The European Union's Ecodesign Directive – Analysis of Carbon Footprint Assessment Methodology and Implications for Photovoltaic Module Manufacturers

Abeer Ali Khan, Pamela Molina, Christian Reichel, Alexander Aguilar Protti, Dirk Holger Neuhaus, Jochen Rentsch, and Sebastian Nold**

With an increasing shift away from fossil fuels toward renewable energy sources within the European Union (EU), photovoltaics (PV) are projected to see substantial growth with estimates of nearly 600 GWp of capacity by 2030. As the use of PV technology continues to expand, the European Commission has introduced various policy instruments, enabling consumers to make informed choices. Among those, the Ecodesign directive 2009/125/EC sets a carbon footprint threshold as a minimum qualification for the European market to cut out the least sustainable PV modules. For this directive, the methodological guidelines for the complex carbon footprint calculation of PV modules are under development. To this end, this analysis compares the two methodologies, namely *Electronic Product Environmental Assessment Tool (EPEAT)* and the Ecodesign adaptation of *Product Environmental Footprint Category Rules (PEFCR)*, emphasizing the implications of choosing one over the other for the PV industry. This study illustrates how varying parameters, like module lifetime, degradation rate, and purchased renewable electricity certificate allowance limit, stemming from the differing methodological approaches can influence the carbon footprint calculation. Apart from the strengths and weaknesses of each methodology, this article emphasizes the need for globally harmonized standards to ensure consistency in evaluating the carbon footprint of PV modules. The observations made in this study should be considered not just for Ecodesign directive but for any such market regulation policy like the recently passed EU Net Zero Industry Act or the EU Ecolabel for PV modules. It underlines the significance of choosing a transparent and fair approach to ensure the credibility of carbon footprint labels and meet the EU's decarbonization objectives successfully, propelling the transition toward a more sustainable energy landscape.

1. Introduction

The 2 °C limit for the global warming compared to pre-industrial levels requires a fast-paced decarbonization of the global energy system by shifting from fossil-based to renewable energy sources.[1] To comply with this target, the European Union (EU) is aiming for a significant reduction in the global warming potential (GWP) by 2030 and reach climate neutrality by 2050.[2] Photovoltaic (PV) is predicted to be a key technology for this goal as it is projected to deploy more than 320 GWp p.a. by 2025 and almost 600 GWp p.a. by 2030.[3] In 2022, the cumulative installed capacity of PV was 208.9 GWp in the EU, compared to 167.5 GWp in 2021. Noteworthy, 41.4 GWp of installed capacity in 2022 corresponds to 10 million PV modules, assuming that the modules have a power of 414 Wp. It is expected that even more modules for residential, commercial, and industrial applications will be installed in the EU in the upcoming years to achieve climate neutrality. Additionally, the REPowerEU plan will boost the influx of PV to achieve energy independence from Russia.[4] Therefore, it is of high importance to consider the environmental impacts of PV module manufacturing to prevent future burdens, given the role that PV is expected to have in the decarbonization of the EU energy system.

Environmental impact assessment as a non-financial criterion is already used within the EU- a successful example being the tenders for solar projects on the public grid exceeding 100 kWp organized by the French national government "Commission de Régulation de l'Energie" (French Energy Regulation Council, "CRE").[5] The EU commission also conducted a research process to develop a policy mix with mandatory instruments such as energy labeling and Ecodesign legislation,[6] as shown in **Figure 1**, that includes different product categories including solar panels and inverters. The aim of the EU energy label is to empower consumers to choose energy-efficient products based on a common reference that allows for the

A. A. Khan, P. Molina, C. Reichel, A. A. Protti, D. H. Neuhaus, J. Rentsch, S. Nold
Photovoltaic
Fraunhofer Institute for Solar Energy Systems (ISE)
Heidenhofstrasse 2, 79110 Freiburg, Germany
E-mail: abeerali.khan@firstsolar.com; sebastian.nold@ise.fraunhofer.de

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/solr.202301011.

DOI: 10.1002/solr.202301011

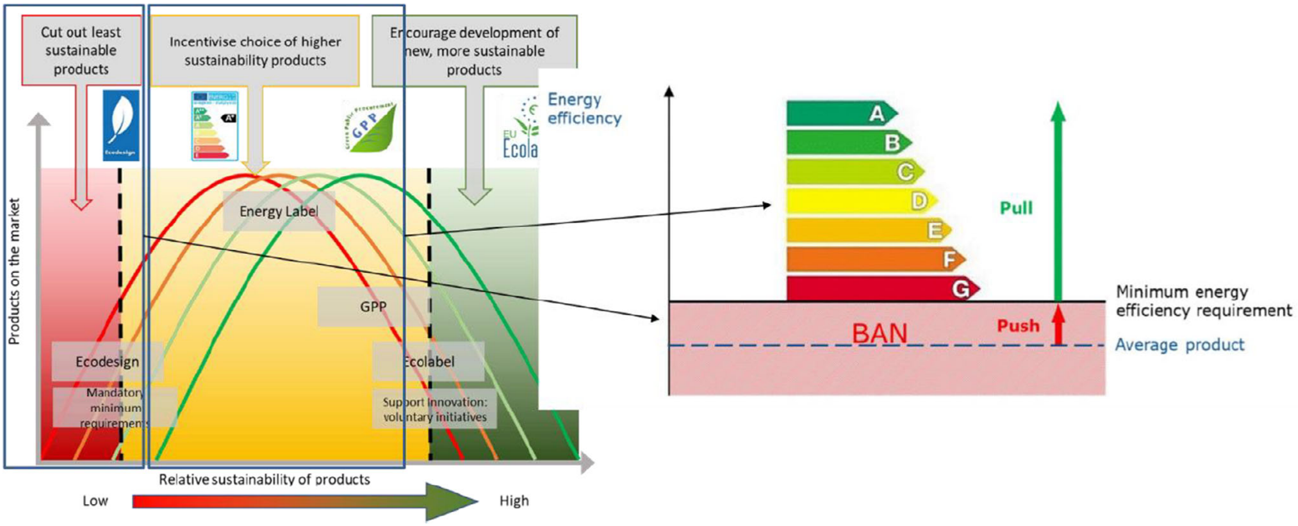

Figure 1. Overview of policy instruments considered by the EU Commission (taken from[40]).

comparison of different products. In contrast, the goal of Ecodesign is to define carbon footprint thresholds and restrict the least performing products to be placed in the EU market. In addition, the EU Ecolabel[7] scheme is intended to promote those products which have a high level of performance with respect to environment, health, climate, and natural resources.[8] Such legislations promote industrial competitiveness and innovation for more circular products with lower environmental impacts.[9] A complementary legislation to Ecodesign is the Green Claims Directive that stamps out greenwashing, which distorts the market and creates disadvantages for authentically sustainable products.[10]

In the framework of the Ecodesign Directive of the EU, the European Commission identified PV modules as a product group with large potential for environmental improvement.[6] A study by the European Commission Joint Research Centre evaluated past life cycle assessment (LCA) studies on PV technologies in order to define the environmental impacts of PV modules, inverters, and systems. It was found that the manufacturing phase has the highest influence on climate change and other impact categories throughout the lifetime of PV technologies.[11,12] The areas for potential regulatory implementation were addressed and the need to establish rules for a transparent and consistent quantification of emissions arose due to the plentiful methods available to calculate the carbon footprint. The Electronic Product Environmental Assessment Tool (EPEAT)[13] by the Global Electronics Council and Product Environmental Footprint Category Rules (PEFCR)[14] for the European Commission are examples of reference documents that establish methodologies for calculating environmental impacts.

