Technology Collaboration Programme
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International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability

PVPS

Review of PV Sustainability Standards

2025

Report IEA-PVPS T12-30:2025

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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What is IEA PVPS Task 12?

The goal of Task 12 is to foster international cooperation and knowledge sharing on the sustainable aspects of PV technology, emphasizing environmental and social factors. Its mission is to provide essential information to stakeholders, enhancing consumer and policy-maker confidence in PV systems, and thereby accelerating the shift towards sustainable energy. The objectives of Task 12 are to: (1) Quantify PV electricity's environmental profile to enhance supply chain sustainability and enable comparisons with other energy technologies. (2) Enhance PV technology and materials circularity through novel analysis, legislative tracking, and technical standards development. (3) Investigate synergies between PV system deployment and its environmental and ecosystem impacts. (4) Identify and tackle both real and perceived social and socio-economic challenges to PV market growth. (5) Share analytical findings with technical experts, policymakers, and the public.

Task 12's first objective focuses on employing Life Cycle Assessment (LCA) for detailing energy, material, and emission flows across PV life cycles, including human health assessments. The second objective involves advancing the circular economy for PV modules and system components through research and metric development. The third objective is met by evaluating the impact of PV projects on ecosystems, including both standard and integrated systems like agrivoltaics. The fourth objective promotes sustainable practices within the solar value chain and assesses environmental, social, and socio-economic impacts of PV technology. Lastly, the fifth objective engages a wide audience through publications, presentations, and media collaboration, disseminating information and fostering industry-wide sustainable actions.

Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and TotalEnergies. Support from the U.S. Department of Energy and TotalEnergies is gratefully acknowledged.

Further information on the activities and results of the task can be found here: https://iea-pvps.org/research-tasks/pv-sustainability/.

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COVER PICTURE

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INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Review of PV Sustainability Standards

IEA PVPS
Task 12
PV Sustainability Activities

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TABLE OF CONTENTS

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LIST OF ABBREVIATIONS

ADEME	French Agency for Ecological Transition (Agence de la transition écologique)
AFNOR	French Standardization Association (Association française de Normalisation)
BAT	Best Available Techniques
BHRRC	Business and Human Rights Resource Centre
BOS	Balance of system
BSI	British Standards Institute
BTM	Beyond the Megawatt
C2C	Cradle to Cradle
CAB	Conformance Assurance Body
CDP	Carbon Disclosure Project
CSDDD	Corporate Sustainability Due Diligence Directive
CSR	Corporate Social Responsibility
CSRD	Corporate Sustainability Reporting Directive
EC	European Commission
EEA	European Environmental Agency
EEE	Electrical and electronic equipment
EPBT	Energy Pay-back time
EPEAT	Electronic Product Environmental Assessment Tool
EPIA	European Photovoltaic Industry Association
EPD	Environmental product declarations
EPR	Extended Producer Responsibility
ESG	Environmental & Social Governance
EVA	Ethyl vinyl acetate
FiT(s)	Feed in Tariff(s)
GEC	Global Electronics Council
GHG	Greenhouse Gas
GPP	Green Public Procurement
GRI	Global Reporting Initiative
IASB	International Accounting Standards Board
IEA	International Energy Agency
IIRC	International Integrated Reporting Council

IIM	Influence Interest Matrix
IEC	International Electrotechnical Commission
IECRE	International Electrotechnical Commission Renewable Energy
IFRS	International Financial Reporting Standards
ILO-MNE	International Labour Organization - Multinational Enterprises
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Standardisation Organisation
ISSB	International Sustainability Standards Board
ITCs	Investment Tax Credits
LCA	Life cycle assessment
NSF	National Scientific Foundation
OECD	Organisation for Economic Co-operation and Development
PAS 2050	Publicly Available Specification
PCF	Product carbon footprint
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PET	Polyethylene terephthalate
POM	Placed on the market (often referred as *Put on market* as well)
PV	Photovoltaics
QA	Quality Assurance
RBA	Responsible Business Alliance
RPSs	Renewable Portfolio Standards
R2	Responsible Recycling Standard
SASB	Solar Energy Sustainability Accounting Standard
SDGs	Sustainable Development Goals
SEC	Securities and Exchange Commission of United States
SEIA	US Solar Energy Industries Association
SERI	Sustainable Electronics Recycling International
SFDR	Sustainable Finance Disclosure Regulation
SME	Small and Medium Enterprise
SSI	Solar Stewardship Initiative
SVTC	Silicon Valley Toxics Coalition's

TCFD	Task Force on Climate-related Financial Disclosures
UFLPA	Uyghur Forced Labour Prevention Act
UL	Underwriters Laboratories
UNEP FI	United Nations Environmental Programme Finance Initiative
VALERI	Valuation of Energy Related Investments
WBCSD	World Business Council for Sustainable Development
WEEE	Waste electrical and electronic equipment
Wp	Watt peak
WRI	World Resources Institute
XUAR	Xinjiang Uyghur Autonomous Region

EXECUTIVE SUMMARY

As of 2025, less than 3,000 days remain for countries to achieve the Sustainable Development Goals (SDGs), a global initiative aimed at eradicating poverty and hunger while ensuring equal opportunities for all. Sustainability standards and frameworks are useful in reaching these targets, as they help companies apply the SDGs to benefit the environment, economy, and communities, as well as to identify business opportunities. This report offers a comprehensive review of the status of sustainability standards and organized schemes in the photovoltaics (PV) sector, covering the entire value chain.

The PV value chain, like any industrial sector, operates within a complex web of societal, regulatory, technological and economic contexts. Meaningful evaluation of performance indicators across the value chain requires codification and harmonization of methodologies and metrics. This harmonization provides a framework for granting, maintaining, or withdrawing operating licenses for value chain participants. Implementation of these frameworks can occur through commercial avenues (e.g., procurement requirements), regulatory measures (e.g., product policy instruments), and social mechanisms (e.g., stakeholder engagement in community-based initiatives).

We categorize the standards and frameworks into three main sections, noting that some standards have attributes leading to their inclusion in multiple sections:

1. Sectoral Reporting:
   - This section addresses industrial reporting obligations, further divided into corporate reporting, environmental performance declarations, and other industry standards and benchmarks.
2. Product-Related Standards:
   - This section covers typical standards associated with the PV industry, including harmonized documents that set requirements and rules for production, processes, and services. Examples include the NSF 457 PV ecolabel, developed by NSF International; and the horizontal[1] standards series EN 4555x, developed by the CEN-CENELEC, supporting the introduction of ecodesign requirements on material efficiency aspects across energy-related products by providing horizontal methods.
3. Regulatory Frameworks:
   - This section classifies standards related to regulatory frameworks, further divided into mandatory (e.g., EU Ecodesign), voluntary (e.g., Ecolabel), and waste-related frameworks (e.g., WEEE Directive).

In section 3 of the report, we evaluate the effects and impacts of these standards using methodologies such as the Organisation for Economic Co-operation and Development (OECD) six criteria, which provide a comprehensive framework for assessment:

1. **Relevance**: The extent to which the standards meet the needs and priorities of stakeholders.
2. **Effectiveness**: The degree to which the standards achieve their intended outcomes.

[1] Horizontal standards apply to several industries, while vertical standards apply to just a specific industry.

3. **Efficiency**: The measure of how efficiently resources are used to achieve the standards' objectives.
4. **Impact**: The broader, long-term effects of the standards on the sector and society.
5. **Sustainability**: The likelihood that the benefits of the standards will continue over time.
6. **Coherence**: The alignment and synergies between different standards and policies.

This evaluation provides insights into how these standards influence the PV sector's sustainability performance and highlights areas where improvements can better align with the SDGs.

Key Conclusions

From our analysis, several top-level insights emerge:

- **Gaps and Overlaps**: There are noticeable gaps in the existing standards, particularly in addressing the end-of-life management of PV products. Conversely, some areas show significant overlap, such as reporting requirements, which can be both beneficial for robustness and burdensome due to redundancy. Streamlining overlapping standards could enhance efficiency without sacrificing comprehensiveness.
- **Maturity of Standards**: The maturity of these standards varies widely. For example, regulatory frameworks like the EU Ecodesign are well-established and mature, whereas newer ecolabels and product-specific standards are still in nascent stages of development. This maturity spectrum indicates the PV industry's evolving approach towards comprehensive sustainability.
- **Novelty and Comparison with Other Sectors**: This analysis appears to be one of the first comprehensive reviews of sustainability standards specifically for the PV sector. While similar analyses have been conducted in other industries, such as electronics and automotive, the scope and application differ significantly. For instance, the automotive industry has more mature life cycle assessment standards, while the PV sector could be catching up.

Conclusions and Future Work

Given the dynamic nature of the PV industry and the rapid advancement of sustainability goals, periodically updating this analysis would be useful for tracking progress and incorporating new standards and frameworks. Continuous monitoring could help ensure that the PV sector remains aligned with the SDGs and adapts to emerging sustainability challenges and opportunities.

By mapping the connections between standards and the SDGs, this report aims to facilitate a deeper understanding of how the PV industry can contribute to a more sustainable future. We used the SDG Mapper tool, developed by the European Commission, to visualize the relationships between policies and the SDGs, helping stakeholders identify which goals and targets are addressed in their documents. This tool provides visualizations that enable users to make informed decisions and mainstream the SDGs into policy and decision-making processes.

Overall, this report serves as a resource for industry stakeholders, policymakers, and researchers, providing a structured overview of sustainability standards in the PV sector and select those that help in their alignment with global sustainability goals. This foundational analysis sets furthermore, the stage for future research and development in harmonizing and advancing sustainability standards within the PV industry.

1 INTRODUCTION

The socio-economic value of photovoltaic (PV) electricity generation is inextricably linked to sustainability attributes. The global deployment of PV systems at all scales has been supported by regulatory frameworks such as Feed-in-Tariffs (FiTs), Investment Tax Credits (ITCs), Renewable Portfolio Standards (RPSs), Building Standards, and other financial and non-financial incentives. This global support is based on the sustainability profile of the technology, which is a key enabler for achieving a transition towards a decarbonized global economy by mid-century, in line with the agreements of the Paris Accord.

Today, in some countries PV is already competitive against other sources of electricity. In fact, in many scenarios adding PV is already the most cost-effective way to add new capacity. Having been on an exponential growth trajectory for decades and conceivably continuing that way toward terawatt-scale deployment in the coming years, stakeholders increasingly pay attention to the sustainability performance of topics like material and energy supply chains, manufacturing capacities, and PV project development and life cycle management practices. This growth in attention is indicated by Environmental, Social & Governance (ESG) surveys being deployed to technology manufacturers as part of technical and financial due diligence during procurement and general transparency and benchmarking activities. Additionally, regulatory initiatives, such as the European Commission preparatory study for Eco-Design, Ecolabeling, Energy Labelling and Green Public Procurement (Dodd & Espinosa, Preparatory study for solar photovoltaic modules, inverters and systems – Task 8 Policy recommendations, 2020), are recommending policy instruments to further improve the environmental, energy and socio-economic efficiency of photovoltaic modules, inverters, and systems.

In recent years, the industrial, financial, and scientific communities involved in the PV value chain have responded to these requirements by developing comprehensive frameworks to measure and report the sustainability performance of PV systems on a life cycle basis. The subsequent chapters of this report portray the standards and frameworks that have been developed to provide a comprehensive overview and identify potential gaps and improvement opportunities.

As the industry enters the next growth phase—propelled by PV’s low-cost electricity generation—a granular focus on sustainability performance will help evolve the regulatory and non-regulatory framework conditions for further decarbonization of the economy. It will also help delineate what sustainability truly *is:* at present, terms such as “green”, “sustainable”, and “ESG” have many different meanings.

These terms, each with different approaches, are an overarching attempt to address one of the great failures of modern economics: i.e., to capture “externalities”, such as the impact of the emissions on the climate, and how these impacts translate into day-to-day costs of company operations. Risks to the environment, people, and infrastructures force companies to enact positive changes in order to satisfy consumer demands and improve public opinion. There is also pressure on industry and financial institutions to be more upfront: countries such as the UK are considering mandatory risk disclosures around climate-related risks to an organization’s business strategy. In the United States, there are prospects to impose climate risk reporting.

Messages from businesses are clearly stating the need to set global standards for carbon accounting and offsetting. Right now, there is a lack of clarity that promotes greenwashing and delays meaningful actions. This report is intended to clarify how standards relate to sustainability goals in the PV sector.

1.1 Motivation for reviewing PV sustainability standards

Following a first classification of sustainability initiatives in the PV value chain proposed by (Wade, Sinha, Drozdiak, Mulvaney, & Slomka, 2018), an Influence-Interest-Matrix (IIM) can be used to further characterize the dimensions of sustainability standards. In Table 1, the matrix maps the main focus areas of sustainability standards against key drivers and dimensions of impact. It is organized into four primary categories: “Reporting & Disclosure”, “Product performance”, “Manufacturing” and “Procurement”. These categories represent the main focus areas of the standards already developed; however, most of the standards and guidelines also cover aspects of all categories.

Table 1. Influence-Interest-Matrix for sustainability standards along the PV value chain. The "(X)" typically indicates optional fulfilment, while "X" represents a specific condition that is always fulfilled.

Influence-Interest-Matrix		DRIVERS							DIMENSIONS OF IMPACT				
		Regulator	Investor/Lendor		Customer		Competitor	Society	Market Access	Bankability	Compliance	Value Proposition	(Social) License to Operate
			Manufacturing	PV Systems	B2B	B2C							
SUSTAINABILITY STANDARDS	Reporting & Disclosure[1]	X		X	X		X	X	(X)	X	X	(X)	X
	Product[2]	X	X	X	X	(X)		(X)	X	X	X	(X)	X
	Manufacturing[3]	X	X	(X)	(X)	(X)		(X)		X	X	X	X
	Procurement[4]	(X)		X	X	(X)			X	(X)		(X)	

1: CDP, SASB, GRI
2: NSF 457 Sustainability Leadership Standard, Cradle-to-Cradle Certification Standard, Energy Label, Ecolabel, IECRE
3: IECRE, Eco-Design, Recycling
4: Green Public Procurement, Privat RfQs & Tender Requirements

The **Key Drivers** are the factors motivating the adoption or enforcement of standards, such as regulatory requirements, market expectations, or societal pressures.

The **Dimensions of Impact** are the areas where standards create measurable outcomes, such as environmental compliance, social equity, or economic resilience.

Onto the insights of the matrix, for instance, in the category of **Product Performance**, the matrix might reveal that most standards prioritize environmental attributes (e.g., energy efficiency, recyclability), whereas social criteria are less frequently addressed. In the **Manufacturing** category, standards often focus on workplace safety and emissions control, reflecting regulatory drivers.

