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Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive

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ABSTRACT

As announced in the European Green Deal, it is critical to decarbonise the European Union energy system in order to reach climate objectives by 2030 and 2050. According to the REPowerEU plan, photovoltaics (PV) is expected to play a major role in this. Therefore, it is crucial to ensure that newly installed PV modules in the EU are affordable and competitive on the one hand and environmentally friendly on the other. Bearing in mind that the environmental hotspots for PV modules mainly occur during the manufacturing phase, the aim of the paper is to develop a fully-fledged and adapted methodology for calculating the carbon footprint of PV modules, with particular regard to the manufacturing and shipping phases, following a cradle-to-gate approach based on the Product Environmental Footprint Category Rules for PV modules. The implications of requirements for the carbon footprint of PV modules, under the existing legal framework of the Ecodesign Directive, are also discussed.

1. Introduction

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

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 on Russian fossil fuels. By the end of 2020, the EU reached approximately 136 GW of solar PV installed generation capacity, having added more than 18 GW in 2020. This delivered around 5 % of total EU electricity generation. The REPowerEU strategy aims to bring online over 320 GW of solar PV by 2025 (more than double compared to 2020) and almost 600 GW by 2030. To address the challenge of climate change, societies and economies will need to transform, phasing out unsustainable practices in production and consumption. Despite PV being considered a green or low-carbon technology, the manufacture is an energy-intensive process and it has obvious impacts on land due to the large space required. PV cannot be designed without taking environmental criteria into account, just because it produces green energy. In order to maximise emissions reductions, not only must PV modules and inverters have a high conversion efficiency, but materials should have been sourced – and products manufactured, used and disposed of – in an environmentally sensitive manner.

If solar energy is going to play a significant role among the energy sources of the future, this is the right moment to reflect and to steer this production towards truly sustainable technology. To reduce the carbon footprint of the PV sector, it is therefore of paramount importance to identify, quantify and assess the material and energy flows of PV (waste).

Globally, many countries have declared national decarbonisation goals. For example, the United States aspires to decarbonise its electricity grid by 2035 (The White House, 2021). France and South Korea have already worked out 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 Economy and Finance, 2021).

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To improve the sustainability of PV, not only voluntary goals, but compulsory regulations are needed that could set limits or targets for the next generations of PV modules to come on the market. It will then be necessary to set rules for clear quantification of the emissions.

Quantification of the carbon footprint of a product (CFP) is one of the first steps to complete in order to maximise reduction in GHG emissions. A number of companies in the PV sector are currently aiming to significantly reduce GHG emissions along their value chain and are closely aligning with the United Nations Sustainable Development Goals (SDGs) (Energy Global, 2022).

The units of CFP are ‘gCO_2eq/kWh’, i.e. grams of carbon dioxide equivalent per kilowatt-hour of electricity generated. Carbon dioxide is the most significant GHG and is produced, for example, when fossil fuels are burned. 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 from ‘low-carbon’ generation technologies do not arise directly from the operation of the generators. Their carbon footprints are therefore dominated by indirect emissions, such as those produced during construction and the production of fuels (where applicable). For solar energy, the location-specific energy resource also has an important influence on the footprint. This is because higher electricity outputs cause lower footprints, as total emissions are spread over a greater amount of electricity.

Ecodesign (European Union, 2009) and Energy Labelling (European Union, 2017) are EU market regulations that make it easier and less costly for businesses, citizens and governments to contribute to the clean energy transition and deliver on the EU energy efficiency and 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 promote supply and demand for more sustainable products, while significantly reducing energy user expenditure: estimates indicate that savings in 2021 exceeded EUR 120 billion and could reach double this in 2022. Furthermore, these policies will help to achieve the EU target of reducing GHG emissions 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), which identified PV modules and inverters as one of the non-regulated product groups with the largest potential for environmental savings and indicated the need for more detailed investigation into possible environmental improvements. Following the inclusion of PV products in this Ecodesign Working Plan, the Joint Research Centre of the European Commission conducted a study of the environmental impact of PV products (Dodd et al., 2020).

The policy relevance at EU level of the potential carbon footprint requirements for PV modules has been also announced in the recently published EU Solar Energy Strategy (European Commission, 2022a): ‘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’.

This paper elaborates on the findings of the study (Dodd et al., 2020), focusing in particular on analysing potential requirements for the carbon footprint of PV modules.

The aim of this paper is to contribute to the knowledge base by developing a methodology for quantifying the carbon footprint of PV modules, which can be applied in regulatory contexts.

This paper is organised into five sections. Starting with an analysis of existing studies and legislation affecting the carbon footprint of products (Section 2), it develops a ready-to-use methodology to be applied in the specific case of PV modules (Section 3). Section 4 presents the results and Section 5 outlines potential policy approaches to regulate the carbon footprint of PV modules, in particular through requirements within the legal framework of the EU Ecodesign Directive. Finally, Section 6 presents the conclusions of this paper.

2. BACKGROUND: Literature review of existing studies and legislation

2.1. Preparatory work on PV modules

The Commission recently carried out a preparatory study (Dodd et al., 2020) to analyse technical, environmental and economic aspects of PV modules, inverters and systems.