Representatives of the photovoltaic value chain from the European Technology Innovation Platform Photovoltaics (ETIP PV) in cooperation with SolarPower Europe, PVThin, the European Solar Manufacturing Council (ESMC), and IEC Certification to Standards Relating to Equipment for use in Renewable Energy Applications (IECRE) reviewed the Ecodesign Directive proposal of the European Commission Research Centre and presented suggestions for improvement.[15] In the EU, the PV industry participated in the Product Environmental Footprint Pilot project,[16] which established a common methodology to conduct a LCA to evaluate the environmental performance of products and to identify so-called hotspots in the life cycle through the application of PEFCRs.[14] Hence, the PEFCR supports the EU in the decision-making processes on sustainable product policies and establish industry standards for environmental impact.[16,17] Except for the functional unit (FU), this approach is aligned to that of EPEAT which in fact includes a criterion (7.2.2) to evaluate LCA performance based on the PEFCR. The reason EPEAT's low carbon solar criteria chose a kilo watt peak (kWp) FU instead of per kilo watt hour (kWh), similar to the French method, is because, it is more representative of the product (i.e., the PV module) and it makes it harder to cheat and manipulate data which can be seen with labels based on kWh.

For the criteria of the Ecodesign Directive it is proposed to use the PEFCR methodology with modifications for the carbon footprint calculation of PV modules. In this study, the carbon footprint of a silicon PV module is estimated according to the methodology proposed by the Ecodesign Directive as well as the EPEAT guidelines to reflect the impact of the inherent differences between these two approaches and their implications on the footprint.

2. Methodological Difference

This LCA further followed the framework of the ISO standards 14 040-4[18,19] as well as the IEA PVPS 12.[20] The Ecoinvent 3.8 database[21] is used for modelling with the aid of the Umberto 11 software.[22]

In order to visualize the differences between the two top-choices of methodology, i. EPEAT[13] and ii. Ecodesign adaptation of PEFCR,[23] a LCA is conducted on a p-type M6 (Cz-Si) wafer and passivated emitter and rear contact (PERC) PV module.

Further methodological details can be found in our LCA study preceding this analysis.[12] The life cycle inventory (LCI) is obtained from Müller et al.[24] but updated for a production scenario where electricity consumption for the Cz ingot crystallization is calculated to be lower, with 25.1 kWh kg^{-1}-Si[25] compared to the 38.5 kWh kg^{-1}-Si of the literature as well as for wafering, 2.25 kWh m^{-2} of wafer compared to 2.35 kWh m^{-2} of wafer. In choosing the LCI, the EPEAT offers two options. Path A includes standard lookup tables for carbon values (component by geography, e.g., polysilicon from Germany, wafer from Vietnam, cell from Germany, module from USA, etc.) based on the LCI completed by the International Energy Agency's Technology Collaboration Programme on Photovoltaic Power Systems (PVPS) Task 12: PV Sustainability[20] – a concept followed by the French carbon footprint model (calculation method 1). On the contrary, Path B enables site specific LCA using verified primary data for core components- a concept similar to that of the PEFCR.

The global warming potential (GWP) or carbon footprint can be calculated through different life cycle impact assessment (LCIA) methods which often leads to difference in interpretation of the results. Both the EPEAT and PEFCR requires the GWP to be calculated using the same baseline model of 100 years of the IPCC (based on IPCC 2013).[26] Moreover, both methodologies entail a similar system boundary for the assessment. The EPEAT approach represents a system boundary till module, i.e., cradle-to-gate, along with its transportation as per the recommendations of the Task 12,[20] as seen in **Figure 2**. For all technology and production locations, the default transportation distances reported in the Task 12 LCI are representative of an import to Europe scenario. In contrast, the adapted PEFCR methodology also represent a system boundary till module, however, the transportation is specified to the European market, i.e., cradle-to-European market with default transport scenario. Both methodologies included module frame in the system boundary-a component excluded from the French model[5] by definition, which can lead to incomplete footprint of some modules, for example.

Furthermore, regarding the FU, the GWP of the EPEAT methodology is calculated as g CO$_2$-Eq. per kilo watt peak (kWp), while that by the Ecodesign adaptation of the PEFCR is g CO$_2$-Eq. per kilo watt hour (kWh). It is observed that although the PEFCR FU is based on overall electricity generation, dependent components required to generate electricity such as the balance of system (mounting structures, inverters, wiring, and electrical components among others) are not included in the methodology for the assessment.

The calculation required for the functional unit kWp of the EPEAT methodology is based on the simple formula

$$\mathrm{kWp} = A \times \eta \times E \tag{1}$$

which considers the PV module area A, and the maximum efficiency [power conversion efficiency (PCE)] η, under standard test conditions, with the AM1.5 g spectrum, an irradiance E of 1000 W m^{-2} and a cell temperature of 25 °C, according to the standard IEC 61 215. Although analyzed in kWp, the EPEAT methodology includes a minimum requirement of 25 years lifetime as well as less than 20% lifetime performance degradation ($\leq$1.9% annual degradation rate).