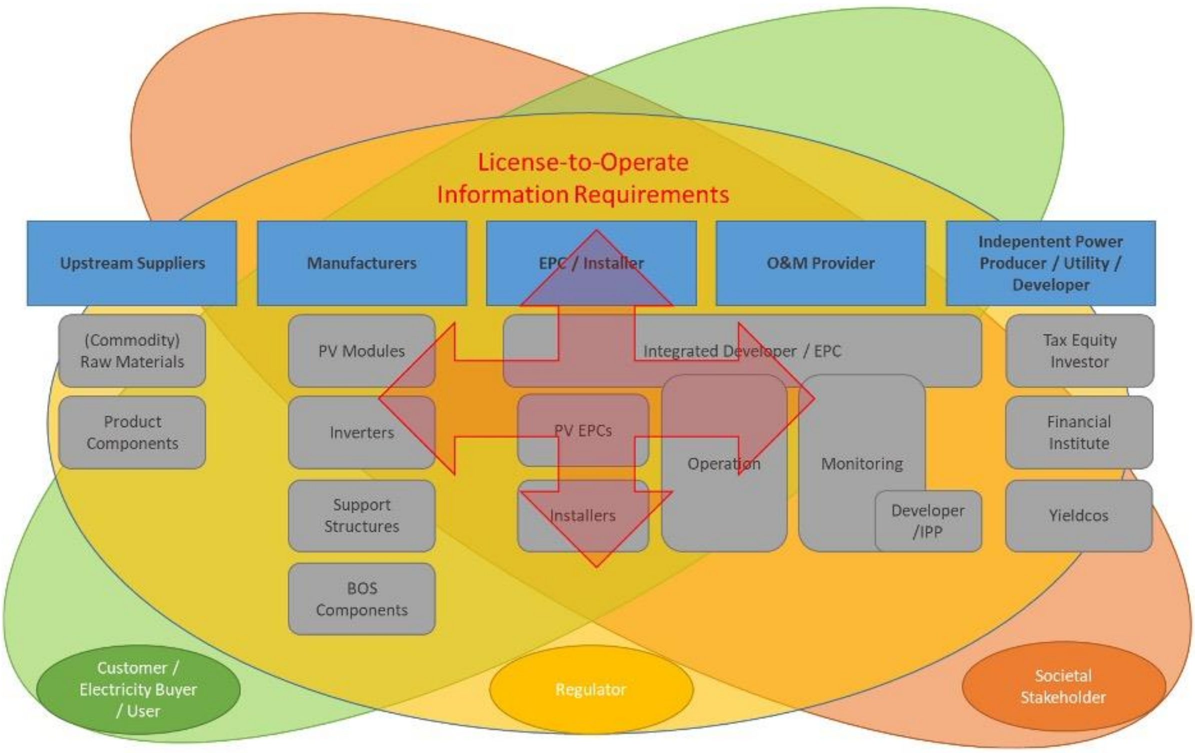
This structured approach facilitates informed decision-making by policymakers, industry participants, and other stakeholders, ensuring that sustainability initiatives effectively address both the immediate and long-term needs of the PV sector.

The PV value chain does not exist in a vacuum, as depicted in Figure 1. The subsequent chapters of this report will provide: (1) definitions of the terms and concepts used; (2) an overview on the structure of product and sector-specific sustainability standards and frameworks, which help to address the information and disclosure requirements identified in Figure 1; and (3) the effectiveness and impacts of those standards and frameworks.

Figure 1 below (adapted after (IEA PVPS Task 1 - 32, 2017; IEA PVPS Task 1 - 32, 2017) shows meaningful evaluation of performance indicators along the value chain -reflecting different societal, regulatory and economic backgrounds. Based on those, a definition of framework conditions for granting, maintaining or withdrawing operating licenses for value chain participants can take place. Implementation of these frameworks can then occur commercially through procurement requirements, regulatorily through product policy instruments restricting or enhancing market access, and socially through permitting.

Despite the exponential growth of PV over the last decades globally, as well as a fast-changing landscape of actors involved, codification and harmonization only recently took shape with sector-specific requirements, which now help to define comparable sustainability performance standards.

However, as the sustainable investment market evolves, the question is whether contributing to the energy transition is enough. Important topics remain unaddressed like forced labor in the supply chain, solar panel recycling, and managing commodity demand. Now the question is whether it is time for the solar sector to transform from product-led sustainability to one of sustainable operations?



The subsequent chapters of this report will provide: (1) definitions of the terms and concepts used; (2) an overview on the structure of product and sector-specific sustainability standards and frameworks, which help to address the information and disclosure requirements identified in Figure 1; and (3) the effectiveness and impacts of those standards and frameworks.

Figure 1. License-to-Operate information and disclosure requirements and interactions across the PV value chain.

1.2 Understanding the terms and concepts

This section gives definitions to help readers understand subsequent sections. Terms such as quality assurance, standards, accreditation bodies, reporting & disclosure and so on, will be hereafter used extensively.

1.2.1 Quality Assurance

Quality Assurance (QA) is part of the quality management system that ensures that stakeholders, including investors and developers, will meet quality requirements. Compliance with international standards and certifications at the market level helps to ensure quality and safety in the solar PV sector (International renewable energy agency [IRENA], 2015). Current QA standards in the solar PV industry primarily focus on production quality and module performance but do not address sustainability practices during the module's life cycle.

1.2.2 Standards

Standards are sets of requirements and rules for production, processes, and services. They aim to harmonize the market by defining methods and equivalent specifications. Recognized bodies establish and approve standards to achieve specific objectives.

Examples in the solar PV industry include:

- IEC 61215-1-1, IEC 61215-2, IEC 61730-1, which are quality assurance and safety qualification standards by the International Electrotechnical Commission for solar PV modules followed by Europe, Australia, China, and India.
- UL 61730, a quality assurance standard by Underwriters Laboratories (UL) for solar PV modules followed in America.
- ISO 9001, 14001, 45001, which check the conformity of sustainable manufacturing processes of solar PV modules.

1.2.3 Certification

Certification is a procedure used to assess whether a product, service, organizational management system, or individual's qualification meets the requirements of a standard. It involves "written assurances" provided by independent bodies and is voluntary in nature.

Examples in the solar PV industry include:

- Certification of management systems according to ISO 9001, 14001, 45001, which check the conformity of sustainable manufacturing processes of solar PV modules and guide designers and manufacturers through a continual improvement process.
- Certification of standards as IEC 61215 or IEC 61730
- Certification bodies like TÜV Rheinland, TÜV SÜD, VDE, UL, DNVGL, RISE, CERTISOLIS, etc.

1.2.4 Testing processes

The aim of testing is to verify the conformity of the test object to established quality, performance, safety, and reliability standards.

Examples in solar PV industry

Included in the IEC 61215 standard are 19 module quality tests, e.g., temperature cycling, outdoor exposure test, UV preconditioning, humidity freeze test, damp heat test, hail test, *interalia*.

1.2.5 Accreditation

The accreditation involves the independent evaluation of conformity by assessment bodies against recognized standards to ensure impartiality and competence to carry out specific services, such as tests, calibrations, inspections, and carbon footprint certifications.

Examples of accredited certification/inspection bodies[2] in the solar PV industry include testing laboratories such as TÜV Rheinland, TÜV SÜD, UL, DNVGL, CERTISOLIS, etc.

1.2.6 Inspection bodies

Inspection bodies, whether private organizations or government authorities, examine the design of products, services, procedures, and installations and evaluate their conformity with requirements found in laws, technical regulations, standards, and specifications.

Examples in the solar PV industry include inspection bodies like TÜV Rheinland, TÜV SÜD, UL, etc. Some organizations like TÜV and UL not only have testing facilities but also offer certification and inspection services.

1.2.7 Disclosure and reporting

Reporting and disclosure refer to the act of making facts and information available to the public. In the financial world, these terms pertain to the timely release of all information about a company that may influence an investor's decision.

Environmental disclosure has a long history, and various standard setters such as Carbon Disclosure Project (CDP), Internacional Integrated Reporting council (IRC), Solar Energy Sustainability Accounting Standard (SASB), and Task Force on Climate-related Financial Disclosures (TCFD), have been developed to promote transparent reporting on environmental aspects.

Creating manageable disclosure and reporting has become more urgent due to concerns about greenwashing. Deceptive ESG representation has drawn scrutiny from government and regulatory agencies, increasing general skepticism about ESG practices.

For instance, the U.S. Securities and Exchange Commission has been focusing on funds claiming to be environmentally friendly, and recommended climate-related disclosures, including information about climate-related risks and greenhouse gas emissions.

Measuring ESG-related data remains a challenge, particularly in assessing social factors, which will be further discussed in section 2.1.

1.3 Sustainability: dimensions and metrics

Sustainability is understood as an integrated approach that takes environmental concerns along with economic development into consideration. The United Nations (UN) defines sustainability as: “meeting the needs of the present without compromising the ability of future generations to meet their own needs’’ (World Commission on Environment and Development, 1987).

Reflective of the nested three dimensions of sustainability (Figure 2) , this framework has become a common reference point in the scientific, societal, and political discussions on sustainability. It emphasizes the fundamental hierarchy between the three dimensions of sustainability: the environment, society, and economy. This hierarchy acknowledges that a functioning economy depends on a healthy society, which, in turn, relies on a healthy and functioning environment. Unlike earlier representations, this conception avoids presenting the

[2] In the EU, there is one National Accreditation Body (NAB) per Member State according to Regulation (EC) No 765/2008. As an authoritative body appointed by its national authorities, the National Accreditation Body performs accreditation by assessing Conformity Assessment Bodies against international standards. See https://european-accreditation.org/accreditation/for-regulators/ for further info on accreditations.

three dimensions as equally weighted or implying a "balance" that could prioritize one dimension at the expense of another.

Sustainability is increasingly integrated into decision- and policy-making processes. This is reflected in the development of the Sustainable Development Goals (SDGs), accepted by all UN Member States in 2015. The SDGs framework is a call to promote prosperity while respecting the planet.

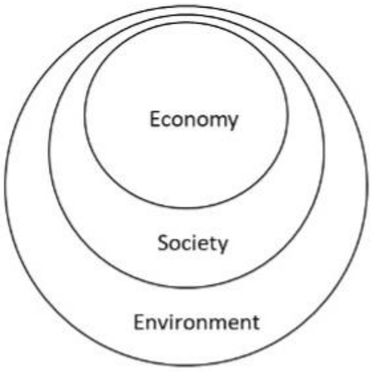


Figure 2. Nested representation of sustainability, adapted after (Purvis, Mao, & Robinson, 2019)

Along those dimensions and in line with the overall objectives of standardization, the standards aim to define a precise, concise, and widely applicable set of metrics and evaluation methodologies that characterize the performance of photovoltaic products and manufacturers. As such, those standards enable comparability and independent evaluation—the so-called "level playing field"— which form the basis for voluntary and regulatory frameworks aiming at validation of performance claims to protect consumer, share- and stakeholder rights, enhance the socio-economic performance of a product category, or restrict market access for non-performing products or value chain actors. Those mechanisms will be detailed in Chapter 2, where we provide an overview on the existing standards in conjunction with the implementing frameworks.

In line with the dimensions of sustainability, a classification of metrics and methodologies can be developed. A differentiation between LCA-based environmental performance metrics, single-issue metrics and social and economic governance metrics and indicators are common in the available sustainability standards for photovoltaics.

1.3.1 LCA-based environmental performance metrics

One of the best-known tools to account for environmental impacts is the life cycle assessment (LCA) methodology, complying with standards ISO 14040 and 14044. By using data from life cycle inventories, quantitative results for impact categories can be obtained at midpoint and then aggregated in endpoint categories of damage (e.g., global warming potential, human health damage, ecosystems damage, and resources depletion) following several impact methodologies (Table 2). When solar PV is compared to other renewable, fossil fuel, and nuclear electricity production, solar electricity has much lower impacts than fossil fuel electricity in most categories.

LCA can be used to evaluate the environmental impacts of PV products over their full lifetime, and it is extensively used to compare the environmental impact of different PV technologies. However, this framework leaves the individual practitioner with a range of choices that can affect the results—and thus the conclusions—of an LCA study. Therefore, the IEA PVPS programme published LCA guidelines for PV, offering sectoral guidance on how to do this (Frischknecht, y otros, 2020). PV-specific product category rules for environmental product declarations (EPD) have also recently been published by international EPD platforms (Norge; Italy; Commission, PEFCR, EU).

In addition to traditional LCA, the Life Cycle Sustainability Assessment (LCSA) framework is increasingly recognized as a comprehensive tool for evaluating the sustainability performance of PV products. LCSA extends the scope of conventional LCA by integrating social and economic dimensions, alongside environmental aspects, into the assessment. This holistic approach provides a more complete understanding of how PV technologies contribute to broader sustainability goals, such as fostering social equity or improving economic resilience.

As discussed in the next section, a number of simplified methods for analysing the life cycle of PV technology have been also used by the scientific community to address data and resource limitations in specific cases.

1.3.2 Single-issue metrics

When it comes to sustainability standards for PV systems, several single-issue metrics can be used to assess different aspects of sustainability. These metrics help evaluate the environmental impact and performance of PV products and processes. Here are some of the key single-issue metrics:

1. Materials & chemicals in products and processes:
    - Toxicological properties: Assessing the presence of hazardous materials in PV modules and their potential impact on human health and the environment.
    - Critical raw materials: Special attention is given to critical materials such as silver, indium, and rare earth elements, which play a pivotal role in PV technology but present challenges in terms of environmental impact and resource scarcity.
    - Management systems & policies: Evaluating the effectiveness of management systems and policies to ensure safe and responsible materials and chemicals handling throughout the PV modules life cycle.
2. Emissions:
    - Carbon footprint (carbon dioxide and other greenhouse gases): Quantifying the greenhouse gas emissions associated with the production, use, and disposal of PV modules. The GHG Protocol provides guidelines for calculating and reporting these emissions. IEA Task 12 Methodology Guidelines on Life Cycle Assessment of Photovoltaic[3] also provide specific recommendations for PV carbon footprint assessment; for example to use the most recent global warming potential (GWP) factors published by the IPCC.
3. Embodied energy and energy yield:
    - Energy payback time (EPBT): Measuring the time required for a PV system to generate the same amount of energy that was consumed during its manufacturing and installation. According to Fraunhofer ISE, it can range from 0.44-1.5 years for a PERC module rooftop system with ~20% efficiency[4].
    - Energy return on investment (EROI): Assessing the ratio of energy generated by a PV system over its lifetime to the energy invested in its production and installation. This metric links the energy yield of PV systems to their embodied impacts.

[3] https://iea-pvps.org/wp-content/uploads/2020/07/IEA_Task12_LCA_Guidelines.pdf

[4] Fraunhofer ISE: Photovoltaics Report, updated: 30 July 2024

Calculation methodologies and boundary definitions are described in the Task 12 LCA Guidelines[3].