One of the main indications provided by the preparatory study is that the carbon footprint of the manufacturing phase of PV modules is one of the most salient aspects of this product group. This is also intuitive: given that PV modules are energy-generating products, the use phase – an important contributor to the environmental impacts of products such as refrigerators (European Union, 2016) or washing machines – here contributes negligibly to the (negative) environmental impacts, while also offset by the electrical energy produced by the module. A similar indication can be found in the Product Environmental Footprint Category Rules (PEFCRs) used for PV power systems (PEFCR PV Technical Secretariat, 2019) developed under the Product Environmental Footprint (PEF) pilot phase. This established the methodology for calculating environmental impacts for the main PV technologies and for a representative (virtual) product. The climate change impact category is expressed in $kgCO_2eq/kWh$. When considering the weighting of the environmental footprint for the raw material acquisition and pre-processing phase (including manufacture of the PV modules), this study also discusses how the ‘climate change’ impact (i.e. the one measured with the carbon footprint) is one of the most significant categories for the manufacturing phase. The composition of carbon footprints and their sensitivity to underlying assumptions varies among technologies. However, it is clear that for all PV modules, the carbon footprint is largely determined at the design stage (Mueller et al., 2021). Firstly, the manufacturer’s choice of materials and components – in terms of their volume, origin and quality – largely decides the overall carbon intensity of the module. Secondly, the inverse ratio between the output of the module (also largely dependent on its design) and the carbon intensity of these material inputs then determines the carbon footprint. In addition to these design factors, the carbon intensity of the energy mix used during the manufacturing process also influences the carbon footprint (Leccisi et al., 2016). The preparatory study (Dodd et al., 2020) therefore showed that there is significant potential for improvement through such design choices.

A widely used tool for industries to report carbon emissions and environmental impact is the International EPD (Environmental Product Declaration) System. As an example, the Norwegian EPD Foundation and EPD Italy have Product Category Rules to conduct a life cycle assessment (LCA) for PV modules, which is coded EN15804:2012+A2:2019. These are valid for 6 years. The allocation is made in accordance with the provisions of ISO 14025, which means for example that incoming energy and water, and waste production in-house, is allocated equally among all products through mass allocation. Following this standard, a number of companies have recently issued Environmental Product Declarations. The Global Electronics Council has also developed EPEAT (Electronic Product Environmental Assessment Tool), which is a ranking system that helps purchasers in the public and private sectors to evaluate, compare and select products within the IT sector based on their environmental attributes. EPEAT evaluates products according to seven environmental performance criteria: materials selection, supply chain GHG emissions reduction, design for circularity and product longevity, energy conservation, end-of-life management and corporate responsibility. In following these performance objectives, organisations can meet one of three performance levels (bronze, silver or gold) depending on the percentage of criteria conformity. A new criterion, 'ultra low-carbon solar', is under development.

2.2. Carbon footprint product (CFP) requirements in the European Union and worldwide

In specific cases, CFP requirements are set by national authorities. There are currently two countries that have such criteria in their public tenders: France and South Korea.

France has had specific carbon-footprint criteria in place for public tendering for PV modules since January 2019. Revised specifications and a new scope for public tenders have been issued by the CRE (Commission de régulation de l'énergie, 2021). These criteria aim to select the most sustainable modules on the market by setting a maximum threshold for the carbon footprint. Up to November 2020, the threshold was 1 150 $kgCO_2eq/kW$, but for the period 2021–2026 this value has been revised to 550 $kgCO_2eq/kW$ for PV in the ground and in buildings, and 500 $kgCO_2eq/kW$ for innovative PV technologies. The methodological approach is to quantify and verify the total amount of GHG per unit output (1 kW) emitted by the entire process of manufacturing solar modules (polysilicon, ingot, wafer, cell, module and frame), for products from domestic and foreign PV module manufacturers.

The South Korean Ministry of Trade, Industry and Energy has developed a CFP system with the objective of contributing to global reduction in GHG emissions but also further strengthening the competitiveness of the domestic solar energy industry. This system will be applied to the Renewable Portfolio Standard (RPS)[1] and public projects.

The calculation of the CPF in South Korea will be used to classify solar modules into three grades, depending on their carbon emissions (Ultra Low-Carbon Solar Alliance, 2021). The score will be directly linked to incentives in the RPS selection bidding market, and government projects (to be implemented in the near future). The rating I corresponds to a CFP below or equal to 670 $kgCO_2eq/kW$, being therefore slightly less stringent than the French rating.

These regulations, largely inspired by the French public tender rules, require module manufacturers to submit an application to the government for verification and approval of the calculated carbon footprint. This calculation can be done by two methods: Method by Standard Emission Factor or Methods by Life Cycle Assessment (LCA).Evaluation of the Standard Emission Factor of PV modules.

The South Korean CFP default calculation is based on official default values per component and country (as per French tenders) without breakages and losses (as per French methodology CRE3), as shown in Fig. 1.

3. Methodology

In the carbon accounting field, there is a plethora of methods, guidance documents and standards that can be applied to calculate the carbon footprint. These are listed in Table 2.