In contrast, the lifetime energy yield calculation required for the Ecodesign adaptation of the PEFCR is a step further which uses the formula

$$EY_{\mathrm{M(DC)LT}} = EY_{\mathrm{M(DC)Y1}} \times T_{\mathrm{LT}} \times \left(1 - \tau_{\mathrm{degM}} \times (T_{\mathrm{LT}}/2)\right) \tag{2}$$

where $EY_{\mathrm{M(DC)Y1}}$ 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. T_{LT} is lifetime of the PV module, which is assumed as a fixed 30 years for all modules. τ_{degM} is the PV module lifetime performance degradation rate, expressed here in decimal format. A degradation rate of 1% should be applied which is changeable with justification. However, the τ_{degM} may be fixed in the upcoming update of this directive's methodology which may be classified based on PV technology, meaning a specific degradation rate defined for PERC technology while a different for TOPCon technology.[22]

The energy yield of the first year is obtained through the $CSER$ (Climate Specific Energy Rating). Both are related as follows

$$CSER = \frac{\left(EY_{\mathrm{M(DC)Y1}} \cdot G_{\mathrm{ref}}\right)}{\left(P_{(\mathrm{max,STC})} \cdot H_{\mathrm{p}}\right)} \tag{3}$$

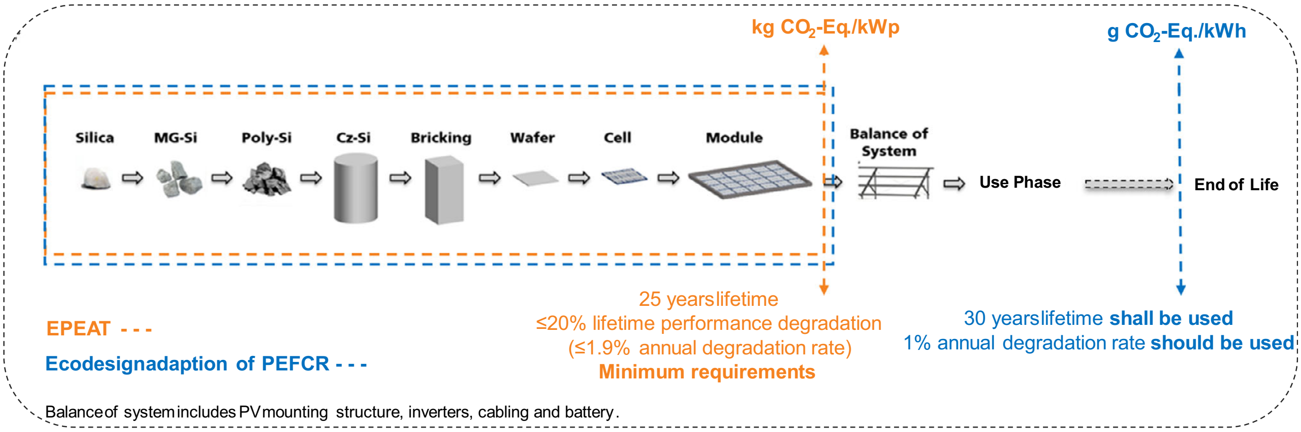

Figure 2. System boundary and functional unit for the LCA of PERC PV module as stated in the methodologies provided by EPEAT and PEFCR.

where, G_{ref} is 1000 W m^{-2}, the irradiance used to measure the $P_{\mathrm{max,STC}}$ which is the maximum power output of the PV module under STC conditions. H_{p} is the yearly total global in-plane irradiation, expressed in kWhm^{-2} for the reference climatic conditions. In this regard, currently the DC energy yield of three climatic locations is required for the Ecodesign adaptation of PEFCR based on EN IEC 61 853-4,[27] namely temperate coastal (global in-plane irradiation of 973 kWh m^{-2}a), temperate continental (1266 kWh m^{-2}a) and subtropical arid (2295 kWh m^{-2}a). In the upcoming issue of this methodology, this selection is expected to be reduced to only temperate continental to represent average European condition.[28] Lastly, this methodology further included provision for bifaciality advantages according to IEC TS 60 904-1-2.[29]

For EPEAT, the standards EN IEC 61 215[30] and IEC 61 730[31] are most relevant to maintain the quality of the modules entering the market along with the minimum quality requirements. These standards ensure design qualification of terrestrial photovoltaic modules suitable for long-term operation in open-air climates and for module safety. In addition, the EPEAT ecolabel addresses multiple sustainability issues, including climate change, sustainable use of resources, chemicals of concern and Environmental, Social, and Governance (ESG) due diligence as per the NSF 457 – Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters.[32] Similarly, the EN IEC 61 215 standard series[33] is also required for the methodology under development for Ecodesign[9] to ensure reliability of PV modules. Specific tests covered under this standard series include thermal cycle, damp heat test, humidity freeze test, UV test, static mechanical load test, hot spot test and finally, hail test. In addition, the EN IEC 62 093[34] – an European standard that defines terminology, test methods, and general requirements for evaluating the performance and safety of power conversion equipment used in PV systems. Specific tests covered under this standard are voltage (dielectric strength) test, bus link capacitor thermal test, power transistor module thermal test, humidity freeze test, thermal cycling test, damp heat test, dry heat test, and lastly UV weathering test. Furthermore, the PEFCR also requires the modules to qualify EN 45 558:2019[35] in an effort to regulate critical raw material (CRM) content.

In the following analysis, only the sensitivity of the different parameters used in the calculation required by the two methodologies on the resulting GWP will be investigated. For the EPEAT (GWP in kg CO_2-Eq./kWp) calculation, the required parameter is limited to module peak power (Wp). On the contrary, in addition to Wp and efficiency (%), the PEFCR (GWP in g CO_2-Eq./kWh) calculation also included module lifetime (years) and degradation rate (%/year).

One of the most influencing factors to GWP on the manufacturers side is the electricity mix and the share of renewables through power purchase agreement (PPA) used in the complete module production.[12] Schemes such as the PPA are important non-public instruments, low in carbon footprint and used to boost the share of renewables in the production electricity mix which results a cleaner module irrespective of the production location grid. The PEFCR prioritizes the specific electricity mix for production, setting no cap to the PPA use as long as qualification criteria are met. In contrast, the EPEAT "Ultra Low Carbon Solar Criteria" (Path B) has capped the PPA or similar renewable energy purchase at 25% and the Renewable Energy Attribute Credits (e.g., RECS) must meet RE100/ISO 14 067 criteria[36] and must be retired (not resold). The EPEAT Path A is restricted to standard national level grid carbon intensities as published by IEA[20] to tackle misuse, making its success less dependent on verification. Both PEFCR and EPEAT path B provide guidelines toward maintaining the quality of the PPA or equivalent certificates as well as quality of the LCI. However, effectiveness of one over the other is not assessed within the scope of this study.

