-crystalline Si PV panels, old data based on PV PEFCR were used.

The approach adopted for modelling the electricity used in the PV panel manufacturing is in accordance with Section 3.10.2 "Alternative approach".

5.4.3 Silicon mix

The silicon mix is an artificial production mix for manufacturing the polysilicon that have been implemented in the life cycle inventories for representing an average share from a geographical production and technological process perspectives.

The new data for the amount of silicon mix is based on the same report as electricity scenario, as documented in Table 6. This represents a potential update compared to old values.

5.5 Interpretation of carbon footprint results for Mono-Si:

In the analysis conducted on monocrystalline silicon photovoltaic, a total of 28 scenarios were examined. The findings, as presented in Table 12, span from the most unfavourable scenario, with a carbon footprint of 4.40 E-02 $kgCO_{2\ eq}$ per kWh, to the most favourable scenario, which records a significantly lower emission of 1.08 E-02 $kgCO_{2\ eq}$ per kWh. This represents a fourfold difference between the two extremes.

In the context of photovoltaic production in Country 4, which has been selected due to its energy mix mainly based on fossil fuels, using 0.58 kg of Silicon per square meter, a reduction in the product's lifespan from 30 years to 20 years results in a 1.5-fold increase in the carbon footprint. As reported in Table 12, this means it increases from 2.44 E-2 $kgCO_{2\ eq}$ to 3.65 E-2 $kgCO_{2\ eq}$. Furthermore, when the quantity of Silicon per square meter is increased from 0.58 kg to 1.58 kg, the carbon footprint escalates by 1.8 times, reaching 4.4 E-2 $kgCO_{2\ eq}$.

The stages of transportation to regional storage and the end of life of the PV module yield the same results across all three scenarios. This is attributed to the assumption that these stages occur in the European Union, and the same data sets are utilized to analyse the carbon footprint. Photovoltaics manufactured in Country 4 with a default silicon mix have a slightly lower impact than those with an entirely supply chain based on Country 4. This can be explained by the fact that some of the silicon is produced in countries with a lower carbon footprint for electricity.

Table 12 Example of Carbon footprint of mono Si photovoltaic panel per life cycle stage: Si 0.58 kg per m^2.

Sc. No.	Scenario	Total	raw material and productio n	transporta tion to regional storage	End of Life of PV Module
3	Produced in Country 2	1.77E-02	1.89E-02	3.16E-04	-1.53E-03
28	Produced in Country 4 with default silicon mix	2.33E-02	2.45E-02	3.16E-04	-1.53E-03
11	Produced in Country 4 with default silicon produced in Country 4	2.44E-02	2.56E-02	3.16E-04	-1.53E-03

Source: JRC elaboration

The detailed outcomes of the mono silicon photovoltaic panel, under the country 2 (Scenario 3), are illustrated in Table 13 to Table 15. An analysis of the results from these tables reveals that materials significantly impact the carbon footprint. For instance, Aluminium ingot contributes

16.9%, glass accounts for 11.3%, and metal grade silicon makes up 6%. Additionally, electricity from the entire supply chain contributes a substantial 40.7%.

Table 13 Carbon footprint of Monocrystalline silicon photovoltaic Panel process, Scenario 3.

Process	**Climate Change – total kg $_{CO2\ eq.}$ per 1 kWh**	**Percentage [%]**
Total	1.89E-02	
Electricity Mix 2022	2.17E-04	1.15%
PHOTOVOLTAIC CELL. MONO-SI. AT PLANT (Silicon0.58)EF3.1	1.07E-02	56.24%
Articulated lorry transport. Euro 4. Total weight >32 t EF 3.1	5.19E-05	0.27%
Articulated lorry transport. Euro 4. Total weight >32 t EF 3.1	3.78E-06	0.02%
Copper Cathode. production mix EF 3.1	6.29E-05	0.33%
Diesel mix at refinery EF 3.1	1.47E-08	0.00%
Flat glas. tempering EF 3.1	4.01E-04	2.12%
Flat glass. uncoated EF 3.1	1.76E-03	9.29%
Freight train. average EF 3.1	1.16E-04	0.61%
glass fiber EF 3.1	7.32E-05	0.39%
Lead (primary) EF 3.1	1.83E-07	0.00%
Tap water EF 3.1	5.67E-07	0.00%
Solar glass Quantis	1.16E-03	6.14%
Aluminium ingot (silicon and magnesium main solutes)	3.20E-03	16.92%
Copper Wire Drawing	2.22E-06	0.01%
Corrugated board. uncoated	1.18E-04	0.62%
HDPE granulates	6.11E-06	0.03%
Packaging film. High barrier PE/EVOH/PE	3.26E-04	1.72%
Pallet. wood (80x120)	4.05E-05	0.21%
PET granulates. amorphous	1.35E-04	0.71%
Silicone. high viscosity	8.75E-05	0.46%
Treatment of residential wastewater. small plant	1.08E-06	0.01%
Waste incineration of hazardous waste	9.72E-08	0.00%
Waste incineration of municipal solid waste	1.06E-07	0.00%
Waste incineration of plastics (unspecified)	2.39E-04	1.26%
Diesel combustion in construction machine	8.64E-08	0.00%
Glass SMD diode EF 3.1	1.33E-04	0.70%

Process	Climate Change - total kg $_{CO2\ eq.}$ per 1 kWh	Percentage [%]
Polyvinyl fluoride EF 3.1	9.28E-05	0.49%
potassium hydroxide production	1.32E-05	0.07%
Tin EF 3.1	1.00E-05	0.05%
photovoltaic panel. single-Si	2.92E-06	0.02%
1-propanol production	8.08E-06	0.04%
hydrogen fluoride production	1.32E-05	0.07%
isopropanol production	3.74E-08	0.00%
soap production	1.68E-06	0.01%

Source: JRC elaboration

Table 14 Carbon footprint of Monocrystalline silicon photovoltaic Cell process.

Process	Climate Change - total kg $_{CO2\ eq.}$ per 1 kWh	Percentage [%]
Total	1.07E-02	
photovoltaic cell factory	4.83E-05	0.5%
LC1: single-Si wafer. photovoltaics. at plant (Si0.588kg).	9.38E-03	88.1%
Electricity Mix 2022	7.84E-04	7.4%
Silane. at plant	6.56E-05	0.6%
photovoltaic cell. single-Si. at plant	2.69E-05	0.3%
Ammonia. as 100% NH3 production EF 3.1	5.79E-06	0.1%
Articulated lorry transport. Euro 4. Total weight >32 t	2.27E-06	0.0%
Freight train. average EF 3.1	3.89E-06	0.0%
Tap water EF 3.1	1.80E-05	0.2%
Thermal energy from natural gas	5.25E-07	0.0%
Treatment of residential wastewater. small plant	3.19E-05	0.3%
Waste incineration of hazardous waste	9.71E-06	0.1%
Metallization paste. back side EF 3.1	2.63E-05	0.2%
Metallization paste. back side. aluminium EF 3.1	5.38E-05	0.5%
Metallization paste. front side EF 3.1	4.86E-05	0.5%
tetrafluoroethane production	6.99E-08	0.0%
Transoceanic ship. containers	3.32E-08	0.0%
Hydrochloric acid production	5.48E-08	0.0%

hydrogen fluoride production	1.28E-07	0.0%
isopropanol production	4.21E-05	0.4%
Lime production	2.21E-06	0.0%
Nitrogen liquid production	3.55E-05	0.3%
phosphoryl chloride production	6.01E-06	0.1%
Sodium hydroxide production	5.81E-05	0.5%

Source: JRC elaboration

Table 15 Carbon footprint of mono-crystalline silicon photovoltaic panels: single Crystalline process.

Process	**Climate Change – total kg $_{CO2\ eq.}$ per 1 kWh**	**Percentage [%]**
Total	9.38E-03	
Electricity grid mix	2.52E-03	26.9%
CZ single crystalline silicon. at plant EF3.1	5.54E-03	59.1%
Silicon carbide. reprocessed. at plant	6.96E-05	0.7%
Triethylene glycol. reprocessed. at plant	1.09E-04	1.2%
Tap water EF 3.1	6.23E-10	0.0%
Articulated lorry transport. Euro 4. Total weight >32 t	7.95E-06	0.1%
Flat glas. tempering EF 3.1	4.38E-07	0.0%
Flat glass. uncoated EF 3.1	1.92E-06	0.0%
Freight train. average EF 3.1	1.01E-05	0.1%
Steel cold rolled coil EF 3.1	2.76E-04	2.9%
Steel wire drawing EF 3.1	2.48E-05	0.3%
Brass die-casting	1.47E-06	0.0%
Acetic acid production	8.71E-06	0.1%
Acrylic binder production	3.77E-07	0.0%
Alkylbenzene production	5.93E-05	0.6%
De-ionised water production	1.90E-06	0.0%
dipropylene glycol monomethyl ether production	1.74E-04	1.9%
Hydrochloric acid production	2.42E-07	0.0%
silicon carbide production	4.69E-04	5.0%
Sodium hydroxide production	1.49E-06	0.0%
triethylene glycol production	6.10E-05	0.7%
Thermal energy from natural gas EF 3.1	3.67E-05	0.4%

Source: JRC elaboration

Other results and contribution analysis of multi-crystalline and CdTe PV panels are reported into the Annex D.

6. Stakeholder Consultations

The harmonised rules for calculating the carbon footprint of PV modules and then the present report is the result of extensive exchange with several involved stakeholders.

All feedback received regarding the proposed method have been analysed and considered.

As such, the present report represents the outcome of a consensus building process based on various position from different stakeholder received at different stages of the development of the method.

Specifically, a first stakeholder consultation has been organised within the "*Consultation Forum Meeting on potential Ecodesign and Energy labelling requirements for photovoltaic modules, inverters and systems*", which was held on June 27th, 2022. A second consultation on "*Technical stakeholder meeting PV module carbon footprint calculation rules and related conformity assessment procedure*" was on March 30th, 2023. The Annex A attached to this report represents the version shared with stakeholders on the second consultation.

These two stakeholder consultations were focused on the following topics:

- Description of the product group/policy framework;
- PV module carbon footprint calculation rules:
  - scope,
  - functional unit,
  - system boundaries,
  - use of company-specific activity data,
  - modelling requirements (electricity and recycled content and material recycling)
- Carbon footprint requirements;
- Comparison with other existing scheme (e.g. the FR case study);
- International standards on carbon footprint;
- Online tool for the PV module carbon footprint calculation.