The carbon footprint indicator refers to the quantification of GHG emissions caused during the processes involved in manufacturing or producing goods or services. The carbon footprint of an individual, organisation or nation can be measured by undertaking a GHG emissions assessment, a life cycle assessment (LCA) or other calculations referred to as carbon accounting.

The carbon footprint indicator known as global warming potential (GWP) has been developed by the Intergovernmental Panel on Climate Change (IPCC, 2021). It refers to time horizons of 100 years for a number of known greenhouse gases, such as CO_2, CH_4, chlorofluorocarbons (CFCs), N_2O, hydrofluorocarbons (HFCs) and other halogenated hydrocarbons. The GWP formula can be expressed as:

$$GWP\ [kgCO_2eq] = \sum GWP_i x\ m_i$$

where m_i corresponds to gaseous emissions of each compound i expressed as kg per functional unit. Table 1 shows the existing standards, documents and guidelines that can be used for calculating the carbon footprint.

In particular, the International Organization for Standardization has set a standard, ISO 14040:2006, that provides a framework for conducting an LCA study (International Organization for Standardization, 2006). The ISO 14060 family of standards provides further tools for quantifying, monitoring, reporting and validating or verifying GHG emissions. In particular, ISO 14067:2018 lists the requirements and guidelines for quantifying the carbon footprint of products (International Organization for Standardization, 2018).

Another method, established by the Greenhouse Gas Protocol, consists of a set of standards for tracking GHG emissions across scope 1, 2 and 3 emissions within the value chain.[2] GHG Protocol have also developed a suite of calculation tools to assist companies in calculating their GHG emissions and measuring the benefits of climate change mitigation projects (World Resources Institute and World Business Council for Sustainable Development, 2011).

Among the methods and standards discussed above, there is a need to harmonise carbon footprint calculation specifically for PV products, at EU level. To address this need, the PEFCR for PV modules represents a useful tool for guiding the development of environmental footprint studies, on the basis of international agreements. It identifies foreground unit processes which require product-specific data, versus background processes which are based on pre-specified data (Wade et al., 2017).

The methodology presented in those category rules is therefore useful for defining harmonised calculation rules for carbon footprints in a regulatory context. It is focused on products that are within the scope of the Ecodesign Directive (European Union, 2009), i.e. energy-related products. This method is applied to the specific case of PV modules, with the objective of being conceptually applicable to different technologies and product groups.

As shown in Fig. 2, the first step (step 1) is a hotspot analysis devoted to identifying the areas where environmental impacts are most significant. In the current example we focus on the carbon footprint, but the same approach may be followed for other impact categories of environmental footprint, such as water use, resource (fossil and mineral) use, etc. Considering the most significant impact categories throughout the life cycle of the product, and the processes that contribute most, helps to identify the hotspots.

Identification of the hotspots (step 2) focuses attention on the areas where policymakers may concentrate regulatory efforts. For instance, in the case of the EU Ecodesign policy, preparatory studies are carried out, with a techno-economic and environmental assessment at product-specific level, to provide policymakers with the evidence basis to assess whether to implement policy instruments.

It is important to define the technologies that are most relevant for

[1] The RPS programme requires the 13 largest power companies (with installed power capacity higher than 500 MW) to steadily increase their renewable energy mix in total power generation over the period 2012–2024. Source: IEA/IRENA Renewable Policies Database.

[2] The GHG Protocol Corporate Standard classifies a company's GHG emissions into three 'scopes'. **Scope 1** emissions are direct emissions from sources that are controlled or owned by an organisation (e.g. emissions associated with fuel combustion in boilers, furnaces or vehicles). **Scope 2** emissions are indirect emissions associated with the purchase of electricity, steam, heat or cooling. **Scope 3** emissions are all indirect emissions (not included in scope 2) that are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials, transportation of purchased fuels, and use of products and services.