For the regionalized scenarios, it is assumed that the complete production line for PV manufacturing is integrated into one factory, metallurgical-Si to module production, under the same national electricity grid. A national electricity grid refers to the interconnected system of power generation, transmission, and distribution that spans an entire country, allowing electricity to be generated in one location and transmitted for use in various regions. In contrast, sub-national electricity grids are smaller-scale grids within a specific region or state, typically connected to the larger national grid. These grids enable localized distribution of electricity and may have specific infrastructure tailored to the energy needs of a particular area. It should already be critically noted here that today, not all components are produced across the entire value chain in one factory with one energy mix. This must definitely be considered in further analyses. Likewise, it is very critical to consider national or even sub-national power grids when in reality they have significant exchanges with other power grids. This, too, should definitely be considered in further analyses. However, it seems to make sense for any methodology to only allow global power grids that include all grids that are in exchange and to only allow national or sub-national power grids if they do not have such an exchange with other power grids. As shown in **Figure 3**, three production electricity mixes are chosen to assess if PV modules of certain regions become vulnerable due to use of purchased green electricity if verification of certificates fail. To present a high fossil share (HFS) production electricity mix the Chinese grid mix has been chosen to represent different national and sub-national grids like in China (1087 g CO_2-Eq./kWh), India (1491 g CO_2-Eq./kWh), Poland (1035 g CO_2-Eq./kWh). Next to it, the moderate fossil share (MFS) production electricity mix of Germany has been chosen to represent different national and sub-national grids like in Germany (537 g CO_2-Eq./kWh), USA (514 g CO_2-Eq./kWh), Portugal (414 g CO_2-Eq./kWh), Italy (392 g CO_2-Eq./kWh) or Spain (329 g CO_2-Eq./kWh).

To put numbers into perspective, although not shown in Figure 3, low fossil share constitutes of national grids like France, Sweden, Norway, among others, which have a carbon footprint below 50 g CO_2-Eq./kWh. Similar to that or with even lower carbon footprint are the PPAs like the one assumed in this analysis, consisting of over 93% hydroelectricity and thus, resulting a mere 25 g CO_2-Eq./kWh.

The following **Table 1** summarized the key parameters analyzed in this study.

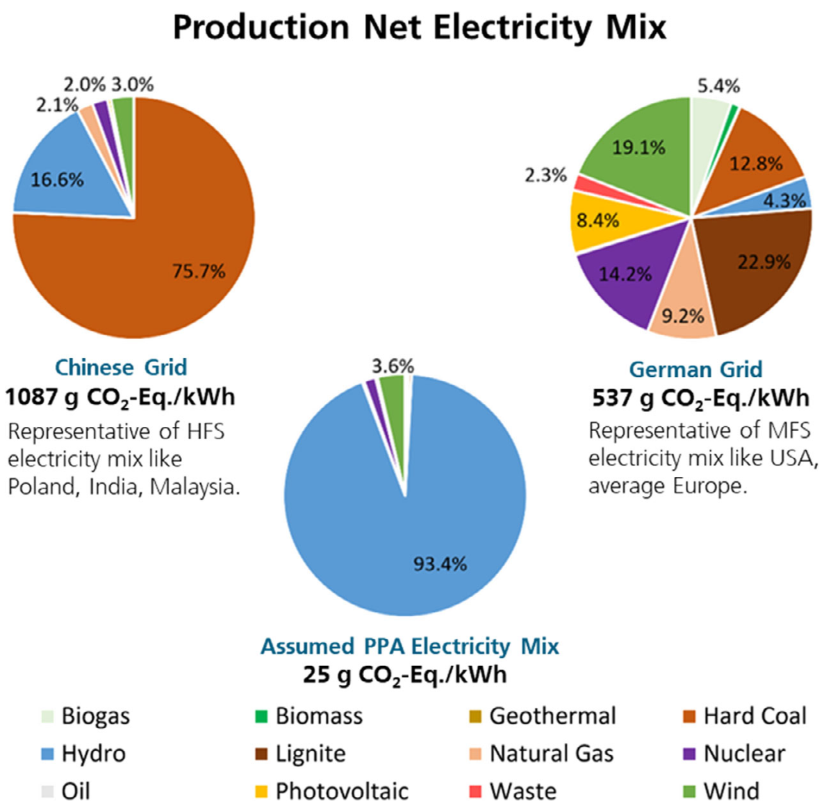

Figure 3. Composition of the net electricity mix representing China and Germany as well as an exemplary power purchase agreement (PPA) electricity mix. The net electricity mixes are modelled according to a preceding study[12] using Ecoinvent 3.8 database.[22] HFS: High Fossil Share, MFS: Moderate Fossil Share.

Table 1. Differences between PEFCRs for PV modules in Ecodesign legislation and EPEAT guidelines for the carbon footprint estimation.

	PEFCR[23]	EPEAT[41]
Functional unit	1 kWh	1 kWp
System boundary	Cradle-to-EU-market	Cradle-to-gate
LCIA method	IPCC2013 GWP100	IPCC2013 GWP100
LCI selection	Supplier specific data for core production processes; secondary data when specific data not available.	Path A: Based on tabulated values accepted by PVPS Task 12: PV Sustainability. Path B: Supplier specific data for specific process steps. Requires additional verification steps to ensure comparability of LCA results.
PV module lifetime	Assumed 30 years	Minimum requirement: 25 years
Degradation rate	1.0%/a (silicon-heterojunction solar cells with a thin-film technology)	Minimum requirement: <20% lifetime performance degradation
Electricity modelling	No restriction on electricity consumption if contractual instruments are available and meet requirements. As a last option the country-specific grid mix, consumption mix.	Path A: National level grid carbon intensities as published by IEA. Path B: National or sub-national regional grid carbon intensities as published by IEA. Max. 25% of renewable energy purchase.

3. Results and Discussion

Figure 4 shows the GWP of PERC modules calculated as per the EPEAT path B methodology (kg CO_2-Eq./kWp) and the influence of PPA certificate allowance on it. It is evident that HFS electricity grids lead to a larger carbon footprint per kWh than MFS grids, which can be significantly reduced with the aid of PPAs. The diagram depicts two module production location, HFS and MFS,