Following the second stakeholder consultation, a total number of 80 written comments were received by 6 commenting stakeholders, including public and private entities. Below there is an overview of the macro-category topics for which the presented harmonised rules for PV carbon footprint received comments and feedback from stakeholders:

- Circular Footprint Formula
- Conformity Assessment
- Data quality
- Definition
- Electricity modelling
- Energy Return on Investment
- PEFCR and alignments
- Kerf Recycling
- Reference flow

- Scope of the regulation
- System boundaries
- Transport
- Verification

In particular, feedback received on circular footprint formula have reflected in changes to the default values proposed for R2 of certain materials (e.g. aluminium); comments on data quality have been reflected in some default activity data proposed in the life cycle inventories (e.g. electricity consumption for manufacturing the silicon wafers); also, the data need matrix have been omitted and the electricity modelling approach has been revised by proposing two alternative scenarios.

7. Support to a PV dedicated tool for calculating carbon footprint

The development of a potential dedicated PV tool for calculating carbon footprint of PV panels has been identified as a strategy to facilitate the calculation by operators, based on the harmonized method described in the previous chapters. On such purpose, EC launched an external service contract to develop a dedicated PV tool, having JRC provided technical support. Currently, this dedicated PV tool is under development and a beta version is expected to be distributed in the short term for stakeholder checking. The JRC followed the development of the tool through meetings, delivery of information and data, and internal testing of the beta version. The main activities are summarized in this section.

Several meetings, exchanges and analyses have been scheduled and conducted for monitoring and supporting the tool development.

As a starting point, JRC provided IT tool developers with the revised Excel spreadsheet[14] containing the life cycle inventories of the PV panel under analysis (including default datasets to be used, activity data, elementary and emission flows, mapping of datasets from EF 2.0 database to EF 3.1 database). It was also provided guidance on how to implement the proposed method into the IT tool.

Technical support has been given also in reviewing the deliverables provided by the IT tool developers (including the i) inception report and ii) interim report). In particular, the revision of the inception report was focused on:

- adding details on the differences between mandatory and non-mandatory processes for which rules are different;
- adding the data quality rating assessment for default secondary datasets;
- general alignment of nomenclatures and rules with the harmonized methodology;
- import of EF compliant datasets;
- adaptability of the tool to future reference packages;
- confidentiality of activity data and company-specific datasets created or modified; inclusion of CFF parameters into the implementation;
- alignment with PV levels (e.g. panel, cell, Cz ingot, silicon wafer, metallurgic grade silicon).

Preliminary results of a representative product calculated within the tool have been revised according to the carbon footprint method proposed in this report. Assumptions (e.g. lifetime, degradation, geographical location) behind results have been checked and refined as well as a preliminary comparison between various products (PV technologies) and different geographical scenarios. A contribution analysis of processes and materials contributing to the carbon footprint has been reviewed as well as a sensitivity analysis of electricity, glass content, aluminium content, and silicon content. In this context, silicon content was identified as a factor dominating results about the carbon footprint of silicon-based PV panels.

Tests have been conducted on different beta versions of the IT tool for aligning the technical features. JRC analysis was focused on key aspects as:

- Information required

[14] https://ec.europa.eu/docsroom/documents/46532

- Unit
- Nomenclature
- Electricity
- Dataset
- Geographical location
- Data Quality Rating
- Methodology
- Carbon footprint results
- Interface of the tool

As for the information requirement, it has been highlighted the relevance of having an alignment of the field to be compiled by the user with the methodological rule, clarifying what information is needed and how the tool use it.

In terms of units of measure, it has been suggested of aligning them with the definitions of reference flow and functional unit. The nomenclature used in the tool should be coherent with the methodological terms (e.g. for what concerns CFF parameters such as R1 and R2) as well as electricity choices and default datasets to be used.

Other relevant methodological aspects were identified by JRC, as:

- Geographical differences (e.g. a material produced in Europe or extra EU countries) of default datasets should be visible allowing the users a proper selection of them.
- For the DQR evaluation, the IT tool should allow the assessment of the representativeness of the default datasets (e.g. GeR and TeR), as described in the methodological rules.
- The IT tool should allow the calculation of carbon footprint results in line with the harmonized methodology using $kgCO_{2\ eq}$/kWh as functional unit of the PV panel under analysis. Other environmental indicators that the tool may calculate are optional and not essential for the aim of the tool which remain the carbon footprint evaluation.
- Results should be possible to be exported in a Word report and in an Excel spreadsheet.
- The IT tool interface should be user friendly for understanding properly the correct function to be selected from the user.

8. Conclusions

Among all the methods and standard that can be applied to calculate the carbon footprint, there is a need of harmonizing the carbon footprint specifically of PV products at the European level.

This science for policy report discusses a proposal of harmonized rules for accounting the carbon footprint of PV panels potentially applicable in the context of the EU Ecodesign Directive.

Overall, these rules have been elaborated based on the Environmental Footprint method and uses as pillar the previous Product Environmental Footprint Category Rules of PV with adaptations for policy purpose that are explained and discussed in this report. The reasoning behind the main methodological and technical assumptions are presented in the report as well as some open points to be further addressed.

In particular, the scope has been adjusted compared to PV PEFCR with the aim of including emerging and innovative PV technologies based on the current market share.

According to this, life-cycle inventories of the PV technologies under analysis (mono-crystalline silicon, multi-crystalline silicon, cadmium telluride) have been adapted, including the associated default secondary datasets that are provided (e.g. for materials, energy, transports). The associated activity data have been updated in terms of electricity consumption of key processes.

Moreover, applying the harmonized rules proposed and discussed in this report, carbon footprint results of PV panels have been calculated among different scenarios illustrated in this report (e.g. of production, various silicon content, electricity yield, recycled content, and operational lifetime).

The primary contributors to the carbon footprint of mono- and multi-crystalline silicon PV panels include:

- electricity for manufacturing the silicon,
- silicon content
- aluminium frame,
- glass.

The product lifetime plays a significant role in terms of the carbon footprint per kilowatt-hour.

Inputs from stakeholder consultations has been considered during the elaboration of these harmonised rules for calculating the carbon footprint of PV modules. This report may be considered as an output built upon a large consensus building process based on various position from different stakeholder received at various stages of the development of the method.

Finally, it is described the support provided to the realisation of a dedicated IT online tool for calculating the carbon footprint of PV panels, based on the harmonized rules proposed.

Future research could also focus on extending current rules to other relevant impact categories beyond carbon footprint - including for example. resource use (fossils), resource use (minerals and metals) acidification and particulate matter. Finally, the proposed method should be adapted and extended to innovative PV technologies (e.g. single-junction perovskite panels) that will be potentially scaled up from laboratory to commercial scale as well as on existing PV panel technologies with technological improvements in their manufacturing (e.g. updated life cycle inventories).

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List of abbreviations

CFF	Circular Footprint Formula
CdTe	Cadmium Telluride
CI(G)S	Copper-Indium-Gallium-Selenide
DNM	Data Needs Matrix
DQR	Data Quality Rating
EF	Environmental Footprint
EoL	End-of-life
FU	Functional Unit
GeR	Geographical Representativeness
ILCD	International Life-cycle Data
JRC	Joint Research Centre
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life-cycle Inventory
LCIA	Life-cycle Impact Assessment
LCDN	Life-cycle Data Network
LT	Lifetime
micro-Si	Micromorphous Silicon
mono-Si	Mono-crystalline Silicon
multi-Si	Multi-crystalline Silicon
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PV	Photovoltaic
RF	Reference Flow
RP	Representative Product
SB	System Boundary
TeR	Technological Representativeness

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Annex A – “Harmonised rules for the calculation of the carbon footprint of photovoltaic modules” version of 30 March 2023

WORKING DOCUMENT ON PV carbon footprint

ANNEX IV

Harmonised rules for the calculation of the carbon footprint of photovoltaic modules

Part 1 – Harmonised calculation rules

1. Definitions

For the purposes of this Annex, the following definitions shall apply:

(a) ‘Activity data’ means the information associated with processes while modelling Life Cycle Inventories (LCI). The aggregated LCI results of the process chains that represent the activities of a process are each multiplied by the corresponding activity data and then combined to derive the carbon footprint associated with that process;

(b) ‘Aggregated dataset’ means life cycle inventory (LCI) of multiple unit processes (e.g. material or energy production) or life cycle stages (cradle-to-gate), but for which the inputs and outputs are provided only at the aggregated level. Aggregated datasets are also called "LCI results", “cumulative inventory” or “system processes” datasets;

(c) ‘Bill of materials’ means list of the materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture the product in scope of the study;

(d) ‘carbon footprint’ (CF) means the sum of greenhouse gas (GHG) emissions and GHG removals in a product system, expressed as carbon dioxide (CO_2) equivalents and based on a Product Environmental Footprint[1] (PEF) study using the single impact category of climate change;

(e) Company-specific information: it covers all kind of information (including company specific data) the applicant may have regarding either processes, materials or flows occurring during the phases under control of the company and along the supply chain that can have an impact on the representativeness of the dataset (geographical, technological, time representativeness);

(f) ‘Company-specific data’ refers to directly measured or collected data from one or multiple facilities (site-specific data) that are representative for the activities of the company. It includes company-specific activity data and direct elementary flows. It is synonymous to 'primary data'; or “supply-chain specific data” or “manufacturer-specific” data;;

(g) ‘Functional unit’ means the qualitative and quantitative aspects of the function(s) and/or service(s) provided by the product being evaluated;

(h) ‘Life cycle’ means the consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal;

(i) ‘Life cycle inventory (LCI)’ means the combined set of exchanges of elementary, waste and product flows in a LCI dataset;

(j) ‘Life cycle inventory (LCI) dataset’ means a document or file with life cycle information of a specified product or other reference (e.g., site, process), covering descriptive metadata and quantitative life cycle inventory. A LCI dataset could be a unit process dataset, partially disaggregated or an aggregated dataset;

(k) ‘Partially disaggregated dataset’ a dataset with a LCI that contains elementary flows and activity data, and that only in combination with its complementing underlying datasets yield a complete aggregated LCI data set

(l) ‘Reference flow’ means the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit;

(m) ‘Secondary data’ means data not from a specific process within the supply-chain of the company performing a carbon footprint study. This refers to data that is not directly collected, measured, or estimated by the company, but sourced from a third party LCI database or other sources. Secondary data includes industry average data (e.g., from published production data, government statistics, and industry associations), literature studies, engineering studies and patents, and may also be based on financial data, and contain proxy data, and other generic data;

(n) ‘System boundary’ means the aspects included or excluded from the life cycle study;

(o) ‘Circular Footprint Formula’ (CFF) describes how burdens and benefits from disposal and recovery of the product or service assessed as well as use of secondary materials (i.e. recycled content) into that product or service are allocated to the system under study;

(p) ‘Data Needs Matrix’ (DNM) describes the requirements for the use of company specific data and secondary data, depending on the level of influence the applicant has on the processes along the value chain;

(q) ‘Manufacturer’ producer of the PV modules;

(r) ‘Unit process’ is the smallest element considered in the LCI for which input and output data are quantified (based on ISO 14040:2006);

(s) ‘Tracking system’ (electricity) means a system applying the process of assigning electricity generation attributes to electricity consumption;

(t) ‘Regional storage’ physical place, located in the EU, where PV panels are stored before they are transported to the place of installation;

(u) “TiR “ is the Time Representativeness;

(v) “TeR” is the Technology representativeness;

(w) “GeR” is Geographical Representativeness.