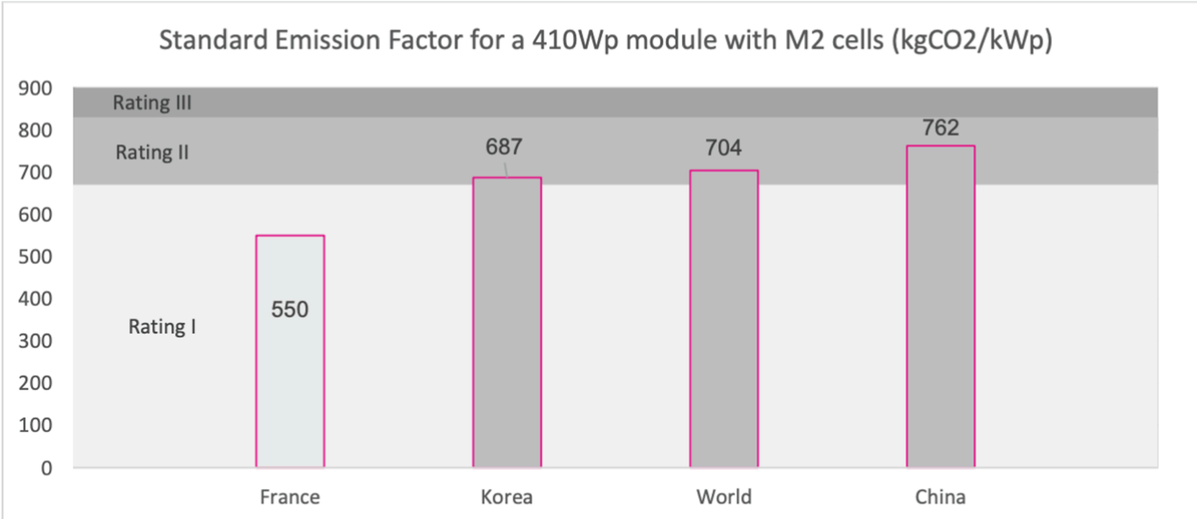

Fig. 1. Rating of modules in the South Korean standard according to the standard emissions model. Source: Ultra Low-Carbon Solar Alliance, 2021.There is also a list of default values for calculating the Standard Emission Factor of PV modules, depending on the origin of the raw material (see Table S1, Annex).In light of the existing scientific indications, policy regulations and industry certifications analysed above, it seems relevant to further investigate the carbon footprint of the PV manufacturing phase because it is among the most salient aspects of this product group. The following section discusses the methodological aspects that can be applied to calculate the carbon footprint.

the market being assessed and that are covered by the analysis. The hotspot analysis aims to identify the processes and stages that contribute most to the overall impacts in the life cycle.

As discussed in Section 2, the PEFCRs are needed to provide guidance on carrying out a life cycle assessment based on the Environmental Footprint method (European Commission, 2021). PEFCRs reflect international agreements and technical/scientific progress in the area of life cycle assessment. Specifically, the PEFCRs can cover 16 environmental impact categories, including their normalisation and weighting, with the aim of identifying the most significant ones.

These rules help to direct focus to those aspects and parameters that matter most, and hence contribute to increased relevance, reproducibility and consistency of the results. Finally, PEFCRs are a useful tool for providing consistent comparisons between different PV manufacturing technologies and various products.

As per step 3 of Fig. 2, the harmonised calculation rules build on the latest version of the PEF method and PEFCR. The list and coverage of existing PEFCRs is being expanded to cover different product groups[3].

The next step (step 3a) of the analysis is to check whether a PEFCR is already available for the product group in scope and whether it can be adapted for the purpose of setting ecodesign requirements.

If a PEFCR is not available, it must be developed for the product in scope (step 3b), since PEFCR is used as a basis for defining harmonised calculation rules. The process of developing category and sector rules is articulated and involves several steps which are described in detailed guidance (European Commission, 2017).

If a PEFCR is available (step 3a), the harmonised calculation rules are developed following the same standardised structure as the PEFCR. Since the PEFCR could have a larger scope, including a larger system, it should be adapted to suit the scope of the analysis (step 4).

Each section of the PEFCR needs to be checked and modified according to the chosen policy in developing ecodesign requirements. The main aspects (not exhaustive) to be considered in adapting the PEFCR for inclusion in the harmonised calculation rules are shown in Table 2.

At step 5, the harmonised calculation rules are defined and can be used to calculate the results. A sensitivity analysis (step 6) needs to be performed to evaluate the results under various scenarios. Interpretation of the results (step 7) is fundamental for identifying the quantitative values that may result in a threshold for acceptance of a product. Throughout the process, stakeholders must be involved to ensure a more comprehensive view (step 8). Finally (step 9), the proposed methodology could be applied to set market entry requirements.

The methodology described above has been applied to a set of representative PV modules for potential ecodesign requirements. It represents a quantitative example of the concept defined in the flow chart in Fig. 2. Each step in the flow chart was applied as follows.

As mentioned in the introduction, PV modules have been identified by the Ecodesign Working Plan 2016–2019 (European Commission, 2016) as one of the non-regulated product groups with the largest potential for environmental savings. This indicates the importance of more detailed investigation into potential environmental improvements (Fig. 2, step 1). As discussed in the previous sections, the Commission carried out a preparatory study (Dodd et al., 2020) which identified a number of areas for potential regulatory intervention; the manufacturing phase was found to be highly significant for the life cycle of this product group, especially in terms of climate change impact (step 2).

Thus, individual PV modules placed on the EU market and intended for use in PV systems for grid-connected electricity generation have been identified as a good product group for application of the method.

As described in step 3 of Fig. 2, it is therefore relevant to identify how rules for calculating the carbon footprint of PV modules, as derived from the PV PEFCRs, could be modified or adapted to potentially serve the purposes of the Ecodesign Directive.

As discussed, in 2019 PEFCRs were developed for PV modules under the Environmental Footprint pilot phase (PEFCR PV Technical Secretariat, 2019). This document sets detailed requirements on how to conduct a Product Environmental Footprint (PEF) study and assesses several life cycle impact categories for PV modules (including climate change).

PEFCRs for PV modules have been adapted and streamlined for use in ecodesign secondary legislation (i.e. implementing measures) for PV modules, in particular for calculating the *carbon footprint of the manufacturing phase* of PV modules (step 4). The structure of the PV PEFCR is kept as a blueprint and changes and adaptations are highlighted.

[3] List of existing PEFCRs is available at: ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm.