4. Waste:
   - Product & production: Evaluating the amount of waste generated during the manufacturing and installation of PV systems, as well as the recyclability and disposal methods of end-of-life PV modules and inverters. Regulations like the **French AGEC law[5]** require higher recycling rates, emphasizing the need for effective end-of-life strategies to recover critical materials such as silver, silicon, and copper.
   - Management systems & policies: Assessing the effectiveness of management systems and policies to minimize waste generation, promote recycling, and ensure proper disposal of PV module waste.
5. (Waste) Water:
   - Water use & wastewater: Examining the amount of water consumed during the manufacturing and installation of PV modules, as well as the treatment and management of wastewater generated.
   - Management systems & policies: Evaluating the implementation of management systems and policies to minimize water consumption, promote water conservation, and ensure proper wastewater management.

These single-issue metrics are essential for assessing the sustainability performance of PV systems. They provide insights into the environmental impact, resource efficiency, and waste management practices associated with the production, use, and end-of-life treatment of PV modules and systems. By integrating these metrics into sustainability standards, the PV industry can strive for more sustainable practices throughout the life cycle of PV systems.

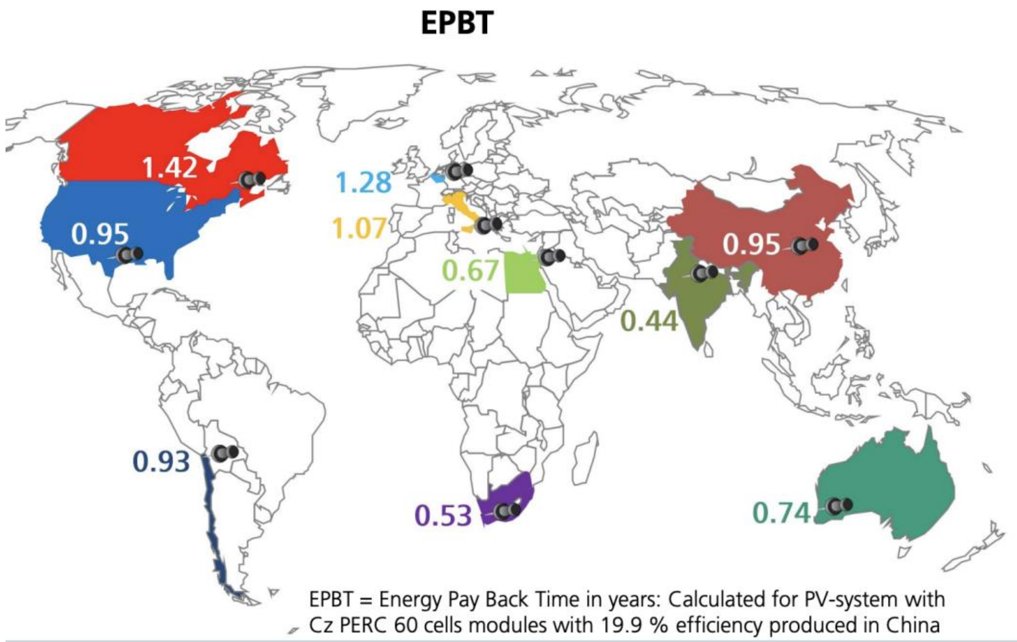


Figure 3. World Map EPBT of Silicon PV Rooftop Systems. From: [Fraunhofer ISE: Photovoltaics Report, updated: 30 July 2024][4]

[5] https://www.ecologie.gouv.fr/loi-anti-gaspillage-economie-circulaire

Table 2. Life cycle assessment results for production (material input) of 1 kWh by a multi-Si PV module using the EcoReport tool and Ecoinvent database for background data, e.g. electricity. The PV modules are considered to be ground-mounted at optimal fixed angle; Module-rated efficiency – 18%; Degradation rate –0.5% annually]; Lifetime of PV – 30 years; Installation location – Southern Europe with annual irradiation –1700 kWh/m²; Performance ratio –80%. Reproduced from (Polverini, Dodd, & Espinosa, 2021).

	Weight	GER	Water (proc.+cool)	Haz. Waste	Non-haz. Waste	GWP	AD	VOC	POP	HMa	PAH	PM	HMw	EUP
Photovoltaic cell	4%	72%	0%	98%	91%	79%	80%	70%	77%	91%	12%	76%	35%	86%
Interconnection - Tin	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	0%	0%
Interconnection - Lead	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Interconnection - Copper	1%	0%	0%	0%	0%	0%	2%	0%	1%	1%	0%	0%	6%	0%
Encapsulation - ethylvinylacetate	7%	3%	0%	0%	1%	1%	0%	9%	0%	1%	0%	0%	0%	3%
Backsheet - PVF	1%	1%	0%	0%	1%	1%	1%	2%	1%	1%	0%	0%	0%	2%
Backsheet - PET	3%	1%	13%	0%	0%	1%	1%	2%	0%	0%	0%	1%	0%	0%
Pottant & sealing	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%
Aluminium frame	16%	15%	0%	0%	4%	11%	9%	1%	19%	2%	87%	17%	46%	0%
Solar glass	66%	6%	0%	0%	4%	6%	6%	15%	2%	4%	0%	3%	2%	6%
Junction box - diode	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Junction box - HDPE	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Junction box - glass fibre	2%	1%	84%	1%	0%	1%	1%	0%	0%	0%	0%	1%	9%	1%

Note. In columns are the environmental categories: GER (Gross Energy Requirement), Haz./non Haz. waste (Hazardous/Non-hazardous waste), GWP (Global Warming Potential), AD (Abiotic Depletion), VOCs (Volatile Organic Compounds), POP (Persistent Organic Pollutants), HMa (Heavy Metals to air), PAH (Polycyclic Aromatic Hydrocarbon), PM (Particulate Matter), HMw (Heavy Metals to water), EUP (Eutrophication Potential).

contribution to impact category	X > 50%
contribution to impact category	25% < X < 50%
contribution to impact category	10% < X < 25%
contribution to impact category	X > 10%

1.3.3 Social & Economic Governance metrics

In the realm of sustainability standards for PV systems, the social and economic dimensions are also relevant. Social and Economic Governance aspects play a significant role in ensuring sustainable practices throughout the PV supply chain.

One critical area of focus is the supply chain, which involves assessing the sustainability and ethical practices of all stakeholders involved in the production and distribution of PV systems. This includes evaluating suppliers' environmental and social performance, ensuring responsible sourcing of raw materials, and promoting fair trade practices.

Labour policies and workers' rights are key considerations. PV sustainability standards aim to ensure fair treatment and safe working conditions; including fair wage policies, promoting non-discrimination and diversity, and ensuring health and safety protocols are in place.

Disclosure and reporting are fundamental in fostering transparency and accountability in the PV industry. Standardized reporting requirements help companies to disclose their social and economic performance, including sustainability progress, labour practices, and supply chain transparency. This allows stakeholders, including consumers and investors, to make informed decisions and hold companies accountable for their social and economic practices.

Social Life Cycle Assessment (Social LCA) is an emerging method to measure the social impacts of a product's life cycle, from raw material extraction to disposal. Still under development, Social LCA faces challenges in capturing regional and socio-political contexts. Tools often lack the granularity to address environmental justice issues or regional disparities, limiting the accuracy of local impact assessments.

By incorporating these social and economic governance metrics into PV sustainability standards, the industry can ensure that the human and economic aspects of PV systems are considered, fostering a more comprehensive and responsible approach to sustainable energy.

1.3.4 Supply Chain traceability and bifurcation: sector-wide challenges

A recurring concern in the governance of responsible sourcing frameworks across industries is the risk of supply chain bifurcation. This occurs when companies maintain parallel supply chains—one certified to meet high sustainability standards for specific markets, and another with lower levels of scrutiny that may continue sourcing from high-risk regions. This phenomenon has been observed in several sectors, including textiles and electronics[6], and is increasingly debated in the context of solar photovoltaic (PV) supply chains.

Supply chain bifurcation poses challenges for traceability and transparency, particularly when sustainability standards do not explicitly require disengagement from suppliers in regions where credible due diligence is not feasible. In such cases, companies may technically comply with a standard by certifying only a portion of their supply chain, while the rest remains unverified or opaque[7]. As an alternative to full and immediate disengagement, some initiatives focus on a continuous expansion of assessments across participants' sites and operations.

In the solar sector, this issue is particularly complex due to the historical concentration of upstream production. As of 2023, nearly 35% of the world´s supply of solar grade polysilicon

[6] Bartley, T. (2018). Rules without Rights: Land, Labor, and Private Authority in the Global Economy. Oxford University Press.

[7] https://www.antislavery.org/wp-content/uploads/2024/01/ASI-HCIJ-IAHR-Investor-Guidance.pdf

supply was sourced from the Xinjiang Uyghur Autonomous Region (XUAR)[8]. This share has been decreasing in recent years - in 2021 it was around 47%- reflecting a trend towards diversification[9]. Manufacturers committed to responsible practices have been gradually shifting and reconfiguring their supply chains away from XUAR[10]. Some analysts suggest that there is now sufficient polysilicon production capacity outside of XUAR to enable the establishment of cleaner supply chains for certain markets[11]. However, some players concerned about indirect exposure to XUAR recommend avoiding Chinese solar components altogether in order to meet the rapidly growing global demand for traceable and responsibly sourced solar components[12].

Another challenge in sustainability governance is the balance between the ambition of criteria and the level of industry adoption. On one hand, strong criteria—such as third-party audits, traceability to raw material origin, or independent governance—ensure rigor and credibility. On the other hand, if standards set a bar too high, few companies may be able to comply, limiting market transformation and potentially discouraging participation.

This strength–uptake trade-off is common in voluntary certification schemes[13]. Inclusive frameworks with sector-wide coverage may adopt a phased approach, requiring gradual improvements over time, while others enforce strict criteria from the outset. Both approaches have merits: the former encourages broad industry engagement and continuous improvement, while the latter provides strong signals for accountability and market differentiation.

This report does not attempt to resolve this tension, but acknowledges that the initiatives covered—both voluntary and regulatory—approach these trade-offs in different ways. As the solar sector matures and supply chain pressures grow, future research will be needed to identify best practices that combine broad adoption with credible impact.

1.4 A guide for how to read the report

This comprehensive review is not intended to be read in one long sitting. Instead, it reports on the *status quo* of sustainability standards and organized schemes in the PV sector, covering the entire value chain.

After the review, the authors divided the standards and frameworks into three main sections:

1. **Sectoral Reporting**: This section addresses industrial reporting obligations and is divided into corporate reporting, environmental performance declarations, and other industry standards and benchmarks.
2. **Product-Related Standards**: This section covers the typical standards associated with the PV industry, including harmonized documents that set requirements and rules for production, processes, and services. Examples include the NSF 457 Solar ecolabel and the horizontal standards series 4555x.

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[8] Crawford, A. and Murphy, L. T. (2023), "Over-Exposed: Uyghur Region Exposure Assessment for Solar Industry Sourcing," Sheffield, UK: Sheffield Hallam University Helena Kennedy Centre for International Justice, https://shura.shu.ac.uk/34917/

[9] According to BloombergNEF's Q4 2024 Global PV Market Outlook, Xinjiang's share further declined to approximately 20%.

[10] https://www.bloomberg.com/news/articles/2021-12-21/china-s-solar-industry-is-slowly-shifting-away-from-xinjiang

[11] https://pv-magazine-usa.com/2021/03/18/making-ultra-low-carbon-solar-the-global-standard-to-decarbonize-the-pv-industrys-supply-chain/

[12] https://www.reuters.com/breakingviews/supply-chain-scrutiny-may-upend-eu-solar-ambitions-2023-05-23/

[13] Auld, G. (2014). Constructing Private Governance: The Rise and Evolution of Forest, Coffee, and Fisheries Certification. Yale University Press.

3. **Regulatory Frameworks**: This section classifies standards related to regulatory frameworks, further subdivided into mandatory (e.g., EU Ecodesign), voluntary (e.g., Ecolabel), and waste-related frameworks (e.g., WEEE Directive).

In the final section, the report evaluates the effects and impacts of these standards by using *inter alia* OECD six criteria methodology.

2 REVIEW OF PV SUSTAINABILITY STANDARDS

We analysed the structure of identified sustainability standards, and they are classified into three main categories: Sectoral reporting policies, Product policies, Regulatory frameworks. Table 2 contains a description of schemes considered under each category.

Table 2. Structure and description of categories of PV sustainability standards used in this report.

Classification categories	Description
Sectoral reporting and disclosure	Set of activities that companies do to make facts and information available to the public. E.g. climate-related risks, disclosure of greenhouse gas emissions.
Product-related	Requirements and rules to be accomplished at production processes and services to PV industry, to harmonise the market by defining methods and equivalent specifications.
Regulatory frameworks	Governmental actions. Sustainable product policies that address different aspects associated with the life cycle of PV products. These policies typically make use of product sustainability standards for proof of compliance

2.1 Sectoral Reporting Standards

Sectoral reporting standards
Corporate responsibility – Environmental, Social, and Governance
Environmental performance declarations
Other industry benchmarks & best practices

2.1.1 ESG reporting initiatives

This section presents the ESG (Environmental, Social, and Governance) activities that companies undertake to make facts and information accessible to the public. These activities often include the disclosure of climate-related risks and greenhouse gas emissions.

Environmental & Social Governance reporting initiatives
Solar Energy Sustainability Accounting Standard (SASB)
Global Reporting Initiative (GRI)
Carbon Disclosure Project (CDP)
Valuation of Energy Related Investments (VALERI) standard
Climate risks- financial disclosure
Renewable electricity criteria RE100 Criteria
Social responsibility

The ability to trace the provenance of components through the supply chain - from input materials to the finished product - upholds corporate social responsibility principles, quality assurance, and environmental performance. Robust product traceability provides openness and transparency.

The EU's influence on climate action means its approach to sustainable investment is highly relevant. Its strategy sits within the Green Deal framework and incorporates ESG considerations to promote long-term investments in sustainable projects. The ESG market has grown substantially, driven by belief that ESG-focused investments can address environmental and social issues without sacrificing returns. A 2021 analysis showed that strong ESG propositions create value, leading to increased demand for sustainable products and services. According to financial services firm Morningstar, the number of ESG funds rose to 534 by the end of 2021, up from 392 the previous year.

ESG investments could soon make one third of projected assets under management. Bloomberg Intelligence projects global ESG assets to reach $50 trillion by 2025, up from $35 trillion in 2020. However, backlash exists due to varied ESG ratings methods, and the lack of standardised metrics. Recent fines and raids on asset managers for exaggerating ESG integrity highlight concerns, with ESG seeing its first outflow in five years in 2022.

ESG has become shorthand for companies with positive environmental and social impacts and strong governance. Governance ensures transparent decision-making, accountability, ethical behaviour, and risk management. Understanding ESG requires recognizing the importance of governance in driving sustainable business practices.