2. Scope

This Annex provides harmonised rules on how to calculate the carbon footprint of photovoltaic modules. It also applies to bifacial photovoltaic modules.

The calculation of the carbon footprint shall be based on the bill of material, the energy, and auxiliary materials used to produce a specific photovoltaic module model. In particular, the photovoltaic cells, the glass, the frame materials and the electronic components (e.g. junction boxes, cabling) have to be accurately identified, for the specific product l, as they may become a relevant contributor to the carbon footprint of a photovoltaic module.

The bill of materials shall be based on company-specific data for the specific product model that cover a time period of at least one year (12 months). If 12 month data are not available, shorter periods and/or product design and pilot scale data may be used. In the latter situation, the carbon footprint calculation shall be updated once data covering 12 month production become available.

The material losses during module manufacturing shall be taken into account.

If the photovoltaic module is supplied without frame, and the photovoltaic module does not require any frame for being installed, no frame shall be accounted in the carbon footprint calculation.

3. Functional unit and reference flow

The functional unit is defined as one kWh (kilowatt-hour) of the total DC electric energy generated over a photovoltaic module's service life. The total DC electric energy generated over a module's service life is calculated according to Annex III, point 4.3 under 'temperate continental' climate conditions.

The reference flow is the amount of product needed to fulfil the defined function and shall be measured in m^2 of photovoltaic module per kWh of the total energy required by the application over its service life. All quantitative input and output data collected by the manufacturer to quantify the carbon footprint shall be calculated in relation to this reference flow.

4. System boundary

The following life cycle stages and processes of the PV modules shall be included in the system boundary:

Life cycle stage	**Short description of the processes included**
Raw material acquisition, pre-processing and module manufacturing	Includes mining and pre-processing, up to the manufacturing of silicon ingot, wafers, photovoltaic cells and the supply chain of electric/electronic components and other components such glass, silver, frame and encapsulant materials. Assembly of photovoltaic cells and assembly of modules with the frame (in case) and the electric/electronic components.
Distribution	Transportation of PV modules from manufacturing plants to a regional storage located in the EU (to be identified and justified).

Manufacturing of equipment (capital goods) for modules assembly and recycling shall be excluded from the assessment.

All other processes belonging to the subsequent life cycle stages, shall be excluded from the lifecycle calculations (i.e., distribution to the final consumer, assembly of the system, use and disposal, dismantling and recycling of the photovoltaic modules. Benefits and burdens of recycled materials in input and of main materials recycled at the end of life are considered in the application of the CFF to the module production.

The manufacturing of photovoltaic modules shall cover raw material extraction to wafer, cell and module production in case of crystalline silicon modules, the supply chain of semiconductors (micromorphous silicon, cadmium sulphide, cadmium telluride, gallium and other materials used in thin film technologies) in case of thin film modules, and the supply chain of carrier and connection materials (such as glass, silver, junction box and frame) in case of all modules. A more detailed depiction of the supply chain of mono-Si, multi-Si, micro-Si, CdTe and CIS / CIGS PV modules is shown in Fig. 1 and Fig. 2.

Figure 1 – System diagram for the PV technologies included in scope. The supply chain of the individual PV technologies is shown in more detail in Fig. 2.

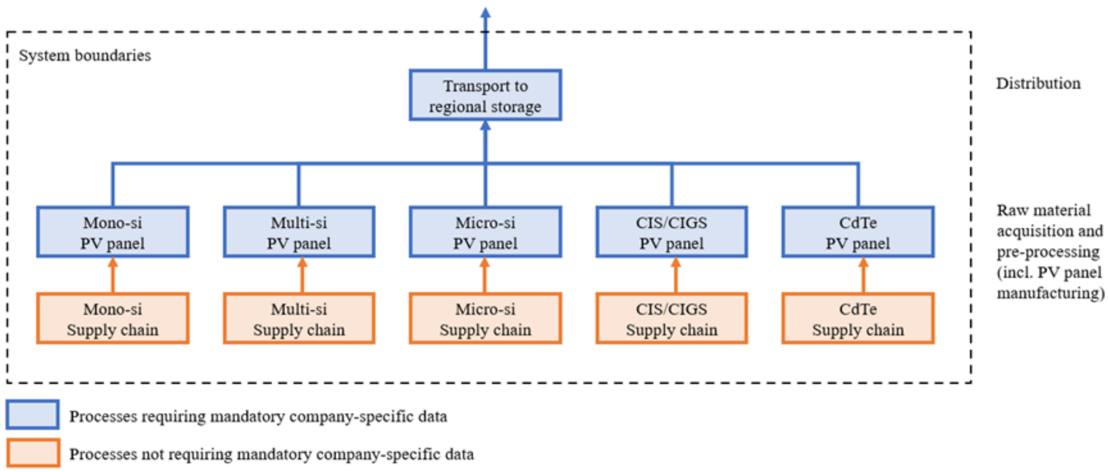
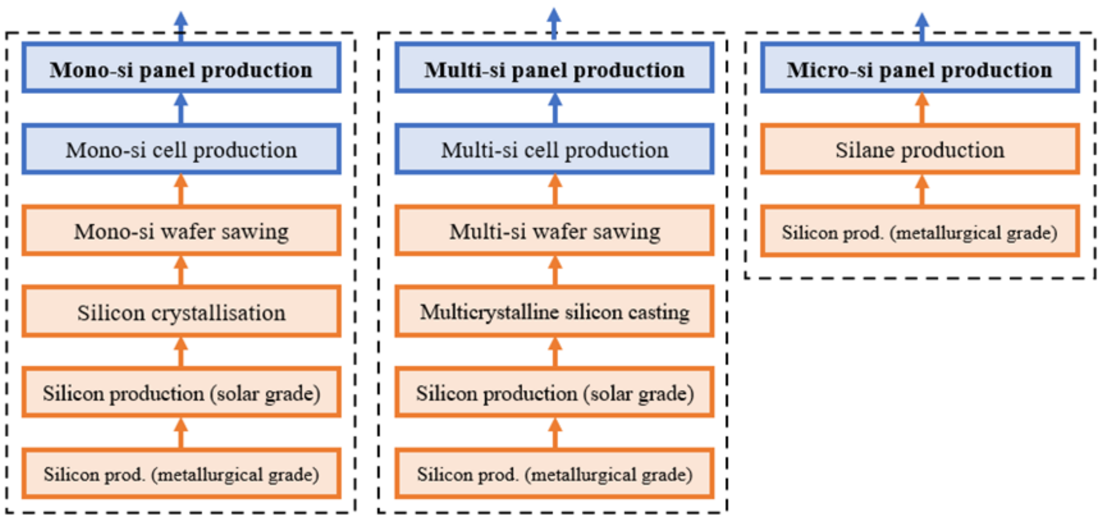


Figure 2 – Excerpt of the supply chain for the PV technologies included in scope.



According to this Annex, no cut-off is applicable to the processes involved in the system diagrams of Fig. 1 and 2, beyond the capital goods identified above.

5. Use of company specific activity data

5.1 Mandatory company specific activity data

The manufacturer shall use company specific data for the processes listed in table 1A and further detailed in Part 2 of this Annex.

Secondary datasets are provided by default in this Annex to model the product (hereinafter they are defined as "default secondary dataset").

When the manufacturer is willing to use default secondary datasets (as listed in the spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory"[2]), their data quality criteria need to be reassessed, based on the rules in the EC recommendation 2021/2279 (Annex I, section 4.6.5.3). If the reassessed data quality criteria of the default secondary dataset are representative for the manufacturer (i.e. TiR≤2 or TeR≤2 or GR≤2), the default secondary dataset may be combined with company-specific activity data.

If the reassessed quality of the dataset is not representative (TiR>2 or TeR>2 or GR>2) of the process, the manufacturer shall adapt the dataset to the manufacturing context (e.g. to what concerns electricity consumption) and recalculate the DQR following the rules in the EC recommendation 2021/2279 (Annex I, section 4.6.5.3). If the recalculated DQR is higher than 3, the manufacturer shall develop an EF compliant dataset following the Guide for EF compliant datasets[3].

If a default secondary dataset is not available (e.g. innovative materials) the manufacturer may use a proxy dataset (selected from the list "CF_Annex_PV_modules-Life_cycle_inventory[8]), if after reassessing its quality (TiR, TeR, GR) the recalculated DQR of the dataset is ≤3.

If not, i.e. the recalculated DQR of the proxy dataset is higher than 3, the manufacturer shall develop an EF compliant dataset following the Guide for EF compliant datasets. To develop an EF compliant dataset, selection of appropriate datasets shall follow the hierarchy described in the spreadsheet "CF_Annex_PV_modules-Life_cycle_inventory[8]" sheet Data sources.

Table 1A – List of processes (for each technology and life cycle stage) for which the use of company-specific activity data is mandatory.

Technology	Life cycle stage	Process
Cadmium-Telluride PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic laminate, CdTe, at plant
	Distribution	Photovoltaic laminate, CdTe, at regional storage
Copper-Indium-Gallium-Selenide PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic laminate, CIS, at plant
	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic panel, CIS, at plant
	Distribution	Photovoltaic panel, CIS, at regional storage

Technology	Life cycle stage	Process
Micromorphous Silicon PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic panel, micro-Si, at plant
	Distribution	Photovoltaic panel, micro-Si, at regional storage
Multicrystalline Silicon PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic cell, multi-Si, at plant
	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic panel, multi-Si, at plant
	Distribution	Photovoltaic panel, multi-Si, at regional storage
Monocrystalline Silicon PV modules	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic cell, mono-Si, at plant
	Raw materials acquisition, pre-processing and PV module manufacturing	Photovoltaic panel, mono-Si, at plant
	Distribution	Photovoltaic panel, mono-Si, at regional storage

5.2 Non-mandatory company specific activity data

For non-mandatory process the manufacturer shall apply the data need matrix (Section 7.2).

6. Life cycle stages

Raw material acquisition, pre-processing and module manufacturing

This life cycle stage includes raw material acquisition and pre-processing, as well as the manufacturing of the photovoltaic modules. The supply chain of the modules shall include the production of the modules, the cells and wafers (if applicable) and the supply chain of the materials required in the module and in manufacturing (such as working materials and process gases, energy carriers), including raw material extraction and refining towards the directly employed material. The supply chain of the frame (if applicable), shall similarly include raw material extraction and refining.

The processes taking place in the life cycle stage raw material acquisition and pre-processing, the inputs and outputs as well as the default secondary datasets to be used are listed in the file named "CF_Annex_PV_modules-Life_cycle inventory[8], sheet "Raw-Materials&Pre-Processing". Processes that are expected to be run by the company are written in capital letters (see column A in the spreadsheet).