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

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 Product Category Rules (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 life cycle environmental impacts of products	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 prioritise projects with low-carbon manufacturing processes	French Agency for Ecological Transition (ADEME) guidelines
South Korean regulations on carbon footprint assessment for PV modules	Carbon footprint assessment method and requirements to prioritise projects with low-carbon manufacturing processes	French methodology CRE3 LCA according to ISO 14040

The specific adaptations mentioned in Table 2 are detailed in Table S2 in the supplementary information. The main aspects (not exhaustive) are summarised below:

- The scope was adapted according to the technologies covered.
- The adapted functional unit is 1 kWh of the total direct current electrical energy generated over the service life of a PV module. The functional unit refers to the electricity yield, calculated according to the methods included in the Ecodesign Regulation under preparation.
- The system boundary is edited to be cradle-to-EU market.
- Life cycle inventory includes only PV modules and their distribution in the EU.
- Use of the Circular Footprint Formula (CFF) is limited to the material part and applied to recycled materials in input. The full formula is reported in the supplementary information.

At this point (step 5), the harmonised calculation rules are developed. They now provide all the recommendations and basis for carrying out the LCA analysis. For PV modules, some aspects deserved deeper analysis to check to what extent their variance in the modelling and selection of datasets can change the results. Therefore, a sensitivity analysis (step 6) was performed on three different parameters of the PV modules: i) silicon content, ii) module yield, iii) electricity grid mix used in the manufacturing phase.

Table 2
Main aspects to be considered when adapting PEFCRs for use in ecodesign requirements.

PEFCR sections	Aspects to be considered
Scope	technologies covered definition of system boundaries (explain and justify what stages are excluded) functional unit (aligned as far as possible with the PEFCR for comparability of results) reference flow (as above) methods and models to calculate the results of the impact category – based on Environmental Footprint (EF) method application of end-of-life modelling (Circular Footprint Formula)
Life Cycle Inventory	elements beyond the scope of the harmonised calculation rules to be left out most up-to-date EF datasets to be used possible limited use of company-specific data relevant to the adapted scope definition of list of processes and components for which company-specific data is to be used, including the most relevant raw materials and production processes in terms of impacts 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 following the rules of the Data Needs Matrix which can be adapted according to the scope allocation rules: if multiple products are produced in the processes under scope, rules from PEFCR and EF method need to be followed

4. Results

Table 3 summarises some values for carbon footprint given in Environmental Product Declarations (EPDs) from Sunpower, Trina Solar, First Solar and REC Solar. The calculated onesare based on assumptions stated in Notes below Table 3.

As discussed, the category rules for PV modules (Product Environmental Footprint Category Rules, 2019) establish the methodology to calculate environmental impacts for the main PV technologies, the values of which are shown in Table 4.

The LCA results, in absolute values according to the Ecoreport tool, for 1 kWh produced by a multi-Si back surface field (BSF) PV module are shown in Fig. 3 (reference year 2014, balance of system excluded). Fig. 3 demonstrates the significance of the environmental impacts of the manufacturing phase (accounting for more than 70 % in all impact categories).

The section below reports on a sensitivity analysis carried out in line with the methodology established in the previous section, and on the basis of the three parameters set out in the table below (silicon content, yield over time and energy mix of the manufacturing phase). Among all physical properties, performance parameters and characteristics of the manufacturing process for PV modules, these parameters are the most significant ones for the carbon footprint value of PV modules, as discussed in the background section. Both yield values are deemed to be representative of the current market; they obviously correspond to different market segments – the top half of the market for the high yield value (LG Business Solutions, 2022), and the lower part of the market for the low yield (Canadian Solar Inc, 2022). In terms of quantity of silicon, the 'low' content should be the one typical of modules currently in production (the 'high' content being more representative of PV modules produced in the 2010 s). Again, the thresholds are targeted to current module production.