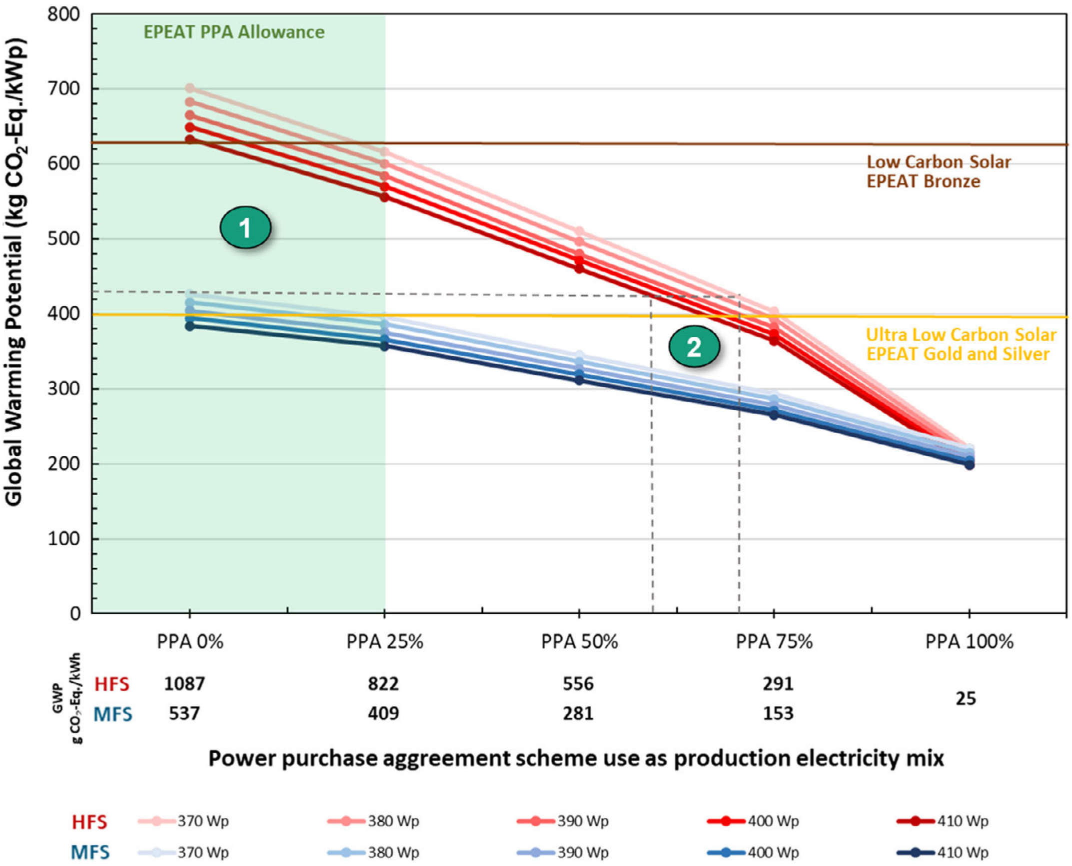

Figure 4. Comparison of the global warming potential (GWP) (kg CO_2-Eq./kWp) of modules produced at a high fossil share (HFS) to moderate fossil share (MFS) electricity grid location and the influence of power purchase agreement (PPA) certificate allowance on it. The share of power purchase agreement (PPA) used in production increases from left to right of the x-axis and the carbon footprint of the resultant electricity mixes shown underneath the labels decrease. The GWP of PERC modules is calculated following the Path B methodology of Electronic Product Environmental Assessment Tool (EPEAT).

and five different modules with peak power varying from 370 to 410 Wp assuming the same module area (module efficiency from 20.11 to 22.28%). Attention, in reality the manufacturing of the entire value chain often does not take place in one place, for example solar cells come from China and modules are then manufactured in Europe. Such products have a GWP that lies between pure manufacturing in an HFS and an MFS region. As Figure 4 shows, the better the production electricity mix and peak power of a module, the lower is its GWP. The green zone at number (1) shows the PPA allowance in the EPEAT methodology, which is capped at 25%. This limit benefits manufacturers located in a region of moderate and low fossil share grids as it leaves limited room for PPA misuse. In addition, EPEAT path B has strict requirements regarding the quality of the PPA certificates. However, the effectiveness of these requirements for PPAs and similar certificates is not assessed in this study but rather focused on the influence that PPAs pose on carbon footprint labels and thus, regulatory policies like Ecodesign and even the Net Zero Industry Act.[37]

As observed at number (2), with the assumed PPA share (here being composed of over 90% of hydroelectricity), the best-in-class module produced within a HFS national grid needs at least ≈60% PPA to break-even with the worst-in-class module produced using a MFS grid without using any PPA. So, the 25% limit is indeed a "sweet-spot" where the use of clean energy is motivated in the production mix and the MFS manufactured modules are also protected from PPA misuse. This creates strong motivation for the HFS national grids to decarbonize and remain environmentally competitive. Until global certificates for the PPA can be reliably verified, such a cap ensures limited dependency on verification processes of the certificate.

Due to the simplified calculations of the functional unit kWp, the EPEAT methodology does not involve relying on warranties for parameters such as lifetime (or power warranty), degradation rate and bifaciality advantages. This is intentional as carbon footprint of only up to the module at market is communicated through this label, hence excluding the module lifetime and degradation rate. However, to maintain the market standard, minimum requirements are set for these parameters- i.e., 25 years power warranty and less than 20% performance degradation over lifetime. The minimum requirements are updated to the current industry standard every 3 years.

One advantage of considering the EPEAT methodology behind a national directive is that it is also the basis of the global

Type-1 ecolabel.[13] This will give the manufacturers a cost and time saving opportunity if one label can satisfy global market. A globally unified assessment methodology is highly desired by and beneficial to different stakeholders of the PV industry, making the kWp functional unit important for the Ecodesign directive. This functional unit also has a track record of being used in the carbon footprint regulation landscape of USA,[38] France and South Korea.[39]

Currently, 630 kg CO_2-Eq./kWp is the requirement for EPEAT Bronze label while 400 kg CO_2-Eq./kWp is the threshold for the optional EPEAT Gold and Silver label. Upon consultation with the authors of the EPEAT label, it is found that the potential market entry limit for Ecodesign directive can be adjusted and different to, e.g., EPEAT bronze limit.

In fulfillment of the goals of the Ecodesign directive, the EPEAT (path A and B) methodology proves itself as a strong contender. The avoidance of warranties (for lifetime and degradation rates) and limited use PPA or equivalent certificates has minimized the green-washing scopes. As the lifetime and degradation rate improvement through R&D are intrinsically incentivized through the economic perspective, both may be excluded from the GWP calculation. That is because the reviewed minimum requirements for degradation along with the IEC performance tests maintain the market standards. Through the comparable labels obtained from EPEATs calculations with the GWP per kWp, it is possible to regulate the European market entry as well as get recognized globally. The overall GWP footprint per kWh can be calculated based on the disclosed lifetime and degradation rate like conventionally done in economic calculations. In order to make the qualitative differences of products and technologies visible for the customer, the specification of the guaranteed module lifetime and the annual degradation would be very important. In the case of the EU Ecodesign, however, this will be the same for all modules, as it will be difficult to prove this in field tests. So, all modules will receive a lifetime of 30 years and a degradation of one percent per year.

Before moving to the PEFCR methodology, it is important to understand the sensitivity of the DC energy yield (kWh) to module peak power (Wp), lifetime (year) and degradation rate (%/year) which are highlighted in **Table 2**. The temperate continental climatic location is shown here to not deviate from the focus of the analysis.