Transport of raw materials and intermediate products

Transport of raw materials and intermediate products to the production site shall be included in this life-cycle stage.

Table 2B shows the default transport distances by train and lorry (lorry >32 t, EURO 4) for some frequently used raw materials and intermediate products. These default values may also be used to estimate default transport distances for similar products required in the supply chain of PV modules. The default transport distances shown in Table 2B shall be used in case company-specific information is not available. For transports by lorry, a default utilization ratio of 64 % shall be used if specific data are not available. This utilization ratio includes empty return trips.

For suppliers located outside Europe, the default transport scenario described in the file named "CF_Annex_PV_modules-Life_cycle_inventory[8]", sheet Transport-Scenarios should be used. This scenario includes the transport of raw materials or intermediate products between the harbour or airport and the factories in and outside Europe, which is estimated to 1'000 km by lorry (>32 t, EURO 4). The intercontinental transport to Europe occurs either by transoceanic container ship (18'000 km) or by cargo airplane (10'000 km). If the location of the supplier is known, specific data may be used to calculate the transport distances and modelling the applicable transport modes to the production site.

Air cargo shipping of semi-finished products such as wafers and cells shall be included according to its share in supply logistics in a three years period.

Table 2B – Default distances for transport of raw materials and intermediate products

	Density [kg/m3]	**consumption in Europe**	
		km train	**km lorry 32t**
mineral products			
gravel/sand	2000	-	50
metals			
steel/cast iron	7900	200	100
copper	8900	200	100
aluminium	2700	200	100
plastics			
PVC	1400	200	100
PE	950	200	100
PP	900	200	100
wood products			
particle board	680	200	50
basic chemicals, inorganic (carrier substance to be considered additionally)			
caustic soda	1045	600	100
soda (sodium carbonate	2532	600	100
hydrochloric acid	909	200	100
sulphuric acid	1840	600	100
nitric acid	1383	600	100
phosphoric acid	1685	600	100
hydrofluoric acid	993	600	100
Basic chemicals, organic			
ethylene		600	100
naphta		600	100
refrigerants		600	100
organ. Solvents		600	100
gases (if not produced on the spot) if bought in cylinders: doubling of transport distances (due to tare weight)			
oxygen		100	50
nitrogen		100	50
hydrogen		100	50
helium		100	50

Packaging materials

The use and disposal of packaging materials shall be considered for the entire product system and modelled as part of the raw material acquisition stage. The raw material consumption of reusable packaging shall be calculated by dividing the actual weight of the packaging by the reuse rate. The reuse rate affects the quantity of transport that is needed per functional unit. The transport impact shall be calculated by dividing the one-way trip impact by the number of times this packaging is reused.

For reusable packaging, the default reuse rates provided below shall be used, unless data of better quality are available:

- Plastic pallets: 50 trips
- Wooden pallets: 25 trips

Modelling recycled content and materials recycling

The recycled content of materials used in PV modules as well as their recycling potential at the end-of-life shall be modelled according to the following formula:

$$(1- R_1)\cdot E_v + R_1 \cdot \left(AE_{recycled} + (1- A)\cdot E_v \cdot \frac{Q_{Sin}}{Q_p}\right) + (1-A)\cdot R_2 \cdot \left(E_{recyclingEoL} - E_v^* \cdot \frac{Q_{Sout}}{Q_p}\right)$$

A: allocation factor of burdens and credits between supplier and user of recycled materials.

R1: it is the proportion of material in the input to the production that has been recycled from a previous system.

R_2: it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R_2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R_2 shall be measured at the output of the recycling plant

Ev: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.

Erecycled (Erec): specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.

$E_{recyclingEoL}$ (E_{recEoL}): specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.

E^*_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

Qsin: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.

Q_{Sout}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.

Q_p: quality of the primary material, i.e. quality of the virgin material**.**

The R1 values applied shall be supply-chain specific or default ones. Material-specific values based on supply market statistics are not accepted as a proxy. The applied R1 values shall be subject to verification.

When using supply-chain specific R1 values other than 0, traceability throughout the supply chain is necessary. The following general guidelines shall be followed when using supply-chain specific R1 values:

- The supplier information (through e.g., statement of conformity or delivery note) shall be maintained during all stages of production and delivery at the converter.
- Once the material is delivered to the converter for production of the end products, the converter shall handle information through their regular administrative procedures.
- The converter for production of the end products claiming recycled content shall demonstrate through his management system the [%] of recycled input material into the respective end product(s).
- The latter demonstration shall be transferred upon request to the user of the end product.
- Company-owned traceability systems can be applied as long as they cover the general guidelines outlined above.

The default parameter values for applying the CFF and the default values for R1 and R2 are listed in the spreadsheet "CF_Annex_PV_modules-Life_cycle_inventory[8]", sheet CFF-parameters. For all materials not listed in the sheet CFF-parameters, it is assumed that R2=0.

Distribution

The transportation of photovoltaic modules from factory to EU borders, shall be modelled within this life cycle stage. The distance and mass transported shall be characterised with company-specific data. For producers located in EU Member States, this step is not applicable

The transport from regional storage to the photovoltaic power system where the photovoltaic modules are installed is excluded from the system boundary. If photovoltaic modules are produced in several production sites, the share of each facility in the European supply mix shall be accounted for in the life cycle stage distribution.

The processes taking place in the life cycle stage distribution, the inputs and outputs as well as the default datasets are listed in the spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory[8]", sheet "Distribution". Processes that are expected to be run by the company applying the Annex are written in capital letters (see column A in the spreadsheet).

7. Other modelling requirements

7.1_Sampling

Sampling is allowed in case of a high number of production sites are involved in the production of the module for which the carbon footprint is calculated. In case sampling used to collect data from different production sites, different sub-populations shall be identified by considering the geographical distribution, the technologies applied and the production capacity of all facilities. The number of sub-populations (*Nsp*) shall be identified as:

$Nsp = g \cdot t \cdot c$

where g is the number of countries in which the plants are located, t is the number of technologies and c is the number of classes of plant capacity.

Once the sub-populations have been identified, for each sub-population the size of sample shall be calculated (the sub-sample size) based on the total production of the sub-population. The total production shall represent the product under analysis (e.g. total amount of multi-Si PV cells or modules produced, measured in m^2). The percentage of production to be covered by each sub-population shall not be lower than 75 %. The data collected from different production sites shall be weighted based on the production volume of each facility.

The company applying this Annex shall describe the sub-populations and report the percentage of the total production that is covered by the collected samples.

7.2 Data needs matrix (DNM)

All processes required to model the product that are not included in the list of -processes for which company-specific activity data are mandatory (Table 1A listed in section 5.1) shall be evaluated using the Data Needs Matrix (see Table 3). The following three situations are found in the DNM and are explained below:

Situation 1: the process is run by the company applying this Annex
Situation 2: the process is not run by the company applying this Annex but the company has access to (company-)specific information.
Situation 3: the process is not run by the company applying this Annex and this company does not have access to (company-)specific information.

Table 3 – Data Needs Matrix.

Situation	**Requirement**
Situation 1: process run by the company applying this Annex	When the manufacturer is willing to use default secondary datasets (listed in the spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory"), their data quality criteria need to be reassessed, based on the rules in the EC recommendation 2021/2279 (Annex I, section 4.6.5.3). If the reassessed data quality criteria of the default secondary dataset are representative for the manufacturer (i.e. TiR≤2 or TeR≤2 or GR≤2), the dataset may be combined with company-specific activity data. If the recalculated quality of the default dataset is not representative (TiR>2 or TeR>2 or GR>2) of the process, the manufacturer shall adapt the dataset to the manufacturing context (e.g. to what concerns electricity consumption) and recalculate the DQR following the rules in the EC recommendation 2021/2279 (Annex I, section 4.6.5.3). If the recalculated DQR is higher than 3, the manufacturer shall develop an EF compliant dataset following the Guide for EF compliant datasets. If a default secondary dataset is not available (e.g. innovative materials) the manufacturer may use a proxy dataset (selected from the list "CF_Annex_PV_modules-Life_cycle_inventory), if after reassessing its quality (TiR, TeR, GR) the recalculated DQR is ≤3.

Situation	Requirement
	If not, (i.e. the recalculated DQR of the proxy dataset is higher than 3, the manufacturer shall develop an EF compliant primary dataset following the Guide for EF compliant datasets.
Situation 2: process not run by the company applying this Annex but with access to company-specific information	When the manufacturer is willing to use default secondary datasets (listed in the spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory"), their data quality criteria need to be reassessed, based on the rules in the EC recommendation 2021/2279 (Annex I, section 4.6.5.3). If the reassessed data quality criteria of the default secondary dataset are representative for the manufacturer (i.e. TiR≤2 or TeR≤2 or GR≤2), the dataset may be combined with company-specific activity data. If the recalculated quality of the default dataset is not representative (TiR>2 or TeR>2 or GR>2) of the process, the manufacturer shall adapt the dataset to the manufacturing context (e.g. to what concerns electricity consumption) and recalculate the DQR following the rules in the EC recommendation 2021/2279 (Annex I, section 4.6.5.3). If the recalculated DQR is higher than 3, the manufacturer shall develop an EF compliant dataset following the Guide for EF compliant datasets. If a default secondary dataset is not available (e.g. innovative materials) the manufacturer may use a proxy dataset (selected from the list "CF_Annex_PV_modules-Life_cycle_inventory), if after reassessing its quality (TiR, TeR, GR) the recalculated DQR is ≤3. If not, (i.e. the recalculated DQR of the proxy dataset is higher than 3, the manufacturer shall develop an EF compliant primary dataset following the Guide for EF compliant datasets.
Situation 3: process not run by the company applying this Annex and without access to company-specific information	Use default secondary datasets and default activity data listed in the spreadsheet named "CF_Annex_PV_modules-Life_cycle_inventory"

7.3 Allocation rules

There is one instance in the crystalline silicon PV supply chain, where a multiproduct process occurs (see Table 4). Cuttings (circular segments) from monocrystalline wafer production are fed into multicrystalline silicon casting. The cradle to gate efforts and impacts of the supply of solar grade silicon used in Czochralski monocrystalline production shall be fully allocated to the monocrystalline silicon wafers. The (internal) recycling efforts and impacts required to prepare the cuttings for an input into the multicrystalline casting process shall fully be allocated to the multicrystalline silicon wafers.

Table 4 – Allocation rules for the silicon supply chain.