ESG is an investment lens, not a cure-all for sustainability issues, but it has become synonymous with sustainable, responsible, or green investment. MSCI Inc.[14], views ESG ratings similarly to credit ratings, focusing on the financial materiality of operations. The central question is whether investors should prioritize financial materiality or also consider the environmental and social impacts of operations. Different frameworks address this: the International Financial Reporting Standards Foundation focuses on financial significance, while the European Financial Reporting Advisory Group (EFRAG) introduces "double materiality" into the EU Sustainability Disclosure Standards[15], considering both financial and impact materiality. This concept will dictate how companies report to the CSRD (Corporate Sustainability Reporting Directive).

In the PV markets, there is a premium for better ESG performance. Players are willing to pay a premium for PV modules with good warranties, a lower carbon footprint, and delivery security, particularly in European markets. Achieving complete ESG transparency can result in a cost difference of 1.3 to 1.5 EUR ct/Wp[16], highlighting the impact of incorporating ESG factors throughout the value chain. This trend is expected to strengthen as the importance of ESG rises, especially among banking institutions.

In summary, integrating financial risk and impact is essential in the green-ESG market to ensure a comprehensive assessment of financial risks associated with social, environmental, and climate impacts. The emergence of a premium for better ESG performance in the PV markets underscores the need for robust ESG practices.

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[14] Previously named Morgan Stanley Capital Internacional

[15] https://ec.europa.eu/finance/docs/level-2-measures/csrd-delegated-act-2023-5303_en.pdf

[16] https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/building-a-competitive-solar-pv-supply-chain-in-europe#/

2.1.1.1 Sustainability Accounting Standard (SASB) applied to Solar Energy

(/Sectoral reporting standards/Corporate responsibility)

The International Financial Reporting Standards (IFRS) Foundation has established the International Sustainability Standards Board (ISSB) to meet the increasing demand for transparent financial-related sustainability disclosures. The ISSB aims to create a global baseline for sustainability reporting by leveraging existing investor-focused initiatives like the Sustainability Accounting Standard Board (SASB) Standards. In 2022, the IFRS Foundation took over the SASB through its merger with the Value Reporting Foundation. The SASB Standards identify the most relevant environmental, social, and governance issues for financial performance across 77 industries based on rigorous research and broad participation.

Recognized by global investors, the SASB Standards enable organizations to provide industry-specific sustainability disclosures that impact enterprise value. The ISSB plans to build on the industry-focused approach of SASB in its own standards development. The SASB Standards are integral to the Climate-related Disclosures Exposure Draft and the General Requirements for Sustainability-related Disclosures Exposure Draft. The ISSB encourages companies and investors to continue utilizing the SASB Standards until they are eventually replaced by the forthcoming IFRS Sustainability Disclosure Standards.

2.1.1.2 Global Reporting Initiative (GRI)

(/Sectoral reporting standards/Corporate responsibility)

The Global Reporting Initiative (GRI) was established in 1997 in response to public concern over the environmental damage caused by the Exxon Valdez oil spill. Its initial purpose was to create an accountability mechanism to ensure companies adhere to responsible environmental conduct principles. Over time, the scope of GRI expanded to include social, economic, and governance issues, making it a comprehensive sustainability reporting framework.

For the past 25 years, GRI has played a significant role in developing guidelines, standards, and aligning with the United Nations goals and Sustainable Development Goals (SDGs) (see Figure 4). It has become widely recognized as the most comprehensive framework for sustainability reporting. GRI is extensively used by multinational companies and has gained significant traction within the solar industry.

The prominence of GRI in sustainability reporting is reflected in the fact that the corporate reporting criteria in NSF 457, a sustainability leadership standard for solar PV modules, reference both GRI and the SASB. This recognition highlights the importance of GRI's guidelines and standards in promoting transparency and accountability in corporate sustainability reporting practices.

Figure 4. Timeline of GRI´s history. From www.globalreporting.org.

2.1.1.3 Carbon Disclosure Project - Sector Rules
(/Sectoral reporting standards/Corporate responsibility)

The Carbon Disclosure Project (CDP) is a global environmental disclosure platform helping companies and cities to measure and manage environmental impacts, promoting transparency and raising awareness regarding the sector's contribution to climate change mitigation.

By implementing CDP guidelines, companies can better understand their environmental impacts and identify areas for improvement; such as reducing greenhouse gas emissions, optimizing energy use, and adopting sustainable practices throughout their operations.

While CDP does not have specific sector rules dedicated to the PV sector, many organizations are voluntarily reporting their carbon emissions through initiatives such as the CDP.

Carbon Emissions Reporting

CDP encourages companies to disclose their greenhouse gas emissions, according to the **Greenhouse Gas (GHG) Protocol**[17], which categorizes emissions into three scopes:

- **Scope 1 (Direct Emissions):** These are emissions that occur from sources owned or controlled by the company, such as fuel combustion in company-owned vehicles or manufacturing equipment.
- **Scope 2 (Indirect Energy Emissions):** These include emissions resulting from the generation of purchased electricity, heating, cooling, or steam that the company uses.
- **Scope 3 (Other Indirect Emissions):** These encompass all other indirect emissions that occur in the company's value chain, both upstream (e.g., supply chain activities, raw material production) and downstream (e.g., transportation of products, end-of-life disposal of PV modules).

[17] https://ghgprotocol.org/corporate-standard

Energy Use Reporting

CDP also encourages companies to disclose their energy use, including renewable energy consumption. PV companies, being in the renewable energy sector, can highlight their use of clean and sustainable energy sources, showcasing their commitment to reducing reliance on fossil fuels.

Environmental Performance

While not specific to the PV sector, CDP provides a platform for companies to disclose their environmental performance across various metrics. PV companies can report on their water usage, waste management practices, and other environmental indicators, demonstrating their commitment to sustainability and environmental stewardship.

Investor and Stakeholder Engagement

CDP's disclosure platform is widely recognized and used by investors, financial institutions, and stakeholders to assess companies' environmental performance. PV companies that participate in CDP reporting can enhance their transparency and credibility among these audiences, potentially attracting investment and partnerships.

Climate Change Mitigation

By participating in CDP, PV companies contribute to the broader goal of climate change mitigation. PV technology plays a crucial role in decarbonizing the energy sector and reducing greenhouse gas emissions. Reporting through CDP can help showcase the industry's positive impact on addressing climate change.

2.1.1.4 Valuation of Energy Related Investments (VALERI) standard

(/Sectoral reporting standards/Corporate responsibility)

The CEN - EN 17463 standard is an important breakthrough in the developing field of “green finance”, and it was the result of the efforts of many European experts invested in this work during the pandemic.[18] It provides a description on how to gather, calculate, evaluate, and document information in order to create solid business cases based on Net Present Value calculations for ERIs.

The standard is applicable for the valuation of any kind of energy related investment. It focusses mainly on the valuation and documentation of the economic impacts of ERIs. However, non-economic effects (e.g., noise reduction) that can occur through undertaking an investment are also considered. Thus, qualitative effects (e.g., impact on the environment)—even if they are non-monetisable—are considered.

2.1.1.5 Climate risks- financial disclosure

(/Sectoral reporting standards/Corporate responsibility)

In today's business landscape, industries and financial institutions face growing pressure to increase transparency in ESG practices. Companies are increasingly aware of climate risks to society, infrastructure and environment, prompting proactive steps towards reducing climate impacts. Balancing public opinion and customer demands, they aim to align their short- and long-term strategies with the evolving macroeconomic context.

Internationally, several regulatory bodies are considering mandatory risk disclosures related to climate change. In the United Kingdom, discussions are underway regarding mandatory

[18] https://standards.globalspec.com/std/14477751/en-17463

climate-related risk disclosures for organizations, impacting their business strategies. Similarly, in the United States, the Securities and Exchange Commission is exploring the imposition of climate risk reporting requirements, signalling a growing awareness of the importance of climate-related financial disclosures.

Within the European Union (EU), significant strides are being made in the realm of sustainability reporting. As mentioned above in section 2.1.1, the EU has recently introduced an update to the Nonfinancial Reporting Directive through the Corporate Sustainability Reporting Directive (CSRD).[19] Under the CSRD, all large companies with over 500 employees and an annual turnover of at least €40 million will be required to report on their sustainability performance. Moreover, the European Commission has taken a significant step toward bolstering transparency in financial reporting by adopting sustainability reporting standards. To ensure effective implementation, these sustainability reporting standards have been developed in accordance with the technical advice provided by the European Financial Reporting Advisory Group (EFRAG).

Key details of the sustainability reporting standards are:

- Effective Date and Application: This regulation comes into force on the third day following its publication in the Official Journal of the European Union. It applies for financial years beginning on or after January 1, 2024.
- Consultation and Consideration: The Commission sought input from the Member State Expert Group on Sustainable Finance, the Accounting Regulatory Committee, and relevant authorities like the European Securities and Markets Authority (ESMA), the European Banking Authority (EBA), and the European Insurance and Occupational Pensions Authority (EIOPA). Their opinions were considered in alignment with Regulation (EU) 2019/2088.

These sustainability reporting standards mark a milestone in promoting sustainable business practices and harmonizing financial reporting across EU member states.

Furthermore, the Task Force on Climate-related Financial Disclosures (TCFD) has emerged as a framework for disclosing climate governance and risks.[20] CDP's Climate Change questionnaire has been in full alignment with TCFD guidelines since 2018, and it is committed financial transparency related to climate disclosures.

In 2022, the U.S. Securities and Exchange Commission proposed a significant climate disclosure rule, marking a step towards more sustainable reporting. While the CDP aligns with federal climate disclosure mandates, it remains committed to advancing voluntary, investor-grade environmental reporting. CDP is expanding its scope to address biodiversity, land use, and oceans, reflecting its dedication to broader sustainability issues.[21]

2.1.1.6 Renewable electricity criteria RE100 Criteria (/Sectoral reporting standards/Corporate responsibility)

RE100 is a global corporate renewable energy initiative bringing together hundreds of large businesses committed to 100% renewable electricity. RE100 defines renewable electricity consumption as the ability to make unique claims on the use of renewable electricity generation

[19] Corporate Sustainability Reporting Directive, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464

[20] https://www.fsb-tcfd.org/

[21] https://www.cdp.net/en/articles/climate/3-vital-things-to-know-about-the-secs-new-proposed-climate-disclosure-rule-and-where-cdp-fits-in

and its attributes. RE100 members must be able to demonstrate that they have an exclusive claim to use of unique renewable electricity generation to meet all its reported renewable electricity usage. Typically, this means ownership of the generation attributes (e.g. energy attribute certificates (EACs) associated with the generation. In markets without available renewable energy certificate systems, companies may be able to use other contractual instruments and arrangements between generators, suppliers, and users to ensure that no other entity may claim use or delivery of the same renewable electricity generation.

The criteria[22] elaborated by RE100 Technical Advisory Group, in consultation with the companies in the campaign, define what counts as sourcing renewable electricity for the purpose of participation in the RE100 campaign, introducing electricity accounting and reporting rules, providing regional or national context, and providing further briefings on emerging best practices.

2.1.1.7 Circular economy standards ISO 59000 series

On 22 May 2024, the International Organization for Standardization (ISO) published a new family of standards to guide the transition to the circular economy. The standards mark the first set of international definitions and rules for the circular economy.

The new ISO series provides a structured approach for organisations to measure and assess their circularity performance. It aims to standardise the process by which organisations collect and calculate data, using mandatory and optional circularity indicators.

The three new ISO Circular Economy standards are shown in Figure 5:

- ISO 59004: Terminology, Principles, and Guidance for Implementation
- ISO 59010: Guidelines for the Transition of Business Models and Value Networks
- ISO 59020: Measurement and Evaluation of Circularity

ISO 59000 divides the circular economy into six primary principles:

1. Systemic thinking, according to which the environmental, economic and social impact of operations must be considered.
2. Value creation through resource-efficient solutions,
3. Value sharing,
4. Ensuring resource availability,
5. Resource traceability along value chains, and
6. Protecting and restoring ecosystem sustainability and biodiversity

Hence the ISO 59000 standard will:

- help organisations align with global sustainability goals
- enhance transparency and accountability in environmental reporting
- support strategic decision-making for sustainable resource management.

The standards also provide support for measuring and assessing circularity performance across entire organizations, advising the measurement of renewability, reuse, and recycling of resource flows and the lifecycle as a whole.

[22] RE100 Technical criteria. Available at: https://www.there100.org/sites/re100/files/2021-04/RE100%20Technical%20Criteria%20_March%202021.pdf

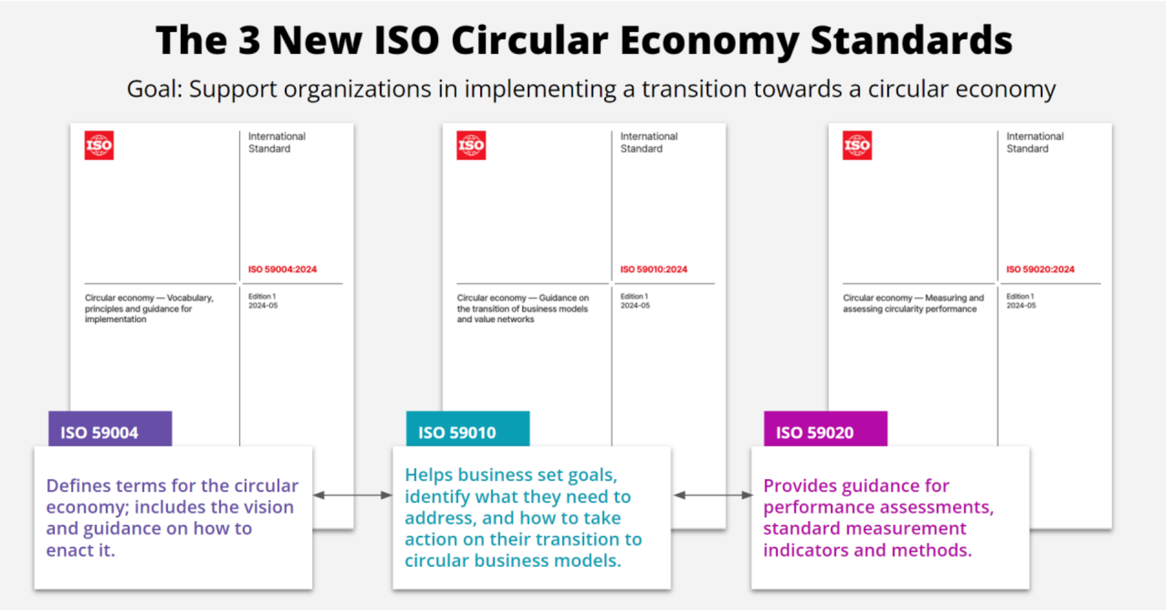

Figure 5. ISO Circular Economy standards. Source: ISO 59000 series.