Fig. 4 shows, for monocrystalline and polycrystalline silicon PV

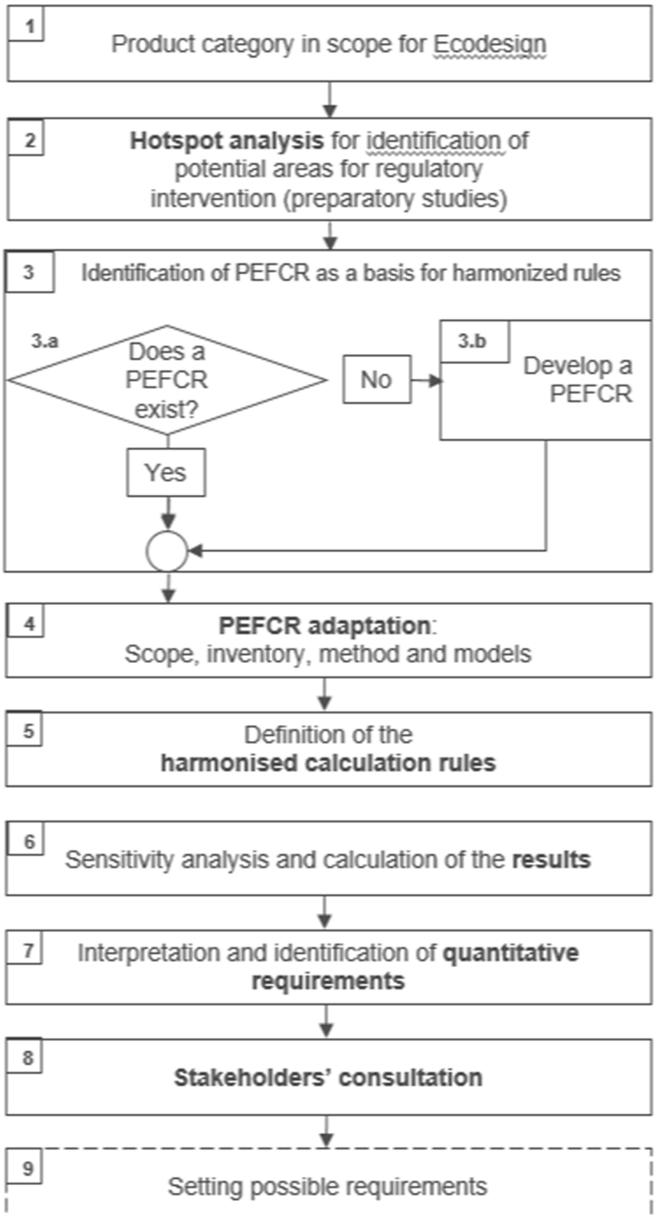

Fig. 2. Method summary for the ecological profile requirement under the Ecodesign Directive.

modules, the distribution of values of the carbon footprint (expressed in $kgCO_2eq/kWh$) based on the sensitivity analysis described in Table 5. When interpreting the results (step 7), it is worth noting that carbon footprint values range between best and worst scenario by a factor of 3.2 for monocrystalline silicon and a factor of 2.3 for multicrystalline silicon. A change of around 5 % in the electricity production efficiency of a PV module has less effect on the carbon footprint than the sources/mix of electricity during the production stage. The analysis also showed that reducing the aluminium frame weight by 50 % is not significant compared to the other scenarios.

Based on the results of the harmonised calculation and feedback from stakeholders (step 8), the proposed methodology suggests setting requirements, for instance based on thresholds (step 9). The policy considerations are addressed in the next section.

5. Policy discussion

The methodology set out in the previous section could provide an approach to calculating the carbon footprint of PV modules for application in regulatory contexts, in particular within the framework of the Ecodesign Directive. Carbon footprint requirements for PV modules would be the first of their kind within ecodesign (or energy labelling) measures.

Based on the analysis in the previous sections, the following alternative regulatory approaches to the carbon footprint of PV modules could be proposed.

1. Quantitative requirements establishing a maximum admitted threshold for the carbon footprint of PV modules.
2. Quantitative requirements for specific relevant parameters influencing the carbon footprint, such as the silicon content or the module yield.
3. Information requirements on the carbon footprint of PV modules.
4. Carbon footprint information to be reported on the energy label of PV modules, and/or in the related product information sheet.

The first typology of requirements (quantitative requirements establishing a maximum threshold) would represent a straightforward policy approach to reduce the carbon footprint of PV modules and achieve the EU's environmental objectives. Maximum thresholds would be set to ensure that only those products that meet a minimum level of ambition in emissions reduction are available on the market. The proposed thresholds could follow a multi-staged approach, e.g. with a first maximum footprint after a period of 2–3 years after the Ecodesign Regulation comes into force, and a second – and more ambitious – maximum footprint after a period of 5–6 years. This would result in progressively phasing out the worst performing products (in terms of CFP) from the EU market.

The second typology of requirements (quantitative requirements for specific relevant parameters) would be close to the previous one in terms of intended effects on the market. In conceptual terms, it would be implemented by targeting specific design parameters, instead of the first

Table 3
Summary table for carbon footprint values reported in EPDs for some PV products.

	$kgCO_2eq$/ W or kg	$kgCO_2eq$/ kWh	Comments
Sunpower EPD	3.42E-01	2.28E-01	400Wp monocrystalline PV module
Trina Solar EPD	1.91E-02	1.27E-02	PV plant 30 MW
First Solar EPD	2.67E-01	1.78E-01	1 Wp of Series 6 CdTe PV module
REC Multi-Silicon block	1.12E + 01	7.47E + 00	Per kg of silicon block
REC Solar grade silicon EPD	1.60E + 01	1.07E + 01	1 kg of manufactured Solar grade silicon (SoG-Si)
Norsun monocrystalline silicon wafer EPD	3.54E + 01	2.36E + 01	Per kg of m^2 of manufactured monocrystalline silicon wafer

Notes:1 500 kWh/kWp

Table 4
CFP values corresponding to the climate change impact category, calculated as per the PEFCR (European Commission, 2019).