Process	Allocation rule	Modelling instructions
single-Si wafer, photovoltaics, at plans	Allocation according to internal book-keeping standards.	The cuttings are considered as waste and the supply chain impacts related to these cuttings shall be fully allocated to the production of monocrystalline silicon wafers.
silicon, multi-Si, casted, at plant	Allocation according to internal book-keeping standards.	The cuttings from monocrystalline wafer production are burden-free. The recycling efforts to prepare the cuttings for use in the multicrystalline silicon casting process shall be fully allocated to the multicrystalline silicon wafers.

Allocation of electricity consumption

Wherever possible, allocation should be avoided by subdivision of the process system. This means for instance, that the electricity demand of a production plant producing several products should be measured separately for each process or product. If this is not possible, the allocation rules for electricity described in Table 5 shall be followed.

Table 5 – Allocation rules for electricity.

Process	Physical relationship	Modelling instructions
PV cell production	Area (m^2 of PV cells)	The allocation of the electricity consumption of a specific production plant shall be based on the total amount of PV cells produced at this site, measured in m^2 on a yearly basis.
PV module production	Area (m^2 of PV modules)	The allocation of the electricity consumption of a specific production plant shall be based on the total amount of PV modules produced at this site, measured in m^2 on a yearly basis.
PV cell and module production in the same plant	Area (m^2 of PV cells and modules), weighted by the default specific electricity consumption per m^2	The allocation of the electricity consumption of a specific production plant shall be based on the total amount of PV cells and modules produced at this site, measured in m^2 on a yearly basis. The areas of PV cells and modules produced shall be weighted based on the specific electricity consumption per m^2 (outer dimensions including production losses). The following formulae shall be used to calculate the allocation factors (AF): $AF_{cells}=\frac{Production_{cells}[m^2]\cdot 51.8\frac{MJ}{m^2}}{Production_{cells}[m^2]\cdot 51.8\frac{MJ}{m^2}+Production_{modules}[m^2]\cdot 13.4\frac{MJ}{m^2}}$ $AF_{modules}=\frac{Production_{modules}[m^2]\cdot 13.4\frac{MJ}{m^2}}{Production_{cells}[m^2]\cdot 51.8\frac{MJ}{m^2}+Production_{modules}[m^2]\cdot 13.4\frac{MJ}{m^2}}$

If the consumed electricity comes from more than one electricity mix, each mix source shall be used in terms of its proportion in the total kWh consumed. For example, if a fraction of this total kWh consumed is coming from a specific supplier a supplier-specific electricity mix shall be used for this part; the requirements on “electricity modelling” below fully apply. See below for on-site electricity use.

A specific electricity type may be allocated to one specific product in the following conditions:

- The production (and related electricity consumption) of a product occurs in a separate site (building), the energy type physical related to this separated site may be used.
- The production (and related electricity consumption) of a product occurs in a shared space with specific energy metering or purchase records or electricity bills, the product specific information (measure, record, bill) may be used.
- All the products produced in the specific plant are supplied with a public available Product Environmental Footprint (PEF) study. The company who wants to make the claim shall make all PEF studies available. The allocation rule applied shall be clearly documented, consistently applied in all PEF studies connected to the site and verified. An example is the 100% allocation of a greener electricity mix to a specific product.

7.4 Electricity modelling

The following section introduces two types of electricity mixes: (i) the average consumption grid mix which reflects the total electricity mix over a defined grid including green claimed or tracked electricity, and (ii) the residual consumption grid mix, which characterizes the unclaimed, untracked or publicly shared electricity only.

The following electricity mix shall be used in hierarchical order:

I. The on-site generated electricity shall be used according to the conditions described below. On-site electricity shall be modelled according to the DNM.

II. Supplier-specific electricity product shall be used if:

  a. available, and
  b. the set of minimum criteria referred to in the section below to ensure the contractual instruments are reliable is met.

  The supplier-specific electricity products shall be modelled according to the DNM.

III. The supplier-specific total electricity mix shall be used if:

  a. available, and
  b. the set of minimum criteria referred to in the section below to ensure the contractual instruments are reliable is met.

  The supplier-specific electricity mix shall be modelled according to the DNM.

IV. The country-specific residual consumption grid mix shall be used. Country-specific means the country in which the life cycle stage or activity occurs. The residual consumption grid mix characterizes the unclaimed, untracked or publicly shared electricity and prevents double counting with the use of supplier-specific electricity mixes. In the case of very large countries in which several electrical grids operate, the grid-specific residual consumption grid mix shall be used if available.

V. As a last option, if no country- or grid- specific residual consumption grid mix is available, the country- or grid- specific average consumption mix shall be used.

The environmental integrity of the use of supplier-specific electricity mixes depends on ensuring that contractual instruments (for tracking) are reliable and unique. Without this, the carbon footprint lacks the accuracy and consistency needed to drive product/corporate electricity procurement decisions and accurate consideration of the supplier-specific mix by buyers of electricity. Therefore, a set of minimum criteria that relate to the integrity of the contractual instruments as reliable conveyers of environmental footprint information has been identified.

The direct use of emission values from e.g., a grid operating or certificate-issuing entity is not permitted. The electricity mix used and the corresponding emission factors shall be reported.

NOTE: certificates for the contractual instruments could include an estimation of the carbon footprint of the electricity delivered. However, there is no guarantee that such data are EF-compliant.

7.4.1 On-site electricity generation

On-site electricity generation is given if electricity is supplied to the plant from a production asset within the premises of the energy-consuming plant or if the production asset is connected to the energy-using plant by means of a direct and dedicated connection.

If the energy-consuming plant is also connected to the electricity grid and electricity is sourced from the grid in addition to on-site generation (e.g., during times of low on-site generation), all energy sourced from the grid shall be accounted for according to the rules laid out in section 7.4.

The amount of on-site generated energy that may be accounted for is the difference between the total energy demand of the production site and the amount of energy sourced from the grid.

Two situations apply to the on-site generated electricity:

1. No contractual instruments have been sold to a third party: the manufacturer shall model its own electricity mix for the amount of on-site generated electricity.
2. Contractual instruments have been sold to a third party: the manufacturer shall use 'country-specific residual consumption (grid) mix'.

If the total amount of electricity produced on-site exceeds the amount consumed on-site within the defined system boundary and is sold to, e.g., the electricity grid, this system may be seen as a multi-functional situation.

The system will provide two functions (e.g., product + electricity) and the following rules shall be followed.

3. If possible, apply subdivision. This applies both to separate electricity productions or to a common electricity production where you may allocate, based on electricity amounts, the upstream and direct emissions to your own consumption and to the share you sell to a third party (e.g., if a company uses a windmill on its production site and exports 30% of the produced electricity, emissions related to 70% of produced electricity shall be accounted for).
4. If not possible, direct substitution shall be used. The country-specific residual consumption (grid) mix shall be used as substitution. Subdivision is considered as not possible when upstream impacts or direct emissions are closely related to the product itself.

Electricity from facilities for which the attributes have been sold off (via contracts or certificates) shall be characterised as having the environmental attributes of the country residual consumption mix where the facility is located.

<u>Set of minimum criteria to ensure contractual instruments from suppliers are reliable:</u>

A supplier-specific electricity product/mix may only be used when the applicant ensures that any contractual instrument used meets the criteria specified below. A contractual instrument used for electricity modelling shall meet the following criteria:

- Criterion 1 - Convey attributes:

  Convey the energy type mix associated with the unit of electricity produced and include an explanation of the calculation method used to determine this mix and the geographical location where the energy is generated.

  The energy type mix shall be calculated based on delivered electricity, incorporating certificates sourced and retired on behalf of the relevant company (for the supplier-specific electricity product) or on behalf of the supplier's customers (for the supplier-specific electricity mix).

- Criterion 2 - Be a unique claim:
  - Be the only instruments that carry the environmental attribute claim associated with that quantity of electricity generated.
  - Be tracked and redeemed, retired, or cancelled by or on behalf of the company (e.g, by an audit of contracts, third party certification, or handled automatically through other disclosure registries, systems, or mechanisms).
  - The quantity of generated electricity associated with the instrument and its energy type mix is reported and considered for the determination of the country- or grid- specific residual grid mix, and this residual grid mix is disclosed publicly.
  - Allows for the unambiguous identification of the type, age and location and capacity of the energy generation facility to which it refers.
  - The energy generation facility to which it refers is located in a country with a tracking system in place that meets the minimum criteria for tracking systems specified in this section.
  - In case the energy generation facility to which it refers is located in a country with a multi-certificate tracking system, it is accompanied by any additional contractual instruments from the supplier necessary to show and ensure there is no double counting.
  - Be issued by a tracking system that fulfils the following criteria:
    - Is based on objective, non-discriminatory and transparent criteria for the issuing certificates;
    - Allows certificates to be valid no longer than 12 months after the production of the relevant energy unit;
    - Relies on accurate, reliable and fraud-resistant mechanisms for the issuance, transfer and cancellation of certificates;
    - Entrusts the issuance of certificates, as well as the supervision of their transfer and cancellation of certificates, to an entity or entities:
    - Is independent of energy production, trade and supply activities, and of any commercial interest of customers on whose behalf certificates are redeemed, retired, or cancelled;
    - Whose activities are governed by transparent rules and procedures laid down by law;

- Whose decisions may be challenged and reviewed in the context of proceedings before an independent judiciary.

- Criterion 3 - Be as close as possible to the period to which the contractual instrument is applied
  - Ensure that certificates are valid no longer than 12 months after the production of the relevant energy unit;
- Criterion 4 - Be sourced from the same market in which the reporting entity's electricity-consuming operations are located and to which the instrument is applied

To claim the use of renewable electricity, companies shall source renewable electricity from within the boundary of the market in which they are consuming the electricity.

The "market boundary" refers to an area in which:

- The laws and regulatory framework governing the electricity sector are consistent between the areas of production and consumption.
- There is a physical interconnection between the point of generation and the point of consumption of renewable electricity. When interconnection happens across different grids, there shall be an entity that coordinates and tracks the exchange between such grids.
- The countries' utilities/energy suppliers recognize each other's energy sourcing instruments and have a system in place to prevent double counting of claims

7.4.2. How to model 'country-specific residual grid mix, consumption mix':

The manufacturer shall use EF-compliant datasets for residual consumption grid mix .registered on the LCDN If no dataset for the specific country/grid is available, the following approach shall be used:

- Determine the country consumption mix (e.g. X% of MWh produced with hydro energy, Y% of MWh produced with coal power plant) as provided by the country-specific issuing body
- Combine them with EF-compliant datasets per energy type and country/region (e.g. LCI dataset for the production of 1MWh hydro energy in the corresponding country/region).

If no country-specific residual consumption grid mix is available, use the country-specific average consumption mix:

1. Activity data related to non-EU country consumption mix per detailed energy type shall be determined based on:
   - Domestic production mix per production technologies
   - Import quantity and from which neighbouring countries
   - Transmission losses
   - Distribution losses
   - Type of fuel supply (share of resources used, by import and / or domestic supply)).
2. Available LCI datasets per fuel technologies and generation technology. The LCI datasets available are generally specific to a country or a region in terms of:

— Fuel supply (share of resources used, by import and / or domestic supply),
— Energy carrier properties (e.g. element and energy contents)
— Technology standards of power plants regarding efficiency, firing technology, flue-gas desulphurisation, NOx removal and de-dusting.