2.1.2 Responsible supply chain

(/Sectoral reporting standards/Corporate responsibility)

2.1.1.9 Responsible supply chain
A. Legal acts: **These are binding regulatory frameworks enforced by governments, which companies must comply with**
- **Uyghur Forced Labor Prevention Act (UFLPA)**
- **EU Forced Labor ban**
- **Corporate Sustainability Due Diligence Directive (CSDDD)**
B. Voluntary initiatives Not legally binding but adopted voluntarily by companies and industry actors to demonstrate commitment to responsible sourcing and human rights
- **Solar supply chain traceability protocol**
- **Responsible Business Alliance (RBA)**
- **Responsible Supply Chains in Asia program**
- **Solar Stewardship Initiative**

Uyghur Forced Labor Prevention Act (UFLPA)

Social responsibility in the context of the solar supply chain is gaining significant attention due to growing concerns about forced labour and human rights abuses. The U.S. government and

G7 countries have identified forced labour as a major issue within the solar supply chain.[23] The 2023 Global Slavery Index lists solar panels as the fourth highest at-risk products in terms of value that are imported by the G20.[24] The U.S. has taken legislative action with the adoption of the Uyghur Forced Labor Prevention Act (UFLPA),[25] which instructs U.S. Customs and Border Protection to presume goods produced in the Xinjiang Uyghur Autonomous Region (XUAR) were made with forced labor and unfit for entry. This has a direct impact on the solar industry, as almost half of the world's polysilicon, a key component of solar panels, is produced in the XUAR[26,27]. Anti-Slavery International, the world's oldest human rights organization, has criticized solar industry associations for not doing enough to get solar companies to relocate their supply chains away from the XUAR[28]. Concerns have been raised by experts that the expansion of polysilicon production in Inner Mongolia could lead to similar risks as Xinjiang or Tibet, as government policies targeting ethnic assimilation are in place.[29]

EU Forced Labor ban and Corporate Sustainability Due Diligence Directive (CSDDD)

The European Union has also a regulation EU forced labor ban[30], including the possibility of incorporating the ban in addition to the Corporate Sustainability Due Diligence Directive (CSDDD)[31]. The EU has been actively promoting corporate social responsibility (CSR) and responsible business conduct (RBC) through various initiatives, including the implementation of international law instruments such as the United Nations Guiding Principles on business and human rights, the International Labour Organization's Multinational Enterprises Declaration, and the OECD guidelines and guidance.[32] Several initiatives have been launched starting from the EC communication 2011[33], to the directive 2014/95/EU[34] and the study commissioned by EU parliament 2020[35].

CSR and RBC are widely recognized as crucial concepts for addressing the negative impacts on society and the environment, including within global supply chains. A recent study published in November 2020 examined international law instruments on CSR, such as the UN Guiding Principles on business and human rights,[36], the ILO-MNE Declaration[37] (International Labour

[23] https://www.csis.org/analysis/operationalizing-g7-commitment-end-forced-labor-global-supply-chains

[24] Walk Free Foundation, Global Slavery Index, available at https://www.walkfree.org/global-slavery-index/downloads/

[25] Public Law, 117-78 (2021), available at https://www.congress.gov/117/plaws/publ78/PLAW-117publ78.pdf

[26] China Renewables: The Stretched Ethics of Solar Panels from Xinjiang, The Financial Times (Jan. 9, 2022), available at https://on.ft.com/3ndq1NE.

[27] https://www.state.gov/wp-content/uploads/2021/07/Xinjiang-Business-Advisory-13July2021.pdf

[28] Anti-Slavery International, Uyghur Forced Labour in Green Technology, available at https://www.antislavery.org/reports/uyghur-forced-labour-green-technology/

[29] https://acrobat.adobe.com/link/track?uri=urn%3Aaaid%3Ascds%3AUS%3Ad360ffab-40cc-4d83-8b8b-a8bd503286a3&viewer%21megaVerb=group-discover

[30] https://data.consilium.europa.eu/doc/document/PE-67-2024-INIT/en/pdf

[31] Legislative Proposal on Sustainable Corporate Governance, European Parliament, Legislative Train (2021), https://www.europarl.europa.eu/legislative-train/theme-an-economy-that-works-for-people/file-legislative-proposal-on-sustainable-corporate-governance; see also Sustainable Corporate Governance, About this initiative, European Commission, available at https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12548-Sustainable-corporate-governance_en.

[32] Corporate Social Responsibility – Recommendations to the European Commission By the subgroup on « CSR » of the Multi-Stakeholders Platform on the Implementation of the SDGs in the EU, https://ec.europa.eu/info/sites/info/files/recommendations-subgroup-corporate-social-responsibility_en.pdf

[33] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0681:FIN:EN:PDF

[34] Directive 2014/95/EU amending directive 2013/34/EU as regards disclosure of non-financial and diversity information by certain large undertakings and groups https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0095&from=EN

[35] Corporate social responsibility (CSR) and its implementation into EU Company law https://www.europarl.europa.eu/RegData/etudes/STUD/2020/658541/IPOL_STU(2020)658541_EN.pdf

[36] United Nations Guiding Principles on business & human rights https://www.ohchr.org/Documents/Publications/GuidingPrinciplesBusinessHR_EN.pdf

[37] Tripartite Declaration of Principles concerning Multinational Enterprises and Social Policy (MNE Declaration) - 5th Edition (2017) https://www.ilo.org/empent/areas/mne-declaration/lang--en/index.htm

Organization – Multinational Enterprises) and the OECD guidelines and guidance[38]. Moreover, the European Commission has responded to citizens' demand for sustainable business initiatives.

CSR as a critical asset to support investment of the energy sector

The expansion of sustainable finance, particularly green financing models based on ESG criteria, could significantly impact the energy sector's investment framework. Indeed, to achieve the carbon neutrality target on the front line, four European oil companies such as BP (UK), Shell (UK/NL), Total Energies (France), and Equinor (Norway) have announced in the end of 2024 **a** $500 million investment commitment to advance access to clean energy in underserved regions[39]. These investments are expected to be deployed in the context of green financing, aligning with UN Sustainable Development Goal 7 (UN SDG7), which promotes universal access to affordable, reliable, sustainable, and modern energy. If included in such green financing schemes, the photovoltaic sector will have to meet sustainability criteria including social criteria that are required to access financing from the "sustainable" taxonomy and be integrated into the portfolios of major financial institutions. Under the EU Taxonomy, companies must comply with minimum safeguards including no breach of labour law or human rights and no refusal to engage in stakeholder dialogue with an OECD National Contact Point or the Business and Human Rights Resource Centre (BHRRC).[40]

As an influential and powerful initiative, the UNEP FI[41] (United Nations Environmental Programme Finance Initiative) has developed guidance dedicated to banks and financial institutions to be used as impact analysis of their portfolios[42]. A full model to assess and enable trade-offs between client engagement and portfolios adjustments have been made available. This includes specific sections on Profile Business and Corporate Banking that map the significant impact areas with the main ones related to environment and social criteria. This will clearly incentivize the investors requests for environmental and social data and justifications to develop projects in the sector of renewable energy including photovoltaics.

Rights and returns at stake—supported by CSR

A report by the Business & Human rights Resource Centre (BHRRC) published in 2018[43] has raised important issues around the lack of consideration regarding CSR of the renewable energy sector. Indeed, 47% of the 59 companies surveyed including solar, bioenergy, and geothermal companies "had no public commitment to human rights, no commitment to consultations and no external facing grievance mechanism". The BHRRC's 2023 report notes that one of the biggest issues for the renewable energy sector and the global transition remains its exposure to the risk of forced labor in Xinjiang. It concludes that in the case of the XUAR, where the severity of the impact is high (as documented by the UN Special Rapporteur on

[38] OECD – Guidelines for Multinational Entreprises http://www.oecd.org/daf/inv/mne/48004323.pdf & OECD - Due Diligence Guidance for RBC http://mneguidelines.oecd.org/OECD-Due-Diligence-Guidance-for-Responsible-Business-Conduct.pdf

[39] https://www.offshore-energy.biz/totalenergies-shell-bp-and-equinor-to-assist-in-tackling-energy-access-woes-with-500m-pledge/

[40] https://finance.ec.europa.eu/system/files/2022-10/221011-sustainable-finance-platform-finance-report-minimum-safeguards_en.pdf

[41] UNEP FI works with more than 350 members – banks, insurers, and investors – and over 100 supporting institutions – to help create a financial sector that serves people and planet while delivering positive impacts.

[42] PORTFOLIO IMPACT ANALYSIS TOOL FOR BANKS https://www.unepfi.org/positive-impact/unep-fi-impact-analysis-tools/portfolio-impact-tool/

[43] Renewable energy risking rights and returns: Analysis of solar, bioenergy and geothermal companies 'human rights commitments: https://media.business-humanrights.org/media/documents/files/Solar_Bioenergy_Geothermal_Briefing_-_Final_0.pdf

Modern Slavery and UN expert body report[44]) and companies lack the ability to undertake human rights due diligence or use their leverage, ending business relationships with suppliers active in or linked to XUAR remains the only tool available for companies that want to ensure supply chains are not at risk of exposure to forced labor. This report provides recommendations directly addressed to investors in the sector to include social criteria in their frameworks.

Solar Supply Chain Traceability Protocol

Amid growing concerns regarding the sourcing of polysilicon, US Solar Energy Industries Association (SEIA) has taken steps to address these issues by creating standards and procedures aimed at tracing and auditing supply chains for PV materials.[45] This collective effort has yielded an industry initiative known as the "Solar Supply Chain Traceability Protocol"[46] . This protocol places emphasis on integrating product traceability into management systems and operational processes, with key focus areas including leadership commitment, resource allocation, competency development, and effective communication.

While this protocol addresses certain aspects of supply chain management, it also has limitations. Notably, the protocol is based on ISO 9001, a quality management standard that primarily concentrates on product traceability. However, it does not comprehensively address social aspects as labor practices. This omission is noteworthy because the identification of potential human rights violations in supply chains hinges on considering these social aspects.

Another notable concern is transparency. Despite global pressure and the introduction of the Solar Supply Chain Traceability Protocol, many companies in the solar industry have not disclosed the results of their adherence to these standards. In fact, according to a recent report by Sheffield Hallam University[47], the solar industry has become less transparent over time.

In addition, organizations signing the protocol are also asked to sign a “Solar Industry Commitment to Environmental & Social Responsibility,” often referred to as the “Solar Commitment.” This commitment serves as an industry code of conduct, outlining common practices and expectations related to environmental responsibility, ethical conduct, labour practices, health and safety, and management systems. It draws from the Code of Conduct version 6.0 (2018) as a foundational reference (see next section).

In conclusion, while the Solar Supply Chain Traceability Protocol and the accompanying Solar Commitment represent efforts to address issues in the solar supply chain, social issues are lacking there. A holistic approach that encompasses social responsibility, labor practices, and transparent reporting with global sustainability objectives.

Responsible Business Alliance (RBA)

The Responsible Business Alliance (RBA), formerly the Electronic Industry Citizenship Coalition (EICC), is the world's largest industry coalition dedicated to corporate social responsibility in global supply chains.[48] The RBA Code of Conduct is a set of social,

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[44] United Nations Human Rights Council, 2022. Promotion and protection of all human rights, civil, political, economic, social and cultural rights, including the right to development “Contemporary forms of slavery affecting persons belonging to ethnic, religious and linguistic minority communities”, at: https://documents.un.org/doc/undoc/gen/g22/408/97/pdf/g2240897.pdf

[45] Solar Industry Forced Labor Prevention Pledge, Solar Energy Industries Association (Nov. 23, 2021), available at https://www.seia.org/sites/default/files/Solar%20Industry%20Forced%20Labor%20Prevention%20Pledge%20Signatories.pdf.

[46] Solar Supply Chain Traceability Protocol 1.0: Industry Guidance, Solar Energy Industries Association (Apr. 2021), available at https://www.seia.org/sites/default/files/2021-04/SEIA-Supply-Chain-Traceability-Protocol-v1.0-April2021.pdf.

[47] Crawford, A. and Murphy, L. T. (2023), “Over-Exposed: Uyghur Region Exposure Assessment for Solar Industry Sourcing,” Sheffield, UK: Sheffield Hallam University Helena Kennedy Centre for International Justice, Online.

[48] https://www.responsiblebusiness.org/

environmental and ethical industry standards that aims to ensure that working conditions in industry and its supply chains are safe, that workers are treated with respect and dignity, and that business operations are environmentally responsible and conducted ethically. Although the RBA Code of Conduct originated with the electronics industry in mind, it is applicable to and used by many other industries and is referenced in the EPEAT Ecolabel for Solar (see section 2.2.2). Founded in 2004, the RBA has a 20-year track record of helping companies improve sustainability and human rights in their supply chains. Based on its Code of Conduct, the RBA's Validated Assessment Program includes onsite compliance verification and shareable audits. Independent third-party onsite social audits are an important part of assessing compliance with human rights and environmental requirements as part of a company's corporate sustainability due diligence on its operations and supply chain.[49] The EU Commission's Guidance on Due Diligence for EU Businesses to Address the Risk of Forced Labour in their Operations and Supply Chains recognizes business networks working in global supply chains, such as the RBA, as a way to take joint action and to make auditing more efficient. In regions where independent audits are possible, the EU Commission's Guidance suggests that third-party social audits can be a useful tool for identifying signs of forced labor.[50]

Solar Stewardship Initiative (SSI)

The Solar Stewardship Initiative[51] (SSI) is a sector supply chain sustainability assurance initiative. Initiated in 2022 by SolarPower Europe and Solar Energy UK, today the SSI is a standalone organisation comprising around 50 corporate members and 20 non-industry stakeholders. It is governed by a multi-stakeholder Board, including experts in human rights, sustainability and solar supply chain, from industry, civil society, international financial institutions as well as independent experts[52]. Representing over 60% of global PV modules shipments[53,54]. The SSI sets out a framework to help companies enhance responsible sourcing and corporate sustainability practices[55]:

The SSI is structured around two standards. The first is the ESG Standard[56], whose goal is to promote ethical solar panel and component production aligned with international standards. Certification is based on independent third-party audits that include inspections of manufacturing sites, unsupervised worker interviews, and documentation reviews. Companies are assessed under three levels (Bronze, Silver, Gold). Sites that do not allow unrestricted audit access cannot be certified to any of the program's three levels. To drive continuous improvement, companies that do not achieve Gold certification must implement improvement plans before reassessment. In January 2025, the SSI published its first ESG site certificates,[57]

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[49] COM (2022) 71 Proposal of a Directive on Corporate Sustainability Due Diligence, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0071

[50] Guidance on due diligence for EU businesses to address the risk of forced labour in their operations and supply chains available at https://media.business-humanrights.org/media/documents/tradoc_159709.pdf

[51] https://www.solarstewardshipinitiative.org/

[52] https://www.solarstewardshipinitiative.org/about-ssi/governance/ and https://www.solarstewardshipinitiative.org/news/the-solar-stewardship-initiative-announces-its-multi-stakeholder-board/

[53] https://www.solarstewardshipinitiative.org/about-ssi/members/

[54] https://www.rts-pv.com/en/blogs/12764/

[55] https://www.solarstewardshipinitiative.org/app/uploads/2023/11/SSI-Principles.pdf

[56] https://www.solarstewardshipinitiative.org/ssi-standards/esg-standard/

[57] https://www.solarstewardshipinitiative.org/news/first-esg-assessments-successfully-completed-and-more-underway-under-the-solar-stewardship-initiative/

and the total pipeline of upcoming ESG site assessments comprised a module production capacity of 100 GW, which is significantly above most estimates for the EU's annual solar installation needs in 2025, commonly cited in the range of 65–70 GW[58].