PV technologies	Life cycle excl. use stage ($kgCO_2$ eq/kWh)	Use stage ($kgCO_2$ eq/kWh)
Representative (virtual) product	5.93E-02	1.05E-05
CdTe	1.99E-02	1.07E-05
CIGS	3.59E-02	1.39E-05
Micromorphous silicon	4.30E-02	1.50E-05
Multicrystalline silicon	4.88E-02	1.02E-05
Monocrystalline silicon	8.04E-02	9.93E-06

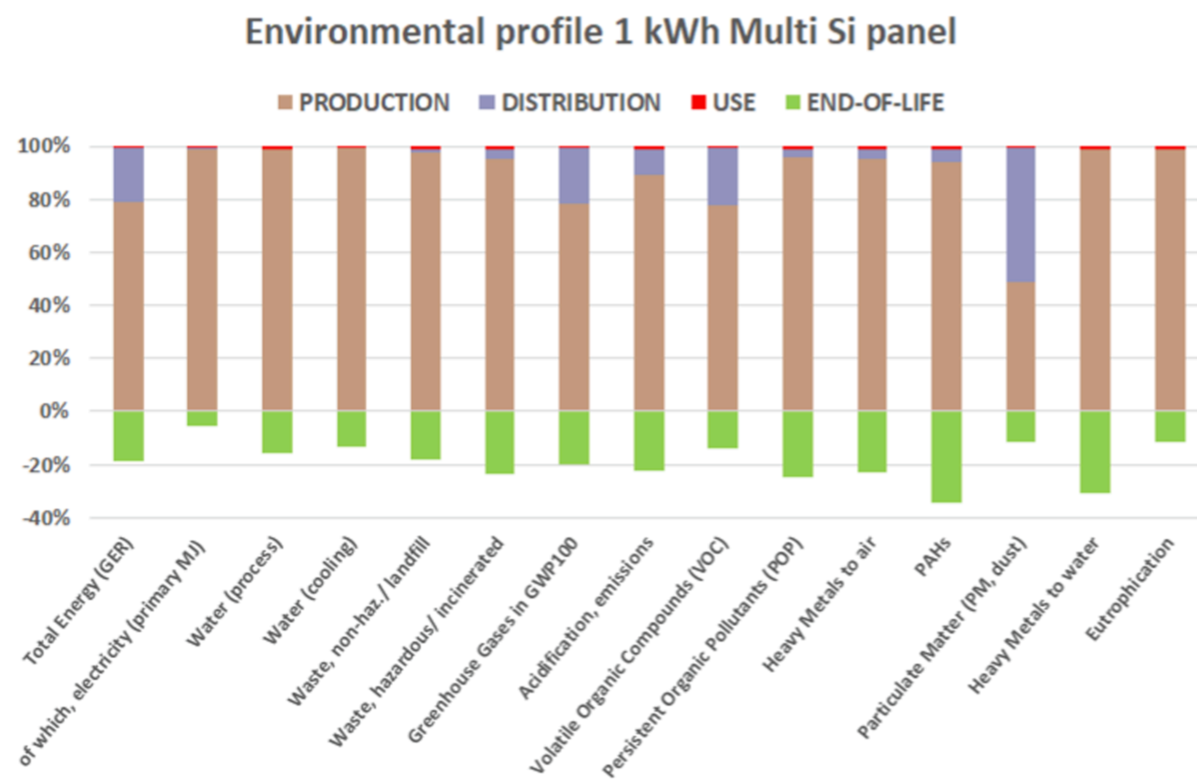

Fig. 3. Environmental profile of a multicrystalline silicon PV module, for 2014 reference year, in absolute values. .
Source: Dodd et al. (2020)

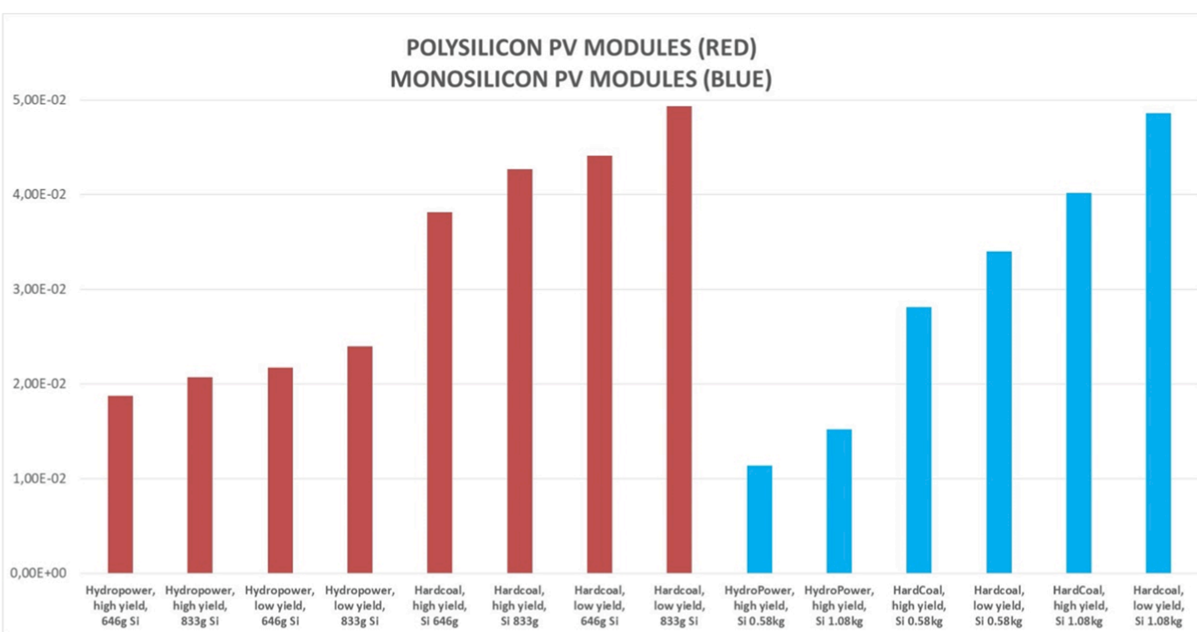

Fig. 4. Carbon footprint values of monocrystalline and polycrystalline silicon PV modules (manufacturing and distribution phase). Source: European Commission, 2022b, 2022c, 2022d).

approach which is more ‘holistic’ (and thus leaves the designer or manufacturer with more room for manoeuvre in terms of choosing which parameter to optimise).