8. Carbon footprint assessment

The carbon footprint shall be calculated according to the impact assessment method reported in Table 6.

Table 6 – method for calculating the carbon footprint

Impact category	**Indicator**	**Unit**	**LCIA method**
Climate change[4]	Radiative forcing as Global Warming Potential (GWP100)	$kgCO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)

The full list of characterization factors is available in the spreadsheet "CF_Annex_PV_modules-Life_cycle_inventory[9]", sheet GWP CF.

The results shall be reported using the unit of measure $gCO_{2\ eq}$/kWh.

The results shall be provided as "cradle-to-EU market" total CF value as well as separate values for the two life cycle stages described in section 4.

Part 2 - List of mandatory company-specific activity data

The following tables show the mandatory company-specific activity data for each of the PV technologies included in the Scope of this Annex.

<u>Cadmium-Telluride photovoltaic modules (CdTe)</u>

Photovoltaic laminate production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Solar glass	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass tempering	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass (uncoated)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg

Photovoltaic laminate production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Copper	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Cadmium sulphide	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Cadmium telluride	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Ethylene vinyl acetate (EVA)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Glass fibre reinforced plastic	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silicone	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silica sand	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tap water	Measurement (e.g. water meter or water bills); Yearly average	kg
Nitrogen	Measurement; Yearly average	kg
Nitric acid	Measurement; Yearly average	kg
Sulphuric acid	Measurement; Yearly average	kg
Hydrogen peroxide	Measurement; Yearly average	kg
Sodium hydroxide	Measurement; Yearly average	kg
Sodium chloride	Measurement; Yearly average	kg
Isopropanol	Measurement; Yearly average	kg
Corrugated board	Measurement; Yearly average	kg
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm

Photovoltaic laminate production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic laminate, CdTe, at plant	Specify the size of the PV panel	m^2
Plastic waste (incineration)	Measurement; Yearly average	kg
Municipal solid waste (incineration)	Measurement; Yearly average	kg

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Photovoltaic laminate, CdTe, at plant	Specify the mass per m^2 PV panel Calculate the share of each facility in the European supply mix in case of several production sites Yearly average	m^2
Freight train transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Share in supply logistics in a 3 years period	kgkm

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
OUTPUT		
Photovoltaic laminate, CdTe, at regional storage		m^2

Copper-Indium-Gallium-Selenide photovoltaic modules (CIS / CIGS)

Photovoltaic laminate production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Solar glass	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass tempering	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass (uncoated)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Aluminium	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Copper wire	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tin	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Zinc oxide	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Molybdenum	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Indium	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Gallium	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Selenium	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Cadmium sulphide	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg

Photovoltaic laminate production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Diode	Bill of materials of the PV panel (including manufacturing losses) Yearly average	p
Flux	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Ethylene vinyl acetate (EVA)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyvinyl butyral (PVB)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyethylene terephthalate (PET)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
High-density polyethylene (HDPE)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyphenylene sulphide (PPS)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silicone	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tap water	Measurement (e.g. water meter or water bills); Yearly average	kg
Nitrogen	Measurement; Yearly average	kg
Argon	Measurement; Yearly average	kg
Ammonia	Measurement; Yearly average	kg
Urea	Measurement; Yearly average	kg
Hydrogen peroxide	Measurement; Yearly average	kg
Sodium hydroxide	Measurement; Yearly average	kg
Hydrochloric acid	Measurement; Yearly average	kg
Sulphuric acid	Measurement; Yearly average	kg
Hydrogen sulphide	Measurement; Yearly average	kg
Butyl acrylate	Measurement; Yearly average	kg
Diborane	Measurement; Yearly average	m3
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm

Photovoltaic laminate production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic laminate, CIS, at plant	Specify the size of the PV laminate	m^2
Inert waste (landfill)	Measurement; Yearly average	kg
Inert waste (incineration)	Measurement; Yearly average	kg
Plastic waste (incineration)	Measurement; Yearly average	kg
Wastewater (wastewater treatment plant)	Measurement; Yearly average	kg

Photovoltaic panel production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Photovoltaic laminate, CIS, at plant	Specify the size of the PV panel	m^2
Thermal energy from light fuel oil	Measurement (e.g. energy meter or energy bills); Yearly average	MJ
Aluminium alloy	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Glass fibre reinforced plastic	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of	kgkm

Photovoltaic panel production		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
	waste materials to treatment site Yearly average	
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic panel, CIS, at plant	Specify the size of the PV panel	m^2
Plastic waste (incineration)	Measurement; Yearly average	kg

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Photovoltaic panel, CIS, at plant	Specify the mass per m^2 PV panel Calculate the share of each facility in the European supply mix in case of several production sites Yearly average	m^2
Freight train transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe	kgkm

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
	Use a weighted average in case of several production sites Yearly average	
Airplane transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic panel, CIS, at regional storage		m^2

Micromorphous Silicon photovoltaic modules (micro-Si)

Photovoltaic Panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Natural gas	Measurement (e.g. energy meter or energy bills); Yearly average	MJ
Aluminium alloy	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Copper wire	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silver	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Solar glass	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass tempering	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Cable	Bill of materials of the PV panel (including manufacturing losses) Yearly average	m
Ethylene vinyl acetate (EVA)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
High-density polyethylene (HDPE)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg

Photovoltaic Panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Injection moulding of HDPE	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silicone	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silane (silicon tetrahydride)	Measurement; Yearly average	kg
Deionised water	Measurement; Yearly average	kg
Decarbonised water	Measurement; Yearly average	kg
Hydrogen	Measurement; Yearly average	kg
Nitrogen	Measurement; Yearly average	kg
Oxygen	Measurement; Yearly average	kg
Carbon dioxide	Measurement; Yearly average	kg
Argon	Measurement; Yearly average	kg
Phosphane	Measurement; Yearly average	kg
Diborane	Measurement; Yearly average	kg
Trimethyl borate	Measurement; Yearly average	kg
Bisphenol A	Measurement; Yearly average	kg
Zeolite	Measurement; Yearly average	kg
Compressed air	Measurement; Yearly average	m3
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm

Photovoltaic Panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
OUTPUT		
Photovoltaic panel, micro-Si, at plant	Specify the size of the PV panel	m^2
Inert waste (incineration)	Measurement; Yearly average	kg
Plastic waste (incineration)	Measurement; Yearly average	kg
Hazardous waste (incineration)	Measurement; Yearly average	kg
Wastewater (wastewater treatment plant)	Measurement; Yearly average	kg
Nitrogen trifluoride (NF3)	Measurement; Yearly average	kg

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Photovoltaic panel, micro-Si, at plant	Specify the mass per m^2 PV panel Calculate the share of each facility in the European supply mix in case of several production sites Yearly average	m^2
Freight train transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe	kgkm

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
	Use a weighted average in case of several production sites Share in supply logistics in a 3 years period	
OUTPUT		
Photovoltaic panel, micro-Si, at regional storage		m^2

Multicrystalline (Multi-Si) Silicon PV modules

Photovoltaic cell manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Thermal energy from natural gas	Measurement (e.g. energy meter or energy bills); Yearly average	MJ
Thermal energy from light fuel oil	Measurement (e.g. energy meter or energy bills); Yearly average	MJ
Wafer, multi-Si	Bill of materials of the PV panel (including manufacturing losses) Yearly average	m^2
Metallization paste, front side	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Metallization paste, back side	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Metallization paste, back side, aluminium	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Ammonia	Measurement; Yearly average	kg
Phosphoric acid	Measurement; Yearly average	kg
Phosphoryl chloride	Measurement; Yearly average	kg
Isopropanol	Measurement; Yearly average	kg
Calcium chloride	Measurement; Yearly average	kg
Hydrochloric acid	Measurement; Yearly average	kg
Hydrogen fluoride	Measurement; Yearly average	kg

Photovoltaic cell manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Nitric acid	Measurement; Yearly average	kg
Sulphuric acid	Measurement; Yearly average	kg
Sodium hydroxide	Measurement; Yearly average	kg
Potassium hydroxide	Measurement; Yearly average	kg
Hydrogen peroxide	Measurement; Yearly average	kg
Ammonium sulphate	Measurement; Yearly average	kg
Lime	Measurement; Yearly average	kg
Tetrafluoroethane (R134a)	Measurement; Yearly average	kg
Silane (silicon tetrahydride)	Measurement; Yearly average	kg
Nitrogen	Measurement; Yearly average	kg
Oxygen	Measurement; Yearly average	kg
Tap water	Measurement (e.g. water meter or water bills); Yearly average	kg
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
Photovoltaic cell factory	Estimation Use a default demand of 4.00E-7 p if specific data are not available	P
OUTPUT		
Photovoltaic cell, multi-Si		m^2

Photovoltaic cell manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Hazardous waste (incineration)	Measurement; Yearly average	kg
Wastewater (wastewater treatment plant)	Measurement; Yearly average	kg

Photovoltaic panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Diesel	Measurement; Yearly average	kg
Photovoltaic cell, multi-Si	Bill of materials of the PV panel (including manufacturing losses) Yearly average	m^2
Aluminium alloy	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Copper wire	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tin	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Lead	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Diode	Bill of materials of the PV panel (including manufacturing losses) Yearly average	P
Solar glass	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass tempering	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Ethylene vinyl acetate (EVA)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyvinyl fluoride (PVF)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyethylene terephthalate (PET)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg

Photovoltaic panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
High-density polyethylene (HDPE)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Glass fibre reinforced plastic	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silicone	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tap water	Measurement (e.g. water meter or water bills); Yearly average	kg
Hydrogen fluoride	Measurement; Yearly average	kg
Potassium hydroxide	Measurement; Yearly average	kg
1-propanol	Measurement; Yearly average	kg
Isopropanol	Measurement; Yearly average	kg
Soap	Measurement; Yearly average	kg
Corrugated board	Measurement; Yearly average	kg
Pallet, wood	Default reuse rate: 25 trips	kg
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
Photovoltaic panel factory	Estimation Use a default demand of 4.00E-6 p if specific data are not available	P
OUTPUT		
Photovoltaic panel, multi-Si, at plant	Specify the size of the PV panel	m^2

Photovoltaic panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Plastic waste (incineration)	Measurement; Yearly average	kg
Hazardous waste (incineration)	Measurement; Yearly average	kg
Municipal solid waste (incineration)	Measurement; Yearly average	kg
Wastewater (wastewater treatment plant)	Measurement; Yearly average	kg