The second SSI standard is the Supply Chain Traceability Standard[59], which establishes a Chain of Custody to trace materials used in solar production. It defines the structure of traceability management systems that sites must implement, but it does not set targets or restrict sourcing of non-certified materials. In the first year, certified companies must trace materials to the polysilicon level as a minimum. If tracing upstream quartzite is not feasible, a corrective action plan with surveillance assessments must be implemented to ensure progress towards full traceability, albeit without a specific timeline [60].

The SSI is designed to support compliance with emerging regulatory requirements in the EU, including the Corporate Sustainability Due Diligence Directive (CSDDD)[61], the Corporate Sustainability Reporting Directive (CSRD)[62], or the EU Forced Labor Ban Regulation[63]. However, it does not exempt companies from the application of these laws[64].

SSI members are required to assess a minimum of two manufacturing sites during the first year and continuously increase the number of sites assessed[65], and to report publicly on their sustainability performance.

Responsible supply chains in Asia

The "Responsible Supply Chains in Asia program"[66] implemented by the International Labour Organization (ILO) from 2015 to 2020 aimed to promote responsible business practices and improve working conditions in supply chains in Asia. The program focused on addressing labor rights issues, including forced labor, child labor, and other forms of exploitation, within global and regional supply chains.

The program emphasized multi-stakeholder collaboration involving governments, employers, workers, and other relevant actors to create sustainable and responsible supply chains. It aimed to strengthen the capacity of these stakeholders to understand and address labor rights challenges in supply chains, as well as to foster dialogue and cooperation among them.

Key components of the program included:

- Research and data collection: The program researched labor rights violations in Asian supply chains, providing a basis for developing targeted interventions and policies.

[58] EU Market Outlook for Solar Power 2024-2028, from: https://www.solarpowereurope.org/insights/outlooks/eu-market-outlook-for-solar-power-2024-2028/

[59] Published in December 2024 at: https://www.solarstewardshipinitiative.org/ssi-standards/supply-chain-traceability-standard/

[60] https://www.solarstewardshipinitiative.org/news/the-ssi-lifts-temporary-suspension-of-ja-solar-membership-following-investigation/

[61] See section 2.1.1.9 of this report.

[62] See section 2.1.1.5 of this report.

[63] See section 2.1.1.9 of this report.

[64] https://www.solarstewardshipinitiative.org/frequently-asked-questions/

[65] SSI ESG standard/principles

[66] *Responsible Supply Chains in Asia* (*China* , *Japan* , *Myanmar* , *Thailand* , *Philippines* , *Vietnam)* : https://www.ilo.org/asia/projects/rsca/WCMS_734860/lang--en/index.htm

- Capacity building and awareness-raising: training governments, enterprises and workers' organizations, to enhance their skills in promoting responsible business practices and ensuring compliance with labor standards.
- Policy and legal framework development: The program supported the development and implementation of policies and legal frameworks at national and regional levels to address labor rights issues in supply chains. This included advocating for the ratification and effective implementation of international labor standards and promoting responsible business conduct.
- Public-private partnerships: The program facilitated dialogue and collaboration between the public and private sectors to encourage responsible supply chain management. It sought to establish partnerships that promote fair and decent work, uphold labor rights, and ensure the protection of workers in supply chains.
- Knowledge sharing and best practices: The program aimed to disseminate knowledge, share best practices, and promote learning among stakeholders. This included organizing workshops, conferences, and other events to facilitate the exchange of experiences and lessons learned in promoting responsible supply chains.

2.1.3 Environmental performance declarations

This section covers key aspects of environmental performance declarations, including product category rules (PCRs) and the Sustainable Finance Taxonomy. These elements support standardizing and communicating the environmental impact and sustainability of products and financial activities.

Environmental performance declarations
Product category rules (PCRs)
Sustainable Finance Taxonomy

2.1.3.1 Product category rules

(\Sectoral Reporting Standards\Environmental performance declarations)

Product Category Rules provide category-specific guidance for estimating and reporting product life cycle environmental impacts, typically in the form of environmental product declarations (EPDs) and product carbon footprints. A lack of global harmonization between PCRs or sector guidance documents has led to the development of duplicate PCRs for same products. Differences in the general requirements (e.g., product category definition, reporting format) and LCA methodology (e.g., system boundaries, inventory analysis, allocation rules, etc.) diminish the comparability of product claims.

In Norway, France, Sweden and Italy[67], specific PCR guidelines are in place for performing EPDs for PV modules since 2020.[68] Key points include:

[67] https://www.epditaly.it/en/pcr_/pcr-for-pv-panel-epditaly-014/

[68] Product Category Rules - Part B for photovoltaic modules used in the building and construction industry, https://www.epd-norge.no/getfile.php/1315101-1601554095/PCRer/NPCR%20029%202020%20Part%20B%20for%20photovoltaic%20modules%201.1%20011020.pdf

- Functional Unit: The EPD should define the functional unit, which is typically 1 Wp (watt peak) of manufactured photovoltaic module. The nameplate capacity of the module, as specified in the data sheet, is used to determine the Wp.
- System Boundaries: The system boundaries should be clearly defined, indicating which processes and components are included in the EPD. For PV modules, it's important to exclude components like mounting systems, inverters, and electrical components necessary for connecting the module to the grid.
- Life Cycle Stages: The EPD should cover the cradle-to-grave life cycle stages of the PV module. This includes stages such as:
  - A1-A3 (Manufacturing Phase): Includes raw material extraction, processing, and manufacturing of the product.
  - A4 (Transport Phase): Covers the transportation of the product to the site of installation.
  - A5 (Installation Phase): Accounts for the installation process, including any materials or energy required.
  - B1-B7 (Use Phase): Represents different aspects of the product's operational life, such as maintenance, repair, and energy performance.
  - C1-C4 (End-of-Life Phase): Covers decommissioning, dismantling, waste processing, and final disposal.
  - D (Beyond the System Boundary - Reuse/Recovery/Recycling Potential): Considers the potential benefits of material recovery, recycling, or reuse after the product’s life cycle.
- Reference Service Life: The EPD should specify the reference service life of the PV module. This is the expected duration where the module's actual power output will be no less than 80% of the labelled power output. The reference service life should be supported by third-party validated reports or certificates. If no third-party report is available, a standard reference service life of 25 years for ≥80% of the labelled power output is typically used.
- Data Selection: The EPD should provide detailed information on the data selection process. It should specify whether EPDs for upstream processes (such as cell, wafer, ingot, or solar grade semiconductor production) are available or if specific data or adjusted generic data from databases are used as proxies. To ensure credibility, the Norwegian EPD guidelines recommend that the electricity mix utilized during the production of components such as cells, wafers, ingot blocks, Silicon on Glass (SoG), solar substrates, solar superstrates, or other solar-grade semiconductor materials should align with the national grid mix of the production country. This includes considerations for imports, direct emissions, infrastructure, and transmission losses. The use of electricity derived from guarantees of origin is not permitted for modeling electricity in the PV value chain in EPDs; however, Life Cycle Impact Assessment (LCIA) results using such electricity can be provided as supplementary environmental data. (Norge, E., n.d.)
- Impact Assessment: The EPD must assess environmental impacts of the PV module throughout its life cycle. This assessment typically covers categories such as global warming potential, energy use, water use, and resource depletion.
- Additional Technical Information: The EPD should provide technical information about the PV module, such as the total mass, rated output, area, number of cells, and conversion factors. The EPD should also specify the technology type (e.g., mono-Si, multi-Si, CIGS, CdTe) and any specific degradation rates or material consumptions.

- Declaration of Environmental Parameters: the environmental parameters derived from the LCA (Life Cycle Assessment), such as environmental impacts, resource use, water use, electricity use, and waste categories.
- Additional Information: The EPD may include data on dangerous substances, carbon footprint, and other relevant details.

Specific Product environmental footprint category rules for photovoltaic modules, is a European Commission initiative that has been included under Regulatory Frameworks, in section 2.3.2.3

2.1.3.2 Sustainable Finance Taxonomy

(\Sectoral Reporting Standards\Environmental performance declarations)

The Sustainable Finance Taxonomy is a classification system created by the EU in 2020[69] to define and categorize economic activities that contribute to environmental sustainability. The main goal of the taxonomy is to provide a common language and framework for identifying environmentally sustainable activities, helping investors, companies, and policymakers align their actions with climate and environmental objectives.

The Sustainable Finance Taxonomy was established as part of the EU's efforts to transition towards a more sustainable and low-carbon economy. It was developed by the Technical Expert Group on Sustainable Finance (TEG) and forms a crucial component of the EU's Sustainable Finance Action Plan. The taxonomy aims to address greenwashing (misleading environmental claims) and facilitate sustainable investments by providing clear criteria for determining whether an economic activity is environmentally sustainable.

The taxonomy focuses on six environmental objectives:

- Climate change mitigation
- Climate change adaptation
- Sustainable use and protection of water and marine resources
- Transition to a circular economy
- Pollution prevention and control
- Protection and restoration of biodiversity and ecosystems

The Sustainable Finance Taxonomy provides specific criteria and thresholds that economic activities, including PV manufacturing and PV electricity production, must meet to be considered environmentally sustainable. Here are some key recommendations for these sectors:

PV Manufacturing:

- Climate Change Mitigation: PV manufacturing should contribute to reducing GHG emissions. For example, the manufacturing process should have low emissions of CO_2 and other GHGs.
- Resource Efficiency: The use of resources, such as raw materials and water, should be efficient and sustainable.
- Chemical Use: The manufacturing process should avoid the use of hazardous substances and minimize chemical risks.

PV Electricity Production:

[69] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852

- Climate Change Mitigation: PV electricity production should significantly reduce GHG emissions compared to conventional fossil fuel-based electricity generation.
- Resource Efficiency: The PV system's design and operation should aim for resource efficiency, optimizing energy output while minimizing resource use.
- Environmental Impact: The PV electricity production should have minimal environmental impact on ecosystems, land use, and biodiversity.

It's important to note that the specific criteria and thresholds for PV manufacturing and PV electricity production may be periodically updated as scientific knowledge advances and technology improves. Companies involved in these sectors can use the Sustainable Finance Taxonomy as a guide to assess their environmental sustainability and align their practices with the EU's climate and environmental objectives.

2.1.4 Other industry benchmarks and best practices

Other industry benchmarks and best practices
Carbon accounting
ISO 14060 family standards
PAS 2050
GHG Protocol
ISO 14040 family
Product Environmental Footprint (PEF)
BP X30-323-0(AFNOR)
EN 15804:2012+A2:2019/AC:2021
Solar Bankability
TÜV SÜD
Intertek
PV ModuleTech Organization
Business & Human Rights
Silicon Valley Toxics Coalition scorecard
Solar Power Europe Sustainability Best Practices Report
Solarcentury report
ADEME Roadmap
Beyond the Megawatt

Sustainability practices, in the context of solar PV module manufacturing process and generally, cover aspects such as responsible life cycle management that minimizes environmental impacts, and having the smallest environmental footprint; e.g., carbon footprint or water consumption. The energy payback time is another parameter that is commonly used. It accounts for the amount of time a PV module or system must operate to recover the energy required to produce it (Table 3).

Table 3. Common sustainability practices in the PV module manufacturing industry

Responsible life cycle management
- **Minimize environmental impacts**
- **Enhance the social and economic benefits across their life cycle**
- **Implement best practices from raw material sourcing to product end-of-life**
Smallest environmental footprint
- **Smallest life cycle carbon footprint (gCO_2e/kWh)**
- **Lowest life cycle water consumption (litres/MWh)**
- **Fastest energy payback time (in years)**

2.1.4.1 Carbon accounting

(Sectoral reporting standards\Other industry benchmarks and best practices)

There is a range of product carbon footprint standards that have been developed in response to the need for transparency about GHG emissions of products at different points in time and by different organizations.

The current methodologies may be grouped into two families:

- Group 1: Single-issue methodologies, covering only emissions and impacts related to climate change.
    - The ISO 14060 family of standards (notably, 14067 and 14064)
    - National standards such as PAS 2050
    - The GHG Protocol Product Standard
- Group 2: Methodologies that have a broader scope, covering environmental issues beyond climate change. You can use the indicator for climate change from these methodologies to determine the product carbon footprint (PCF).
    - ISO 14040 family (14040 and 14044). They cover life cycle assessment (LCA) studies and life cycle inventory (LCI) studies.
    - The Product Environmental Footprint (PEF). This EU-recommended method to perform LCA studies aims to harmonize existing LCA standards. It requires 16 impact categories to be calculated, but some current legislative proposals recommend the method with climate change as sole indicator to report the PCF. Notably, PV was one of the three pilot sectors for PEF Category Rules (PEFCR) during the EU's pilot phase, with IEA PVPS Task 12 experts playing a leading role in their development (Wade, Stolz, Frischknecht, & Heath, 2017).
    - National standards such as BP X30-323-0. This standard was developed by the Association Française de Normalisation (AFNOR), tested in 2011 and finalized in 2015. Similar to the PEF, it covers a number of impact categories. The climate change indicator can be reported separately if needed. Although it was finalized in 2015, the BP X30-323-0 was part of a broader experimental phase and hasn't gained widespread use outside France. Its relevance persists mostly in French environmental communication practices and product labeling contexts.

- EN 15804:2012+A2:2019/AC:2021. This is the European standard providing core product category rules for all construction products and services. Like other multi-criteria methods, it covers a set of mandatory environmental impact indicators, including climate change. While all environmental indicators need to be calculated and reported, the climate change indicator can be used to quantify the carbon footprint of the product in scope.

All standards mentioned above are built on the principles established in ISO 14040 and ISO 14044. They also seek alignment with the latest IPCC reports. Although the methodologies aren't identical, their developers; British Standards Institute (BSI), World Resources Institute/ World Business Council for Sustainable Development (WRI/WBCSD), International Standardisation Organisation (ISO), Association française de Normalisation (AFNOR) and the European Commission (EC), aimed to increase alignment across their methodologies.