Table 2. Sensitivity of the energy yield (kWh/panel) at temperate continental climatic location to module peak power (Wp), lifetime (year), and degradation rate (%/year).

PERC module energy yield			Lifetime (years)		
			15	30	40
20.11%, 370 W_p	Degradation rate (%/a)	1.50	6123	10 693	12 878
		0.70	6537	12 349	18 397
		0.25	6770	13 280	15 822
		0.00	6899	13 798	17 477
21.20%, 390 W_p		1.50	6454	11 271	13 574
		0.70	6890	13 017	16 677
		0.25	7136	13 998	18 422
		0.00	7272	14 544	19 392
22.28%, 410 W_p		1.50	6785	11 849	14 270
		0.70	7243	13 684	17 532
		0.25	7501	14 716	19 367
		0.00	7645	15 290	20 386

Depending on the module peak power, lifetime and degradation rate, the resultant energy yield ranged from 6123 to 20 386 kWh per panel: a difference of more than factor 3. The overall energy yield of a module can vary significantly – approx. +142% based on lifetime increase (15 to 40 years), approx. +29% based on degradation rate improvement (1.5% to 0%) and approx. +11% based on module peak power improvement (370 to 410 Wp). In addition, the energy yield is highly sensitive on location driven factors like irradiation, soiling/maintenance, probability of storm damage (e.g., hail), etc.

The labels obtained using the Ecodesign adaptation of PEFCR show impacts over the complete lifetime, focusing on the performance of the PV module. And as observed at number (1) in **Figure 5**, the CO_2 footprint can vary significantly based on the performance. Although not all solar panels are made equal, by setting the 30-year assumption, lifetimes are equalized for all modules. While this assumption has tackled the complex question of which lifetime to consider, it will not reflect the difference in module performance quality. In contrast, power warranties provided by the manufacturers rely not just on the performance of the modules but their financial capability to ensure the warranty as well. And therefore, the power warranties are not true lifetimes of the module as well, although these are a strong contender to be considered for kWh assessments. It is also possible that the verification efforts can increase if such power warranties are allowed to avoid misuse. So the selection of lifetime still remains a complex issue in the CO_2 footprint calculation.

For the current methodology used in a regulatory sense, there is a potential green-washing scope for modules with a power warranty of less than 30 years. Modules with longer warranties (e.g., 40 years) will not be incentivized by this directive. Such premium performance can be presented through the voluntary labels like the EPD or even the conceptual Ecolabel directive. Looking into the impacts throughout the complete lifetime provides valuable information to research, however, for Ecodesign directive this lifetime will not play a role in the market entry regulation on account of being same for all modules.

Similar observation can be made for the assumed degradation rate of 1%/year within the Ecodesign draft. The degradation rate, although currently changeable with justification, is expected to be fixed in the upcoming release of the Ecodesign methodology draft. The tabulated degradation rates may differ based on technological differences but not reflect product specific degradation which may be different for different modules of the same technology. As observed at number (2) in Figure 5, the GWP of a module manufactured with HFS can reduce from 12.5 to 9.5 g CO_2-Eq./kWh when the degradation rate is improved from 1.5%/year to 0%/year. While using tabulated values fail to reflect the true performance of the module, allowing improvement through justification increases the dependency on a robust verification process. It seems that the manufacturer's performance

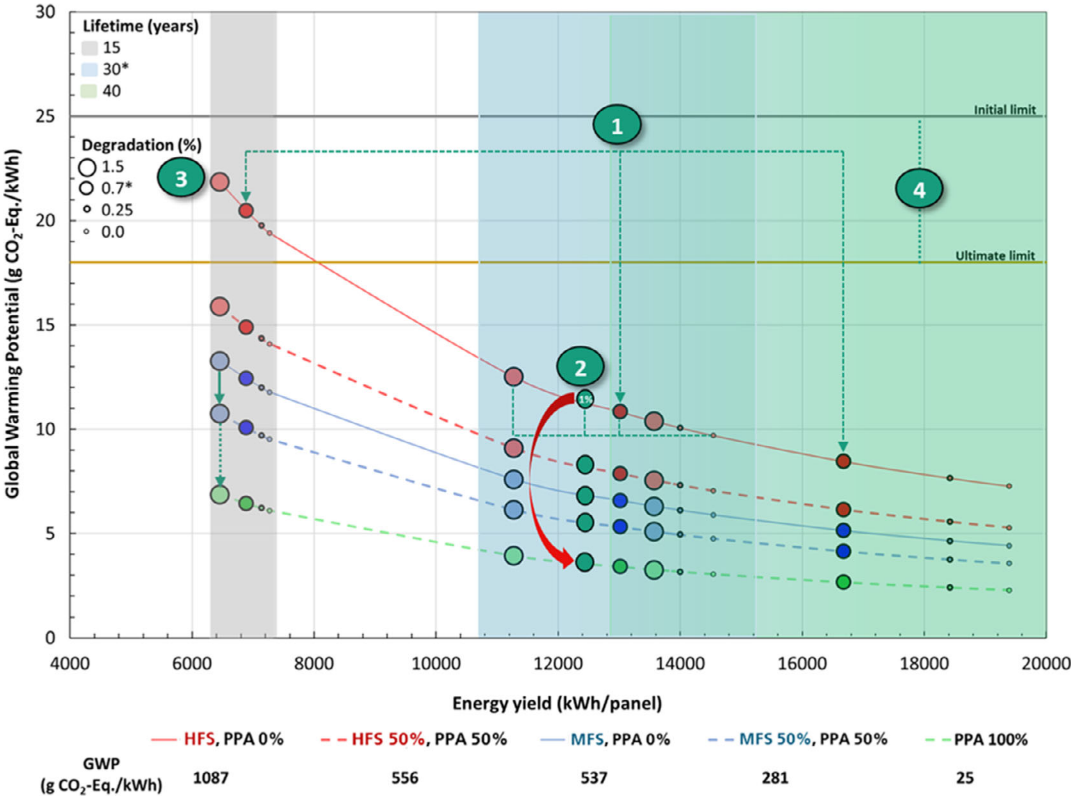

Figure 5. Comparison of the global warming potential (GWP) (g CO_2-Eq./kWh) of modules produced at a high fossil share (HFS) to moderate fossil share (MFS) electricity grid location. Influence of module peak power, lifetime, degradation rate and power purchase agreement (PPA) certificate allowance on the GWP. Calculated according to the guidelines of the Ecodesign adaptation of the PEFCR. Assumed module efficiency is 21.2%. The energy yield (kWh/panel) includes lifetime and degradation.

guarantee for lifetime and annual degradation is the most meaningful and practical statement about module quality. This is not precisely verifiable experimentally, but there are clear indications of which technologies have better performance (e.g., glass-glass is better than glass-backsheet). This goes into the performance guarantee given by the manufacturer, as they have to replace the modules if they are violated. It would be important here to clearly define what conditions a warranty must meet (proof, replacement, reserves built).