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Photovoltaic panel, multi-Si, at plant	Specify the mass per m^2 PV panel Calculate the share of each facility in the European supply mix in case of several production sites Yearly average	m^2
Freight train transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic panel, multi-Si, at regional storage		m^2

Monocrystalline (Mono-Si) Silicon PV modules

Photovoltaic Cell manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Thermal energy from natural gas	Measurement; Yearly average	MJ
Wafer, mono-Si	Bill of materials of the PV panel (including manufacturing losses) Yearly average	m^2
Metallization paste, front side	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Metallization paste, back side	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Metallization paste, back side, aluminium	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Ammonia	Measurement; Yearly average	kg
Phosphoryl chloride	Measurement; Yearly average	kg
Isopropanol	Measurement; Yearly average	kg
Hydrochloric acid	Measurement; Yearly average	kg
Hydrogen fluoride	Measurement; Yearly average	kg
Sodium hydroxide	Measurement; Yearly average	kg
Lime	Measurement; Yearly average	kg
Tetrafluoroethane (R134a)	Measurement; Yearly average	kg
Silane (silicon tetrahydride)	Measurement; Yearly average	kg
Nitrogen	Measurement; Yearly average	kg
Tap water	Measurement (e.g. water meter or water bills); Yearly average	kg
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of	kgkm

Photovoltaic Cell manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
	waste materials to treatment site Yearly average	
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic cell, mono-Si		m^2
Hazardous waste (incineration)	Measurement; Yearly average	kg
Wastewater (wastewater treatment plant)	Measurement; Yearly average	kg

Photovoltaic Panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Electricity	Measurement (e.g. electricity meter or electricity bills); Yearly average	MJ
Diesel	Measurement; Yearly average	kg
Photovoltaic cell, mono-Si	Bill of materials of the PV panel (including manufacturing losses) Yearly average	m^2
Aluminium alloy	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Copper wire	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tin	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Lead	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Diode	Bill of materials of the PV panel (including manufacturing losses) Yearly average	p

Photovoltaic Panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
Solar glass	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Flat glass tempering	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Ethylene vinyl acetate (EVA)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyvinyl fluoride (PVF)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Polyethylene terephthalate (PET)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
High-density polyethylene (HDPE)	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Silicone	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Glass fibre reinforced plastic	Bill of materials of the PV panel (including manufacturing losses) Yearly average	kg
Tap water	Measurement (e.g. water meter or water bills); Yearly average	kg
Hydrogen fluoride	Measurement; Yearly average	kg
Potassium hydroxide	Measurement; Yearly average	kg
1-propanol	Measurement; Yearly average	kg
Isopropanol	Measurement; Yearly average	kg
Soap	Measurement; Yearly average	kg
Corrugated board	Measurement; Yearly average	kg
Pallet, wood	Estimation Default reuse rate: 25 trips	kg
Freight train transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of	kgkm

Photovoltaic Panel manufacturing		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
	waste materials to treatment site Yearly average	
Airplane transport	Calculation (mass x distance) Transport of all input materials to the production site and transport of waste materials to treatment site Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic panel, mono-Si, at plant	Specify the size of the PV panel	m^2
Plastic waste (incineration)	Measurement; Yearly average	kg
Hazardous waste (incineration)	Measurement; Yearly average	kg
Municipal solid waste (incineration)	Measurement; Yearly average	kg
Wastewater (wastewater treatment plant)	Measurement; Yearly average	kg

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
INPUT		
Photovoltaic panel, mono-Si, at plant	Specify the mass per m^2 PV panel Calculate the share of each facility in the European supply mix in case of several production sites Yearly average	m^2
Freight train transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Lorry transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Yearly average	kgkm
Ship transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in	kgkm

Distribution		
Activity data to be collected	**Specific requirements (e.g. frequency, measurement standard, etc)**	**Unit of measure**
	Europe Use a weighted average in case of several production sites Yearly average	
Airplane transport	Calculation (mass x distance) Transport of PV panels from the production site to a regional storage in Europe Use a weighted average in case of several production sites Share in supply logistics in a 3 years period	kgkm
OUTPUT		
Photovoltaic panel, mono-Si, at regional storage		m^2

[1] https://ec.europa.eu/environment/publications/recommendation-use-environmental-footprint-methods_

[2] https://ec.europa.eu/docsroom/documents/46532 -

[3] https://eplca.jrc.ec.europa.eu/permalink/Guide_EF_DATA.pdf

[4] The contribution of the sub-categories “Climate change – biogenic” and “Climate change – land use and land transformation” to the total climate change impacts is lower than 5 %. The environmental impacts shall therefore only be calculated for the category “Climate change” but not for the sub-categories “Climate change – biogenic” and “Climate change – land use and land transformation”.

Annex B – Energy efficiency index and energy yield over the lifetime

Specifically, as in the Annex III of the policy proposal, the EEI_M is expressed in kWh/m^2 and calculated as follows for each of the three European reference climatic conditions: 'temperate coastal', 'temperate continental' and 'subtropical arid':

$$EEI_{M\_c} = {EY_{M(DC)\,Y1\,c}} \Big/ {A_M}$$

where

EEI_{M_c} is the energy efficiency index for a module placed in a European reference climate *c*, expressed in kWh/m^2.

$EY_{M(DC)Y1c}$ is the DC energy yield from a photovoltaic module over one year under the climatic conditions in the reference climate *c*, assuming no degradation, expressed in kWh.

A_M is the area of the photovoltaic module, expressed in m^2.

The photovoltaic module is assumed to be ground-mounted on a rack that is fixed open and facing the equator with an angle of inclination of 20º. Degradation and other losses due to soiling or shadows from surrounding obstacles are not considered. Ground albedo is not considered for bifacial PV modules.

For photovoltaic modules with integrated micro-inverters, the EEI shall be determined without the micro-inverter.

For monofacial PV modules, the yearly DC energy yield ($EY_{M(DC)\_Y1}$,kWh) shall be calculated using the input data:

- matrix of Pmax versus irradiance (at AM1.5) and versus module temperature, which may be interpolated or extrapolated to obtain the instantaneous power at a given irradiance and module temperature. For linear modules, the Pmax dependence on irradiance and on temperature are independent;
- thermal coefficients u0 and u1 describing the module operating temperature as a function of irradiance, ambient temperature and wind speed, which are used to calculate the instantaneous module temperature;
- the angle of incidence response ar, used to calculate the effective light transmission into the module at different incident angles;
- spectral responsivity, used to calculate spectral mismatch and hence to correct reference spectral conditions;
- standard reference climatic profiles for the reference climatic conditions relevant to Europe, defined as 'subtropical arid', 'temperate continental' and 'temperate coastal'.

P_{max} is the DC power output of a module measured at specific temperatures and irradiances according to IEC 61853-1.

The method does not include degradation or losses other than those due to the effect of the angle of incidence, spectral response or module efficiency dependence on irradiance and temperature.

The DC energy yield of the module over its first year of installation $EY_{M(DC)Y1}$ is calculated as follows:

$$EY_{M(DC)\,Y1} = \sum_{j=1}^{j=8760} EY_{M,j}$$

where

j ranges from 1 to 8 760 in the reference period (one year).

$EY_{M,j}$ is the energy output of the module in the period j (1 hour), expressed in kWh, and is calculated as:

$$EY_{M,j} = P_{M,j}\left(G_{corr,j}, T_{M,j}\right) \cdot 1\ hour$$

$P_{M,j}$ is the module power output for the j^{th} hour (W)

$G_{corr,j}$ is the corrected global in-plane irradiance for the j^{th} hour (W/m^2)

$T_{M,j}$ is the module temperature for the j^{th} hour (°C)

The $EY_{M(DC)Y1}$ is one of the outputs along with the CSER (Climate Specific Energy Rating)

They are related as follows:

$$CSER = \frac{EY_{M(DC)Y1} \cdot G_{ref}}{P_{max,STC} \cdot H_p}$$

The DC energy yield of the module over is calculated as follows:

$$EY_{M(DC)\_Y1} = \frac{CSER \cdot P_{max,STC} \cdot H_p}{G_{ref}}$$

where

$P_{max,STC}$ is the DC power output of a module under STC or STC (air mass 1.5 spectrum, 1000 W/m^2, 25°C) measured according to IEC 61853-1.

G_{ref} is 1 000 W/m^2, the irradiance used to measure the $P_{max,STC}$, which is the maximum power output of the PV module under STC conditions.

H_p is the total hourly global in-plane irradiance, expressed in kWh/m^2 for the reference climatic period (1 year).

from the yearly DC energy yield ($EY_{M(DC)\_Y1}$, kWh), by considering 30 years of service life (T_{LT}) and factoring in the degradation rate ($\tau_{deg\ M}$, %/year).

Where

- EYM(DC)_Y1 is the DC energy yield delivered by one PV module over the first year of installation under the applicable reference climate conditions, expressed in kWh.
- TLT is lifetime of the PV module, which is assumed as 30 years.
- τdeg_M is the PV module lifetime performance degradation rate, expressed here in decimal format. A degradation rate of 1% should be applied here as 0.01.

The following prescribed values have to be applied for the corresponding technology:

- Degradation rate for all crystalline silicon wafer technologies, including those with heterojunction passivation layers: 0.5 % per year.
- Degradation rate for thin film and multijunction photovoltaic modules using a crystalline silicon absorber plus any thin film absorber:

For monofacial and bifacial PV modules, the DC total energy yield over the service life ($EY_{M(DC)\,LT}$), shall be calculated from the yearly DC energy yield ($EY_{M(DC)Y1}$, kWh), multiplied by the years of service of service life (T_{LT}) and factoring in the degradation rate (τ_{degM}, %/year).

$$EY_{M(DC)\,LT} = EY_{M(DC)\,Y1} \cdot T_{LT} \cdot \left(1 - \tau_{\deg\,M} \cdot \left({}^{T_{LT}}/_{2}\right)\right)$$

$$EY_{MB(DC)\,LT} = EY_{MB(DC)\,Y1} \cdot T_{LT} \cdot \left(1 - \tau_{\deg\,M} \cdot \left({}^{T_{LT}}/_{2}\right)\right)$$

where

$EY_{M(DC)Y1}$ is the DC energy yield delivered by the monofacial PV module over the first year of installation under the applicable reference climate conditions, expressed in kWh.

$EY_{MB(DC)Y1}$ is the DC energy yield delivered by the bifacial PV module over the first year of installation under the applicable reference climate conditions, expressed in kWh.

T_{LT} is lifetime of the PV module. The lifetime of PV modules is determined by the number of years, indicated in the guarantee of the PV module, for which the guaranteed degradation rate of the photovoltaic module's power output is not higher than the degradation rate given set out in Annex III.1.3, with a maximum limit of 30 years. If the PV module is sold without guarantee, or with a guaranteed degradation rate of the power output higher than the degradation rate given set out in Annex III.1.3, the assumed lifetime of the module will be 10 years.