The third typology of requirements (information) would consist of a mandatory carbon footprint declaration. This would create transparency on the market and allow consumers and public authorities to compare the carbon footprint of different modules placed on the market. As such, PV modules with adverse environmental and climate change impacts could still be available on the EU market. However, the transparency with regard to the carbon footprint content could act as an incentive for manufacturers to improve the environmental performance of their production phase, thus contributing to the ‘ecodesign’ of their products.

Table 5
Main values considered for PV modules based on monocrystalline silicon and multicrystalline silicon.

Parameter	High value	Low value
Silicon content (g per functional unit)		
Monocrystalline silicon	1 080	588
Multicrystalline silicon	833	646
Yield over 30 years[4] (kWh/m^2)		
Monocrystalline silicon	6 730	5 540
Multicrystalline silicon	5 920	5 120
Energy mix of the manufacturing phase	'hard coal' (worst) scenario	'hydropower' (best) scenario

[4]Total energy yield in direct current over service life (30 years), calculated according to Annex III, point 4.3, to the Ecodesign working document (European Commission, 2022).

This standardised information could also serve as a tool for green public procurement schemes, such as those referred to in Table 1.

The fourth typology of requirements (carbon footprint information on an energy label for PV modules) is conceptually close to the previous one, in the sense that it would represent a way to display the information within a tool (the energy label) that helps users to make an informed choice when buying the product. Obviously, it should be carefully designed in order to provide concise but at the same time relevant and effective information. Experiences with other product groups, typically white goods, already regulated with energy labelling show that the energy label can be a very powerful driver for fostering continuous product innovation towards higher energy efficiency (Michel et al., 2017).

Independent of the chosen policy approach, the following considerations are relevant when evaluating the feasibility of regulating the carbon footprint of (PV) products:

- To ensure comparability, the declared carbon footprint should be based on harmonised calculation rules. This is why a specific methodology is presented in this paper.
- The carbon footprint could be calculated using a single, ideally freely accessible calculation tool based on harmonised rules. This would greatly contribute to reducing the administrative burden on manufacturers.
- The carbon footprint calculation should focus on those life-cycle stages where the bulk of emissions occur. In this case, these are the raw material acquisition and pre-processing, the manufacturing, and potentially the distribution phases. The choice of these life-cycle stages is also beneficial from the legal perspective. Ecodesign rules apply to products sold on the EU market, at the moment they are 'placed on the market'. This means that it is not feasible to enforce or verify compliance with ecodesign requirements after placing on the market, only during life-cycle stages prior to that point.
- To ensure that the declared carbon footprint of PV modules is reliable, credible and correct, manufacturers should apply for verification of their declared footprint by an independent conformity assessment body. Third-party verification further ensures comparability of claims and enables more effective management of the environmental and non-compliance risks involved. In particular, verification should ensure the reliability of the company-specific data used by manufacturers. Such data, for example relating to the energy used in the production process, cannot be verified on the product itself, as is also the case for the energy yield. The verified carbon footprint should be valid for a fixed period (e.g. 3 years) and should be updated, including during its validity period, in the event of significant changes.

6. Conclusions

This paper proposes a harmonised methodology for calculating the carbon footprint of PV modules, for use in regulatory contexts, in particular within ecodesign regulations that would affect the EU market. The gross energy consumption associated with PV modules will evolve in line with the expected increase in deployed PV in the EU market. In light of the recent commitments laid down in the EU Solar Energy Strategy (European Commission, 2022a) to boost the installation of PV modules on EU buildings, this increase can be expected to occur at an even faster pace. Due to this expected growth, setting ecodesign requirements for the carbon footprint of PV modules could result in significant energy savings, in particular within the energy-intensive manufacturing stage for these products.

The approach presented in this paper is novel in that it provides a methodology for calculating the carbon footprint of PV modules with the specific aim of applying it in regulatory contexts. The methodology presented in this paper could very well be used to tackle other categories of environmental impact through policy intervention. For instance, in the case of PV modules, other relevant impacts of interest beyond the emission of greenhouse gases may include resource use (fossil fuels), resource use (minerals and metals), acidification and particulate matter/respiratory inorganics. The method could also be adapted to consider the full life cycle of PV modules, including end-of-life phase. This would also extend the applicability of the methodology to policy fields related to secondary and critical raw materials. The methodology could obviously be applied and modified for other product groups, in particular those already covered by PEFCRs. It could thus be seen as a basis for setting market entry requirements based on the 'ecological profile' of products, as referred to in the Ecodesign Directive (European Union, 2009).

7. Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2023.04.001.

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