The verification process becomes most crucial for PEFCR, as it prioritized supplier-specific electricity. This means that power purchase agreement (PPA) or equivalent certificates are allowed without limit when the set of minimum criteria is met to ensure the contractual instruments are reliable. For this matter, the Ecodesign adaptation of the PEFCR also has strict guidelines as well as selective notified bodies, which are not assessed within the scope of this analysis. So long as reliable and effective verification is not in place, only standard values based on the national level electricity grid carbon intensities as published by IEA is recommended for a regulatory scenario as done by EPEAT path A and the French carbon footprint model (calculation method 1).

For example, at number (3) in Figure 5, a module (15 year lifetime, 1.5% degradation rate, HFS) intrinsically improve from 22.0 to 12.0 g CO_2-Eq./kWh due to the fixed lifetime and degradation values by methodology definitions. And secondly, this is further reduced to 8.5 g CO_2-Eq./kWh by using 50% PPA certificates. An MFS module under adapted PEFCR conditions can also improve its ecological profile using 50% PPA but at a lower magnitude- 7.0 to 5.5 g CO_2-Eq./kWh. However, if global certifications cannot be trusted then the EU manufacturers are vulnerable as it is possible to manipulate the GWP of HFS module with 22.1 g CO_2-Eq./kWh to a mere 3.5 g CO_2-Eq./kWh (when 100% PPA is used), significantly out-performing the MFS modules. Serious concern is observed throughout the European photovoltaic industry regarding the credibility of global certificates such as the PPA (or equivalent) and those certifying the raw material purchase. Unless global certificates (such as PPA, material purchase, etc.) can be reliably verified and tracked, there will be green-washing potential which can jeopardize the European PV industry. In contrast, if certificates are credible, comparable impacts of modules are obtained on kWh as well. However, the comparison may be inaccurate as overall performance of the module is considered same for all, which could even lead to false impression. Unreliable certificates would hamper label comparability and thus, the directive may not be successful at regulating the market entry and cutting out the least sustainable products.

Furthermore, as observed at number (4) of Figure 5, the initial market entry requirement of 25.0 g CO_2-Eq./kWh and ultimate market entry requirement of 18.0 g CO_2-Eq./kWh are relaxed for a module using the sate-of-the-art material and energy flows.

The entry limits set by the Ecodesign directive are found to be inclusive of all, but one sample considered in this analysis. It should be noted that with heavy national decarbonization goals, the carbon footprint of the grids shown in Figure 3 will decrease consequently. This will be represented in the latest versions of LCA databases, such as Ecoinvent, meaning that the carbon footprint of the PV module will be reduced without any technological improvements only due to the use of the updated database. Therefore, it is important for a directive to set an optimum market entry threshold which is neither too relaxed nor too strict, and reviewed periodically.

What makes the calculation in kWh functional unit more granular and comprehensive is its inclusion of location based solar irradiation, the module specific lifetime and degradation rate. On the contrary, to comply with the Ecodesign adaptation of the PEFCR, fixed assumed lifetime, tabulated annual degradation rate as well as a fixed temperate continental location must be used in the calculation and is thus not reflecting any specific product quality parameters. It is to be noted that the values obtained from the working document titled "Ecodesign requirements for photovoltaic modules and photovoltaic inverters, version 2" may be different in the latest version as this methodology is under development. However, an important observation for the PEFCR is that variables which makes the calculation comprehensive will reflect equalized tabulated values for all modules rather than the module specific values. Consequently, these parameters will not play a significant role in module differentiation or contribute to whether the modules qualify the market entry boundary.

4. Conclusion

As observed through this analysis, both methodologies show advantages and disadvantages regarding the objectives of the Ecodesign directive. However, in the interest of meeting the goals of the directive, the best fit methodology should be considered for the background assessment. Regarding the electricity choice, the most reliable methodology is the EPEAT path A which relies on standard national level electricity grid carbon intensities as published by the IEA. This is proposed as it has limited green-washing scope and dependence on certificate verification processes. The EPEAT path B enables use of 75% of national or sub-national electricity mix for production based on standard IEA carbon intensities, capping PPA use at 25%. If renewable energy certificates are allowed, such a cap is of great importance to a directive to avoid misuse which can be eventually relaxed with developing confidence on PPA credibility. However, the adapted PEFCR methodology prioritized supplier-specific electricity (with certificate). While this allows heavy influx of renewables in the production electricity mix, this also makes the success of the label heavily dependent on verification process of the quality assuring certificates. If certificates are not credible, EPEAT path A may be preferable to insure a transparent and fair comparison among international manufacturers.

It is clear, that the Ecodesign adaptation of the PEFCR entails a further downstream calculation to GWP impact per kWh. However, since the variables (lifetime, degradation) which makes the calculation granular will reflect equalized tabulated values for all modules rather than the module specific values, the "granularity" will not play any role in module differentiation or contribute to whether the modules qualify for the market entry. Comparison on a regulatory level may be inaccurate as overall performance of the module is considered the same for all modules, which in reality, is not the case. What plays a crucial role in maintaining the performance quality standards of the modules are the IEC performance tests required by both the methodologies. In this regard, the minimum requirements set for lifetime and degradation by EPEAT will be important to maintain state-of-the-art industry standards in the market. The Ecodesign directive will benefit from a similar minimum requirement, updated every 3 years to reflect the status quo.

Apart from the PPA cap, the true benefit of choosing a functional unit of the GWP per kWp rather than per kWh does not lie within its simplified calculations. Rather the global acceptance for GWP per kWp as a functional unit in the regulatory landscape of carbon footprint, such as in USA, France, South Korea, makes it more lucrative for different stakeholder of the PV industry. A globally unified assessment methodology is highly desired by the industry which would provide a cost and time saving opportunity for the manufacturers. And this makes the methodological alignment with EPEAT, being the global type 1 ecolabel, important.

Apart from the parameters analyzed in this study, the quality of PPAs and equivalent certificates used as production electricity as well as the quality of the LCI considered can have significant influence on GWP results. Therefore, it is important to study the effectiveness of the verification guidelines provided by each of the methodology and find necessary measure to close gaps.

Lastly, the current market entry requirements set by Ecodesign directive, 25 and 18 g CO_2-Eq./kWh which may change in the final version, are very relaxed for state-of-the-art PV material and energy consumptions. The entry limits are inclusive of most conventional modules available in the market today and there will be almost no drive toward market sustainability.