All methodologies provide requirements for dealing with specific issues relevant for carbon footprints, including land-use change, (biogenic) carbon uptake and emissions, offsetting, soil carbon stock, green electricity, and characterization factors to be used for biogenic carbon.

Below, only those methodologies targeting the accounting of CO_2 emissions are presented. Group 2 methodologies have been listed elsewhere throughout this report.

1. **The ISO 14060 family of standards**

The ISO standard for quantifying product carbon footprint was updated in 2018 (ISO 14067:2018) (European Committee for Standardization, 2019). This guideline is part of the ISO 14060 family, which also addresses organizational (ISO 14064-1) and project-based (ISO 14064-2) carbon footprints. The family includes requirements for verifying GHG statements (ISO 14064-3) for bodies that validate and verify GHG statements (ISO 14065) and for competencies of validation and verification teams (ISO 14066).

These International Standards address the single impact category of climate change and do not assess other potential social, economic, and environmental impacts arising from the provision of products. Product Carbon Footprints assessed in conformity with this International Standard do not provide an indicator of the overall environmental impact of products.

2. **PAS 2050 and PAS2060 protocols**

PAS 2050 is a Publicly Available Specification (PAS) that specifies requirements for assessing the life cycle GHG of goods and services. It is widely used and is considered the first carbon footprint standard used internationally.

The standard was developed by the British Standards Institute (BSI) in 2008 and then revised in 2011. Its development was also co-sponsored by the Carbon Trust and the Department for Environment, Food and Rural Affairs (Defra).

The specified requirements serve to identify the system boundary, the sources of GHG emissions associated with goods and services that fall inside or outside the system boundary, the required data for carrying out the analysis, and then, the calculation of the results.

PAS2050 does not assess other potential social, economic and environmental impacts arising from the provision of goods and services, such as non-greenhouse gas emissions, acidification, eutrophication, toxicity, biodiversity, labour standards, or other social, economic and environmental impacts.

It does not include category provisions for goods and services; however, it is intended that category specific provisions for goods and services, developed in accordance with ISO14025:2006, will be adopted where available.

3. **GHG Protocol**

The Greenhouse Gas Protocol Initiative is a multi-stakeholder partnership of businesses, non-governmental organizations, governments, academics, led by the World Resources Institute (WRI). Launched in 1998, the Initiative's mission is to develop internationally accepted GHG accounting and reporting standards and protocols, and to promote their broad adoption.

Aligned with the first version of PAS 2050, with the difference that the GHG Protocol Product Standard includes requirements for public reporting, and additional standards for corporate assessments and project-related calculations.

The GHG Protocol is comprised of three separate modules:

- The GHG Protocol Corporate Accounting and Reporting Standard (Corporate Standard), revised edition, published in March 2004.
- The GHG Protocol for Project Accounting (Project Protocol), published in December 2005.
- The GHG Protocol Product Life Cycle Accounting and Reporting Standard, published in April 2013.

2.1.4.2 Solar Bankability

(Sectoral reporting standards\Other industry benchmarks and best practices)

Solar bankability solutions include feasibility and bankability studies for PV power plants to evaluate and analyse the potential of a proposed PV project to give assurance to decision makers. By assessing the strengths and weaknesses of a proposed investment, opportunities and threats as presented by the environment, and the resources required to carry through, the prospects for success can be made clearer.

Evaluating the bankability of a PV power plant project helps to determine the economic, technical, and operational requirements for long-term success of financial investments.

PV module bankability is assessed by combining the manufacturing and financial health scores of producers using nonlinear/power regression analysis. The analysis prioritizes quantitative inputs (e.g., six years back and two years forward in the case of forecasted variables), with minimal qualitative data. At every stage of analysis, the solar manufacturers are compared based on market perception from a bankability/investment perspective.

A solar PV module manufacturer is deemed "bankable", when the company is profitable, highly reliable, thus it is worthy to invest in. Meeting standards ensures that financial institutions will support projects using their panels at a favourable interest rate. In the solar industry, bankable manufacturing companies are more likely to sustain long term business and avoid bankruptcy.

However, the bankability concept is not that straightforward; hence the need for an accurate list of panel manufacturers' bankability.

1. **TÜV SÜD**

TÜV SÜD is a certification, testing, and inspection body that offers a solar bankability project to assess the feasibility of solar PV projects. Their assessment includes technical, financial, and economic analyses, based on meteorological data, site evaluation, and financial context. TÜV SÜD's bankability solutions cover technical assessment, financial assessment, and economic assessment.

2. **Certisolis**

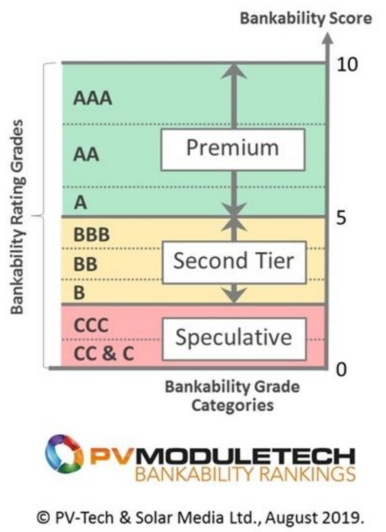
Certisolis, a leading certification body in Europe, specializes in testing and certifying solar modules according to stringent European and international standards. Its certifications ensure compliance with quality, durability, and environmental criteria, making it a valuable contributor to the bankability of PV modules. Certisolis' testing protocols, particularly its focus on reliability in European climates, help investors and developers identify high-performing modules suited for long-term deployment.

3. Intertek

Intertek provides Solar Module Bankability assessments to demonstrate the ability of PV products to achieve subsidies and attract investors. Beyond safety and performance certification, they offer additional testing like Quality Control and Factory Inspections to make PV modules bankable for governments and investors.

4. PV ModuleTech Organization

PV ModuleTech Organization conducts bankability quarterly and yearly reports, evaluating and ranking global PV module manufacturers based on manufacturing and financial metrics. The bankability score ranges from 0 to 10, categorizing manufacturers as premium, second-tier, or speculative (Figure 6). The ratings help investors, developers, and EPCs select reliable module suppliers for maximizing site performance and long-term returns.



Grade Category	Rating Grade	Typical Supplier Profile
Premium	AAA	Exhibiting industry-leading manufacturing & financial metrics
	AA	Typically long-term top-10 suppliers by volume with solid finances
	A	GW to multi-GW level suppliers with average-to-good finances
Second Tier	BBB	GW-level with average finances; lower supply levels with strong financial support
	BB	Widely populated category across a range of manufacturing & financial scores
	B	Similar to above but with lower score ratings, in particular for manufacturing
Speculative	CCC	Mostly low sales volumes & often lacking non-China business
	CC	Dependent mainly on favourable external factors (or major shipment growth uptick)
	C	High risk for deployment, typically arising from low volumes or weak finances

PVMODULETECH BANKABILITY RANKINGS

© PV-Tech & Solar Media Ltd., August 2019.

Figure 6. PV ModuleTech Bankability Terms (scores, categories and rating grades) (left). PV ModuleTech Bankability Table (right). (source: PV-Tech & Solar Media Ltd.)

Only a few manufacturers achieve premium AAA ratings, while many fall into the lowest rating category (C) due to strict criteria and quarterly updates (Figure 7). The rankings help identify which solar manufacturers are performing well in terms of manufacturing and financial health.

Many solar manufacturers can’t consistently make it to the top ranking, as the bankability status is based on a combination of Manufacturing Strength scores and Financial Strength scores that are being monitored, interpreted, and updated quarterly.

The global shipments for utility deployment of each supplier must be in high-volume for it to be in the top rating. The solar module suppliers should not be in the mix for 100-MW-plus projects. If all shipments are domestic, then the companies are impossible to be selected for supply to overseas projects (at least where investor due diligence is involved). If the solar company is going to be technically bankrupt, it will never be included in the list.

These are some of the reasons why there are only a few solar module suppliers in the premium, AAA-rating grades and most of the suppliers are at the very bottom. The strict criteria and methodology of PV-Tech Research are helpful in categorizing which solar manufacturers are profitable and performing well in the industry, in terms of manufacturing and financial statuses.

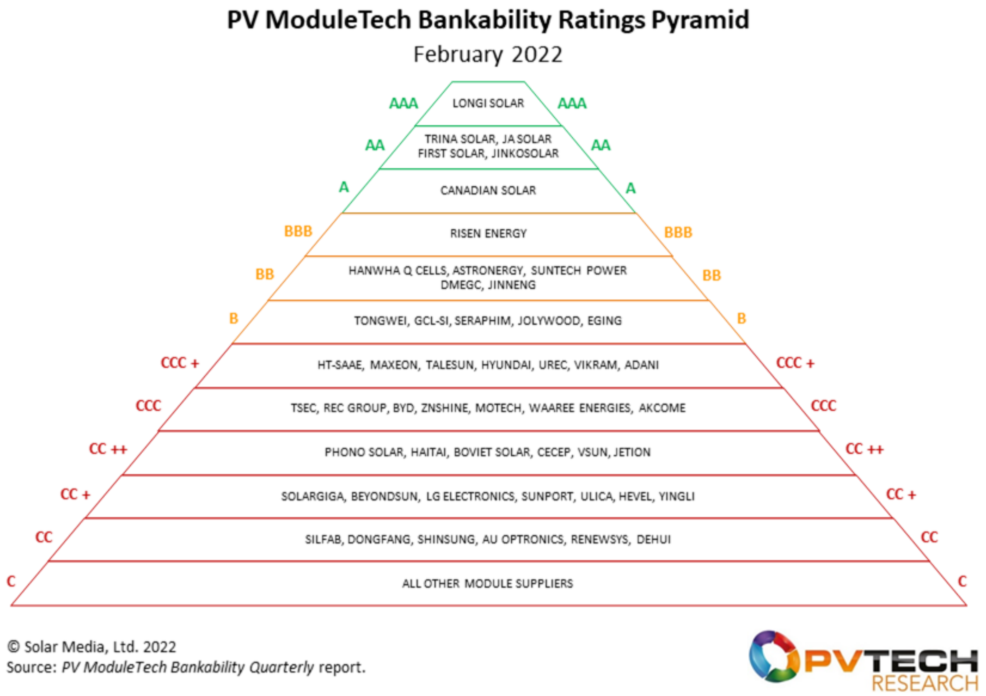


Figure 7. PV ModuleTech Bankability Rankings: Q1’22 Pyramid. (source: PV-ModuleTech Bankability Quarterly Report)

2.1.4.3 *Business & Human Rights Resource Centre*

[(Sectoral reporting standards\Other industry benchmarks and best practices)]

The Business & Human Rights Resource Center (BHRRC) conducted a report titled “Renewable energy risking rights & returns: an analysis of solar, bioenergy and geothermal companies’ human rights commitments” in 2018.[70] The report focuses on assessing the human rights commitments of companies operating in the renewable energy sector, specifically in the areas of solar, bioenergy, and geothermal energy.

The objective of the report was to analyze the extent to which renewable energy companies prioritize and address human rights issues in their operations. It evaluated the commitments made by these companies to protect and respect human rights, as well as their efforts to address any negative impacts that may arise from their activities.

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[70] Renewable energy risking rights & returns: An analysis of solar, bioenergy and geothermal companies’ human rights commitments: https://media.business-humanrights.org/media/documents/files/Solar_Bioenergy_Geothermal_Briefing_-_Final_0.pdf

Various human rights-related topics were examined in the report, including labour rights, indigenous rights, land rights, and the rights of local communities. The aim was to assess the compliance of renewable energy companies' policies and practices with internationally recognized human rights standards.

The findings of the report provided valuable insights into the human rights performance of renewable energy companies. It identified areas where companies demonstrated good practices and highlighted gaps and challenges in their human rights commitments. The report aimed to encourage companies to strengthen their human rights frameworks and promote responsible practices within the renewable energy industry.

Among the evaluated companies in the solar sector, only 50% scored positively in two out of the six assessed aspects, which included human rights, labour rights, and grievance mechanisms, among others. Some notable examples of good practices were identified within this group. For instance, SunPower's human rights policy stood out due to its reference to relevant international standards, executive management ownership, board oversight, and application to suppliers. SunPower explicitly committed to international human rights standards such as the Universal Declaration of Human Rights, ILO Conventions, and UN Guiding Principles on Business and Human Rights. The Chief Operating Officer oversaw the policy, and the Board's Sustainability Council specifically addressed concerns about human trafficking.

Regarding supply chain monitoring, the report highlighted Scatec Solar's requirement for suppliers to sign a Supplier Code of Conduct as part of their contracts, which included human rights criteria. The company monitored compliance with the code and terminated contracts when actions were not taken within the specified timeframe.

The renewable energy industry experienced significant growth, with a 29.3% increase between 2016 and 2017. The impact on land varies depending on project siting and design, ranging from minimal for rooftop installations to more significant for solar farms. The supply chain for solar panels involves resource-intensive processes, including the use of mined minerals like copper, tin, lead, aluminum, boron, gallium, and indium. The majority of solar panel manufacturing occurs in Asia, with China accounting for 69% as of 2016. The report also highlighted human rights allegations faced by solar companies, such as lack of meaningful consultation with local communities in Western Sahara, issues related to solar panel waste affecting the environment and health in China, and labor rights concerns at solar panel installers in the United States. In 2023, the BHRRC is expanding its renewable energy human rights benchmark to also cover wind and solar manufacturers due to the key role they play in the sector.[71]

2.1.4.4 Silicon Valley Toxics Coalition scorecard

(Sectoral reporting standards\Other industry benchmarks and best practices)

The *Solar Scorecard* by the Silicon Valley Toxics Coalition is a relevant initiative in this area. The Solar Scorecard evaluates and ranks solar manufacturers based on their environmental programs and practices. Its purpose is to promote industry-wide transparency, accountability, and high standards of environmental sustainability. The project was initiated by the Silicon

[71] https://media.business-humanrights.org/media/documents/2023_BHRRC_Renewable_Energy_Benchmark_Methodology.pdf

Valley Toxics Coalition (SVTC), which envisions environmentally sustainable and socially just advancements in electronic products.

The Solar Scorecard assesses manufacturers using key performance indicators (KPIs) such as EPEAT certification, chemical reduction goals, chemical management policies, worker exposure reduction to hazardous chemicals, and process chemical data collection and management systems. The project also emphasizes mitigating the adverse impacts of legacy pollution on marginalized communities.

To achieve its goals, the Solar Scorecard engages solar manufacturers representing 80% of the market share, including both industry leaders and smaller companies. The evaluation is based on publicly available information from manufacturers' websites, promoting transparency, and providing stakeholders with accurate data for informed decision-making.