τ_{degM} is the PV module lifetime performance degradation rate, expressed here in decimal format. A degradation rate of 1% shall be applied here as 0.01.

Annex C – Preliminary screening of additional potential datasets needed for key and innovative PV technologies

Name of materials	PV technology	Reference	Link	Amount of material
Phosphorus Oxychloride	PERC	IEA PVPS TASK 12, 2024	Microsoft Word - IEA-PVPS-LCA PERC technology v21.docx	0.000181 kg per 1 m^2 of PV
Trimethylaluminum (TMA)	PERC	IEA PVPS TASK 12, 2024	Microsoft Word - IEA-PVPS-LCA PERC technology v21.docx	2.42E-04 kg per 1 m^2 of PV
Boron trifluoride	TOPCON	Song et al., 2024	Environmental and economic Assessment of China's electricity sector for Carbon Neutrality (els-cdn.com)	0.0218 kg per 1 m2 of PV
Diborane	TOPCON	Song et al., 2024	Environmental and economic Assessment of China's electricity sector for Carbon Neutrality (els-cdn.com)	n.a.
Phospine	TOPCON	Song et al., 2024	Environmental and economic Assessment of China's electricity sector for Carbon Neutrality (els-cdn.com)	n.a.
Iodine	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.933 per 1 kg PbI2
lead iodide	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.00138 kg per 1 m^2 of PV

Name of materials	PV technology	Reference	Link	Amount of material
Hydrogen sulfide	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.139 kg per 1 kg CH3NH3I
Methylammonium iodide	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	1.43E-04 kg per 1 m^2 of PV
Methylamine	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.581 kg per 1kg of Methylammonium iodide
Ethanol	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	7.31 kg per 1 kg CH3NH3I
Diethyl ether	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	20.8 kg per 1 kg CH3NH3I

Name of materials	PV technology	Reference	Link	Amount of material
Ammonium thiocyanate	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.0015 kg per 1 m^2 of PV Panel
Monochlorobenzene	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.0004 per 1 m^2 of PV Panel
N,N-Dimethylformamide	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.00283 kg per 1 m^2 of PV panel
Toluene	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	122.88 kg per 1 kg PCBM
PCBM	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	1.54E-04 kg per 1 m^2 of PV panel

Name of materials	**PV technology**	**Reference**	**Link**	**Amount of material**
Methyl cyclopentane	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.85 kg per 1 kg PCBM
Sodium hypochlorite	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.344 kg per 1 kg PCBM
Sulfur trioxide	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.479 per 1 kg PCBM
Nickel Oxide	Si-perovskite tandem and single junction perovskite	Leccisi et al., 2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV - Leccisi - 2021 - Progress in Photovoltaics: Research and Applications - Wiley Online Library	0.0004 kg per 1 m^2 of PV panel
zinc coating, pieces	CdTe	Fthenakis, 2024	Updated sustainability status of cadmium telluride thin-film photovoltaic systems and projections (wiley.com)	0.133 m^2 per 1 m^2 of PV panel

Details of the Silicon recycling process	Reference	Link	Reference scale
Innovative process for PV recycling, pyrometallurgic and idrometallurgic processes	Latunussa et al., 2016 Ardente et al., 2019	https://www.sciencedirect.com/science/article/pii/S0927024816001227; https://www.sciencedirect.com/science/article/pii/S0956053X19302909	Lab scale
Innovative process allowing to separate the materials and remelt the high purity silicon contained in the kerf losses	Rosi - Circular Economy for the PV industry	https://www.rosi-solar.com/	Pilot - Industrial scale
Technical feasibility laboratory test of thermal treatment	Corcelli et al., 2017	https://www.sciencedirect.com/science/article/pii/S0959652617309563	Lab scale
Review of challenge and opportunities of silicon recycling processes and other materials	Tao et al., 2020	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3316	Lab scale
The FORESi project aims at FOstering a Recycled European Silicon supply through an industrial demonstration of a cradle-to-cradle Silicon value chain	FORESi, FOstering a Recycled European Silicon supply	https://sipow.no/foresi.html	Industrial scale
The objective of the SIKELOR project was to develop an innovative electromagnetic technology for recycling silicon kerf loss which arises from slicing of silicon ingots into thin wafers. The technology proposed for reclaiming silicon from kerf loss combines methods for densification, purification, and casting of ingots.	SIKELOR (Silicon kerf loss recycling)	https://cordis.europa.eu/project/id/603718/reporting	Lab scale
Review of the advancements in silicon recovery research and development over the last decade with key concepts, technologies, and challenges associated	Yu et al., 2023	https://www.sciencedirect.com/science/article/pii/S2452223623001189	Lab scale

Annex D – Details on carbon footprint results according to the scenarios under analysis

In the study carried out on multi-silicon photovoltaic systems, we scrutinized a total of 15 different scenarios. The results, as depicted in the following Table, range from the least desirable scenario, which has a carbon footprint of 5.01 E-02 kg$CO_{2\ eq.}$ per kWh, to the most desirable scenario, which shows a substantially reduced emission of 1.78 E-02 kg$CO_{2\ eq}$ per kWh. This indicates a nearly threefold difference between the highest and lowest emission scenarios.

In the context of photovoltaic production in country 4, using 0.646 kg of Silicon per square meter, a reduction in the product's lifespan from 30 years to 20 years results in a 1.5-fold increase in the carbon footprint. This means it increases from 3.34E-02 kg$CO_{2\ eq}$ to 5.01 E-2 kg$CO_{2\ eq.}$ Furthermore, when the quantity of Silicon per square meter is increased from 0.646 kg to 1.02 kg, the carbon footprint escalates by 1.2 times, reaching 4.14 E-2 kg$CO_{2\ eq.}$

	Photovoltaic scenario	**Description**	**Silicon [kg} per m²**	**Climate Change [kg $_{CO2\ eq.}$ per kwh]**
1m	country1: Multi-Si (country1, 646g Si)	All manufacturing processes are located in country1, with 30 years operation.	0.646	1.78E-02
2m	country2:Multi-Si (country1, 646g Si)	All manufacturing processes are located in country2, with 30 years operation.	0.646	2.63E-02
3m	country3: Multi-Si (country3, 646g Si 25%PV all)	All manufacturing processes are located in country3, with 25% electricity from PV in production, with 30 years operation.	0.646	2.65E-02
4m	country4: Multi-Si (CN, Si646g)	All manufacturing processes are located in country4, with lower electricity consumed in production, with 30 years operation.	0.646	2.74E-02
5m	country4: Multi-Si (country4, Si646g,25%PV all processes)	All manufacturing processes are located in country4, with 25% electricity from PV in production, with 30 years operation.	0.646	2.92E-02
6m	country3: Multi-Si (country3, 646g Si) except MG)	All manufacturing processes are located in country3, with the exception of MG in country2, with 30 years operation.	0.646	2.93E-02
7m	country4: Multi-Si (country4, Si646g, 25%PV for panel and cell)	All manufacturing processes are located in country4, with 25% electricity from PV in panel an cell production, with 30 years operation.	0.646	3.27E-02
8m	country4: Multi-Si (country4, Si646g, R1PEFCR)	All manufacturing processes are located in country4 with 30 years operation, with recycled aluminium 77% as input	0.646	3.29E-02
9m	country4: Multi-Si (country4, Si646g)	All manufacturing processes are located in country4 with only 30 years operation	0.646	3.34E-02

	Photovoltaic scenario	Description	Silicon [kg} per m²	Climate Change [kg $_{CO2\ eq.}$ per kwh]
10 m	country4: Multi-Si (country4, Si833g)	All manufacturing processes are located in country4 with only 30 years operation	0.833	3.74E-02
11 m	country4: Multi-Si (country4, Si646g, 25Yrs)	All manufacturing processes are located in country4 with only 25 years operation	0.646	4.01E-02
12 m	country4: Multi-Si (country4, Si1020g)	All manufacturing processes are located in country4 with only 30 years operation	1.020	4.14E-02
13 m	country4: Multi-Si (country4, Si646g, 20Yrs)	All manufacturing processes are located in country4 with only 20 years operation	0.646	5.01E-02
14 m	country1: Multi-Si (country1, 646g Si)	All manufacturing processes are located in country1, with the exception of the casting and wafer procedures, which are based in country2 with 30 years operation.	0.646	2.06E-02
15 m	country4, Si 646g with default countries mix silicon production	All manufacturing processes are located in country4 except silicon production that some silicon produce in other countries e.g. Europe with only 30 years operation	0.646	3.16E-02

* Per kWh of the total DC electric energy generated over a photovoltaic module's service life

The following presents the carbon footprint of a multi-silicon photovoltaic panel at each stage of its life cycle for three different scenarios. The stages of transportation to regional storage and the end of life of the PV module yield the same results across all three scenarios. This is attributed to the assumption that these stages occur in Europe, and the same data sets are utilized to analyse the carbon footprint. Photovoltaics manufactured in country4 with a default silicon mix have a slightly lower impact than those with an entirely country4 supply chain. This can be explained by the fact that some of the silicon is produced in countries with a lower carbon footprint from electricity.

Example of Carbon footprint of mono silicon photovoltaic panel per life cycle stage: silicon content 646 g per m²

No.	Scenario	Total	raw material and production	transportation to regional storage	End of Life of PV Module - Poly
2m	Multi-Si, country2, Si646g, country2 supply Chain	2.63E-02	2.85E-02	5.18E-04	-2.72E-03
9m	Multi-Si, country4, Si646g, country4 supplyChain	3.34E-02	3.56E-02	5.18E-04	-2.72E-03
15 m	Multi-Si, country4, Si 646g with default countries mix silicon production	3.16E-02	3.38E-02	5.18E-04	-2.72E-03

The following Table presents the carbon footprint of CdTe PV photovoltaic panels. It is assumed that these systems generate 4,820.0 kWh*m² of electricity over a 30-year lifespan, with the bill of materials conforming to the EC PV PEFCR. This assumption reflects the average performance of CdTe PV panels in the EU market during the development of the PEFCR. The stages of the life cycle that contribute most significantly to the carbon footprint are the acquisition of raw materials, pre-processing, and module manufacturing, with electricity and glass being the primary contributors. The potential for material recycling offers a modest credit of 3%, as the major contributors to the carbon footprint are electricity and glass. It is, at present, only 9% of glass can be recycled.

Carbon footprint of Cadmium-Telluride photovoltaic panels

Overall, Carbon footprint [$kg_{CO2\ eq}$ per kWh]	Raw material acquisition, pre-processing, and module manufacturing [kg_{CO2eq} per kWh]	Distribution [kg_{CO2eq} per kWh]	EoL [kg_{CO2eq} per kWh]
1.18E-02	1.15E-02	6.87E-04	-3.58E-04

* Per kWh of the total DC electric energy generated over a photovoltaic module's service life

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