Acknowledgements

The authors would like to thank the European Solar Manufacturing Council (ESMC), European Solar PV Industry Alliance (ESIA), Ultra Low Carbon Solar Alliance (ULCSA), authors of EPEAT and the policy officers of EU Commission for the fruitful discussions which shaped this analysis.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

carbon footprint, ecodesign directive, electronic product environmental assessment tool, life cycle assessment, product environmental footprint category rules

Received: December 5, 2023
Revised: February 26, 2024

[1] UNFCCC, The Paris Agreement, **2016**.
[2] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions, in *Fit for 55': Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality*, European Commission, Brussels **2021**.
[3] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions, EU Solar Energy Strategy, **2022**.
[4] European Commission, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic And Social Committee and the Committee of the Regions, REPowerEU: Joint European Action for more affordable, secure and sustainable energy, **2022**.
[5] French Energy Regulatory Commission, Specifications for the call for tenders relating to the realization and operation Installations for producing electricity from solar energy "Ground-mounted power plants AO PPE2 PV Ground (Cahier des charges de l'appel d'offres portant sur la réalisation et l'exploitation d'Installations de production d'électricité à partir de l'énergie solaire « Centrales au sol ». AO PPE2 PV Sol)", **2023**.
[6] European Commission, About the energy label and ecodesign, https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/about_en, (accessed: November 2023).
[7] European Commission, Regulation (EC) No 66/2010 on the EU Ecolabel of 25 November **2009**.
[8] European Union, Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel, **2010**.
[9] D. Polverini, Technical stakeholder meeting Ecodesign measures under preparation on PV modules and inverters, **2023**.
[10] European Commission, in *Consumer Protection Enabling Sustainable Choices and Ending Greenwashing*, European Commission, Brussels **2023**.
[11] N. Dodd, N. Espinosa, P. van Tichelen, K. Peeters, A. Soares, in *Preparatory Study for Solar Photovoltaic Modules, Inverters and Systems: Final Report*, Publications Office of the European Union, Luxembourg **2020**.
[12] A. A. Khan, C. Reichel, P. Molina, L. Friedrich, D. M. Subasi, H. Neuhaus, S. Nold, *Sol. Energy Mater. Sol. Cells* **2024**, *269*, 112724.
[13] Green Electronics Council dba Global Electronics Council, EPEAT, in *Criteria for the Assessment of Ultra-Low Carbon Solar Modules*, Global Electronics Council, Portland, OR **2023**.
[14] Product Environmental Footprint Category Rules (PEFCR), Photovoltaic Modules Used in Photovoltaic Power Systems for Electricity Generation Version 1.2, December 31st 2021.
[15] ETIP PV, SolarPower Europe, PVthin, European Solar Manufacturing Council, IECRE, Expert Input Paper – Eco-Design & Energy Labelling for Photovoltaic Modules, Inverters and Systems in the EU.
[16] A. Wade, P. Stolz, R. Frischknecht, G. Heath, P. Sinha, *Prog. Photovoltaics* **2018**, *26*, 553.
[17] A. Wade, P. Sinha, K. Drozdiak, D. Mulvaney, J. Slomka, in *"2018 IEEE 7th World Conf. on Photovoltaic Energy Conversion (WCPEC) (A Joint Conf. of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC*), WIP Renewable Energies, Munich, Germany, **2018**, pp. 2600–2605.
[18] DIN EN ISO 14040:2009-11, Umweltmanagement_- Ökobilanz_- Grundsätze und Rahmenbedingungen (ISO_14040:2006); Deutsche und Englische Fassung EN_ISO_14040:2006, Berlin.
[19] ISO 14040, Environmental management-Life cycle assessment-Principles and framework, **2006**.
[20] R. Frischknecht, P. Stolz, G. Heath, M. Raugei, P. Sinha, M. de Wild-Scholten, in *Methodology Guidelines on Life Cycle Assessment of Photovoltaic*, 4th ed., International Energy Agency Photovoltaic Power Systems Programme, Paris, France **2020**.
[21] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, *Int. J. Life Cycle Assess.* **2016**, *21*, 1218.
[22] Hamburg: ifu Institut für Umweltinformatik Hamburg GmbH, Umberto 11.
[23] European Commission, "Ecodesign requirements for photovoltaic modules and photovoltaic inverters" Working document, version 2. This methodology is under development; values may be different in the latest version.
[24] A. Müller, L. Friedrich, C. Reichel, S. Herceg, M. Mittag, D. H. Neuhaus, *Sol. Energy Mater. Sol. Cells* **2021**, *230*, 111277.
[25] China Photovoltaic Industry Association, in *China PV Industry Development Roadmap (2021 Edition*), China Photovoltaic Industry Association, Beijing, China **2021**.
[26] IPCC, in *Climate Change 2013 – The Physical Science Basis*, Cambridge University Press, Cambridge **2014**.
[27] IEC 61853-4, Photovoltaic (PV) module performance testing and energy rating - Part 4: Standard reference climatic profiles, **2018**.
[28] D. Polverini, Updates of Ecodesign Methodology, **2023**.
[29] IEC TS 60904-1-2, Photovoltaic devices – Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices, **2019**.
[30] IEC 61215-1-1, Terrestrial photovoltaic (PV) modules – Design qualification and type approval - Part 1: Test requirements – Requirements for the design qualification of terrestrial photovoltaic modules suitable for long-term operation in open-air climates, **2021**.
[31] IEC 61730-1, Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction, **2016**.
[32] NSF/ANSI 457, Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters, **2019**.
[33] IEC 61215-1, Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements, **2021**.
[34] IEC 62093, Photovoltaic system power conversion equipment – Design qualification and type approval, **2022**.
[35] EN 45558, General method to declare the use of critical raw materials in energy-related products, **2019**.
[36] ISO 14067, Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification, **2018**.
[37] European Commission, Framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) 2023/0081(COD).
[38] United States Environmental Protection Agency, Sustainable Marketplace: Greener Products and Services. Electronic Product Environmental Assessment Tool (EPEAT).
[39] D. Polverini, N. Espinosa, U. Eynard, E. Leccisi, F. Ardente, F. Mathieux, *Sol. Energy* **2023**, *257*, 1.
[40] ETIP PV, SolarPower Europe, PVthin, European Solar Manufacturing Council, IECRE, Eco-Design and Energy Labeling for Photovoltaic Modules, Inverters and Systems – Enabling a Sustainable Value Chain in the EU?
[41] Anthesis LLC, Low Carbon Solar State of Sustainability Research: Prepared for the Global Electronics Council in support of EPEAT criteria development, **2021**.