The Solar Scorecard has planned releases that include the evaluation of manufacturers' websites, publication of scores and rankings for different aspects such as chemical use and reduction, supply chain due diligence, and decent work and sustainable economic growth and development. Future releases in 2024 will cover additional scoring sections like energy use, extended producer responsibility/mining, water use, batteries, and components. These releases will expand the evaluation's scope to encompass other important aspects of sustainability within the solar energy industry.

By setting goals, benchmarking progress, and encouraging collaboration with stakeholders, the Solar Scorecard aims to drive positive change in the solar energy industry. Its ultimate goal is to promote safe and sustainable practices for workers, communities, and the environment, ensuring that the industry's growth aligns with principles of human rights, environmental justice, circularity, and transparency.

The Solar Scorecard project has planned several releases to assess and improve the sustainability practices of solar manufacturers. Here is a summary of the releases[72]:

- *Chemical Use and Reduction (2023):* In this release, the Solar Scorecard team evaluates solar manufacturers' websites based on their practices related to chemical use and reduction. The goal is to encourage manufacturers to reduce the use of hazardous chemicals in their manufacturing systems and products. The scores and rankings obtained from this evaluation provide insights into manufacturers' environmental practices.
- *Supply Chain Due Diligence (2023):* This release focuses on supply chain due diligence within the solar industry. The Solar Scorecard project aims to establish a baseline for evaluating manufacturers' performance in ensuring responsible and sustainable practices throughout their supply chains. Through dialogue and engagement with manufacturers, the project seeks to encourage the adoption of sustainability programs and criteria.
- *Decent Work and Sustainable Economic Growth and Development (2023)*: In this release, the Solar Scorecard project aims to assess the solar industry's performance in promoting decent work and sustainable economic growth. The evaluation considers worker well-being and other criteria related to social and economic sustainability. This assessment contributes to understanding and improving the industry's impact on labor rights and economic development.
- *Future releases planned for 2024* include additional scoring sections such as Energy Use, Extended Producer Responsibility/Mining, Water Use, Batteries, and

[72] https://solarscorecard.org/the-solar-scorecard

Components. These releases expand the scope of evaluation to cover other important aspects of sustainability within the solar energy industry.

2.1.4.5 SolarPower Europe Sustainability Report

(Sectoral reporting standards\Other industry benchmarks and best practices)

SolarPower Europe is a European industry association dedicated to promoting solar power and driving the transition to a sustainable, low-carbon energy system. It represents over 250 companies across the solar value chain, including manufacturers, installers, developers, utilities, and other stakeholders in the solar industry. Formerly known as the European Photovoltaic Industry Association (EPIA), it rebranded as SolarPower Europe in 2015 to reflect its broader focus on solar power beyond photovoltaics.

The primary goal of SolarPower Europe is to create a favourable policy and regulatory framework that supports the growth of solar power in Europe and enables its full potential to be realized. The association advocates for policies that promote the deployment of solar energy, remove market barriers, and ensure fair market access for solar companies.

While playing an active role in shaping EU policies related to renewable energy, climate change, and the energy transition. It engages with policymakers, regulators, and other stakeholders at the EU level to provide expertise, promote the benefits of solar power, and advocate for favourable policies that accelerate solar energy adoption.

The association conducts research, analysis, and market intelligence activities to provide valuable insights into the solar industry. It publishes reports, market forecasts, and policy briefings that inform decision-makers, industry professionals, and the public about the latest trends, developments, and opportunities in solar power.

One of the reports is the "Sustainable Solar - Environmental, social, and governance actions along the value chain"[73]. It is an expanded, and updated version of "Solar Sustainability – best practices benchmark" (2021), (Solar Power Europe, 2021). The 2024 edition presents actions, methods and case studies along the key life cycle phases of PV systems, with a particular focus on environmental, social and governance (ESG) performance.

Here is a summary of the sections included in the report:

- Supply chain phase: This section addresses responsible sourcing, human rights due diligence, carbon footprint in manufacturing, circular product design and traceability. It highlights collaborative approaches such as joint audits, emerging tracking technologies like blockchain, and multi-stakeholder initiatives including the Solar Stewardship Initiative, The Copper Mark, and others aimed at improving transparency and mitigating risks in complex supply chains.
- Use phase: The report explores land use, community engagement, biodiversity protection, and public acceptance of solar energy. It provides examples of decentralised models such as virtual net metering, shared energy initiatives, and community-led investment models that enhance local integration of solar projects.
- End-of-life phase: This section provides best practices in repowering, reuse, repair, recycling, and waste treatment. It promotes the application of a waste hierarchy adapted to circular economy goals in the PV sector.

[73] https://www.solarpowereurope.org/insights/thematic-reports/sustainable-solar-environmental-social-and-governance-actions-along-the-value-chain

The report also addresses current challenges in achieving full traceability across the solar value chain and proposes solutions such as joint sectoral supplier audits, methodologies for verifying upstream data, and the potential of advanced technologies (RFID, IoT, AI, etc.)—some already applied in other sectors—for improving transparency.

Case studies from companies such as Lightsource BP, Fronius, Trina Solar, NextEnergy Capital and Sunrock illustrate how transparency, traceability and ESG practices are being implemented across the value chain.

2.1.4.6 Solarcentury best practices report

In 2021, Solarcentury, a prominent solar energy company, published a report titled "Solar: A Force for Good ESG Expectations for the Solar Sector." (Solarcentury, 2021), Solarcentury specializes in designing, constructing, and operating solar PV projects worldwide. They prioritize community engagement and environmental protection, aiming to create positive social and environmental impacts.

This company actively participates in projects that demonstrate the potential of solar energy in driving sustainability. They collaborate with local communities to implement solar projects and focus on biodiversity conservation and environmental stewardship. Hence, by integrating ESG considerations into their operations, Solarcentury complies with regulatory requirements such as the Sustainable Finance Disclosure Regulation (SFDR) and the EU Taxonomy. They strive to provide investors with a transparent understanding of the environmental and social benefits associated with their solar projects.

The report moreover discusses various aspects of the solar energy industry, including costs, job creation, end-of-life management, regulations, raw materials, and community engagement. Here are some key points from each section:

- Cost and Grid Integration: The costs of solar energy are lower than those of new coal-fired power plants and in the same range as operating costs of existing coal plants in India and China.
- Job Creation and Economic Benefits: The solar industry is responsible for over a third of the total renewable energy workforce globally. In the EU, the transition to a low-carbon economy through renewable energy is likely to have positive impacts on the job market. The solar industry is the most job-intensive sector compared to other energy sources. Workforce policies and practical implementation need attention to ensure the growth of the solar industry. More data collection is needed to determine the effectiveness of job creation initiatives.
- End of Life: Without an appropriate recycling system, there could be 60 million tons of PV panel waste in landfills by 2050. Effective management of solar waste is crucial to avoid a waste crisis due to hazardous materials present in solar panels. The solar panel recycling market is predicted to grow, and advances in technology will enable a higher fraction of materials to be recovered.
- Disclosure and Standards: Regulations like the SFDR and EU Taxonomy require transparency and disclosure from investors and solar entities. Collaboration between financial market participants and the solar value chain can promote transparency and resilience.
- Raw Materials: Solar PV panels require materials like silicon, aluminum, plastic, and glass, each of which has its own carbon footprint. Increased demand for solar panels may impact ethical work practices in the supply chain, particularly in the extraction and processing of critical raw materials like silver and rare earth elements. Advancements

in technology are expected to reduce the use of raw materials and hazardous substances in panel production, supporting more sustainable manufacturing practices.
- Community Engagement: Community ownership and involvement in solar projects can empower local people, reduce carbon emissions, and provide financial investment. Focus on wildlife conservation and biodiversity can enhance the positive environmental impact of solar farms. Engaging with the community and incorporating their input into project design can help mitigate opposition and gain support.
- ESG Integration and Regulatory Landscape: Industry should meet the SFDR and EU Taxonomy in ESG characteristics and impact reporting. Asset managers face increasing demands for ESG data and disclosure. The EU Taxonomy identifies activities contributing to environmental objectives, including climate change mitigation, circular economy, and ecosystem protection.
- BNP Paribas Asset Management's (BNPP AM) ESG Integration: BNPP AM developed an ESG scoring framework to assess companies' performance on material ESG issues. Renewable energy companies tend to rank highly in the ESG scoring framework due to their lower carbon emissions.

2.1.4.7 ADEME Roadmap

(Sectoral reporting standards\Other industry benchmarks and best practices)

ADEME (Agence de la transition écologique) is the French Agency for Ecological Transition responsible for promoting sustainable development and supporting environmental initiatives in France. In 2021, they prepared a PV sustainability roadmap titled "How to lead the PV sector towards environmental excellence?". The roadmap includes four key tasks addressing environmental challenges in PV systems, supported by short-term, medium-term, and long-term actions to achieve environmental excellence in the PV sector.

- *Task 1* involves a thorough literature review on environmental issues of PV systems. This task provides a solid understanding of the current state of knowledge and identifies areas that require further research and improvement.
- *Task 2* builds upon the literature review by conducting a detailed and comparative analysis of the identified environmental documents. This analysis helps identify best practices, key recommendations, and innovative approaches that can effectively address environmental concerns in the PV industry.
- *Task 3* focuses on benchmarking the practices of various stakeholders within the PV sector to assess their efforts in managing and mitigating environmental impacts. By comparing practices and highlighting areas for improvement, this task promotes knowledge sharing and collaboration among industry players, driving the sector towards greater sustainability.
- *Task 4* involves developing a French strategy and roadmap for achieving environmental excellence in the PV sector. This task synthesizes findings from the literature review, comparative analysis, and benchmarking to create a cohesive plan of action. The strategy outlines short-term, medium-term, and long-term actions that need to be undertaken to drive the PV sector towards environmental excellence.

To conclude, there is a number of actions proposed in the report, which are distributed across short-term, medium-term, and long-term timeframes.

- Short-term actions:
  - Encouraging the adoption of renewable self-consumption, innovation, and industrialization of high-performing, competitive, and virtuous PV technologies.

  - Evolving the consideration of carbon footprints in tender processes conducted by the Ministry of Ecological Transition and Regional Energy Commissions.
  - Introducing controls for certifying Energy Storage Certificates in tender processes.
  - Reducing the consumption of primary materials in PV product manufacturing.
  - Identifying and promoting best practices to preserve biodiversity at PV plant sites.
  - Developing new knowledge on the environmental impacts of PV installations.
- Medium-term actions:
  - Stimulating the adoption of standardized environmental quality labels.
  - Promoting local sourcing of PV products and components.
  - Enhancing the repairability of PV products.
  - Reducing or avoiding the use of toxic substances.
  - Modifying the WEEE (Waste Electrical and Electronic Equipment) directive to encourage the recycling of metallic fractions in PV products.
  - Improving the consideration of environmental impacts and harmonizing vigilance points in environmental impact assessments.
- Long-term actions:
  - Promoting the recyclability of PV products.
  - Enhancing the performance of PV modules in terms of conversion efficiency, durability, and reliability.
  - Ensuring responsible use of critical or strategic materials.
  - Enhancing recycling processes and exploring new uses for recycled PV products.

These actions, aligned with the findings and recommendations from the four tasks, collectively aim to drive the PV sector towards environmental excellence. By addressing sustainability aspects and incorporating best practices, the report lays the groundwork for a more environmentally friendly and sustainable future for the PV industry.

2.1.4.8 Beyond the Megawatt

(Sectoral reporting standards\Other industry benchmarks and best practices)

The Clean Energy Buyers Institute launched the Beyond the Megawatt (BTM) Initiative[74] in response to corporate clean energy buyers' desire to procure renewable energy from the most socially and environmentally responsible projects. BTM aims to promote a more environmentally sustainable, socially equitable and resilient clean energy transition by leveraging the demand of the world's largest and most influential energy customers. In 2023, more than 18 leading companies representing over $498 billion in annual revenues signed the Principles for Purpose Driven Energy Procurement[75]. The initiative is developing procurement guidance to help energy buyers embed environmental sustainability, social equity and resilience in energy buyers' clean energy procurement process.

The BTM initiative builds on Salesforce's report published in October 2020 which provides a framework and expert third-party guidance based on several SDGs (1, 2, 5, 7, 8, 10, 12, 13, 15, and 17) carefully considering sustainability evaluation including social criteria. "More than megawatt: embedding social and environmental impact in the renewable energy procurement process" (2021).

Indeed, an energy procurement matrix has been made available for developers as a tool for scoring projects across different economic, environmental and social criteria to enable sustainability trade-offs. This initiative intends and is expected to influence and impact

[74] https://cebi.org/programs/beyond-the-megawatt/

[75] http://cebi.org/programs/beyond-the-megawatt/principles/?utm_source=linkedin&utm_medium=social&utm_campaign=BTMP

positively and proactively the market of the energy sector by implementing sustainability criteria as common practices in the near future.

2.2 Product Standards

Below we list the standards that relate to PV products. These are requirements and rules to be accomplished at production, and for processes and services related to the PV industry, to harmonise the market by defining methods and equivalent specifications. We complement each standard or initiative with a case study to illustrate the process & efforts involved for the value chain actors.

Product Standards
Quality assurance standards
NSF 457/EPEAT for Solar ecolabel
Cradle to Cradle Standard
Horizontal standards series 4555x
IECRE / TEXXECURE rating scheme
Reemployment / reuse standard for PV modules
Standards on PV modules recycling
Blue Angel standard on PV inverters

2.2.1 Quality Assurance standards

This PV sustainability standards report does not cover Quality Assurance standards. While important, this report focuses specifically on sustainability aspects within the PV sector, including environmental, social, and economic factors. It provides an overview of standards and guidelines related to energy efficiency, carbon footprint reduction, waste management, resource conservation, social impact, and supply chain transparency. For information on Quality Assurance standards, it is recommended to refer to industry-specific reports and certifications that specifically address these aspects.

2.2.2 NSF 457/EPEAT for Solar ecolabel

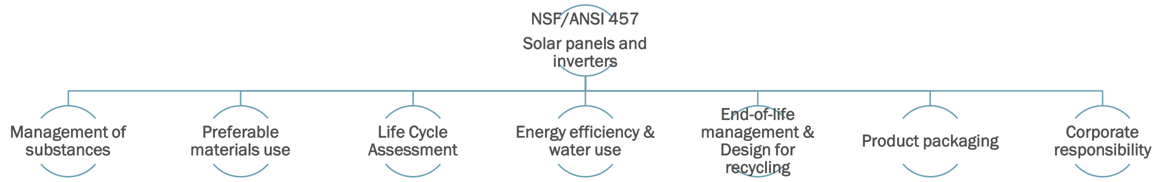
Since 2015, the U.S. organization NSF International, with the support of the Global Electronics Council (GEC), has been leading a process to develop environmental criteria for photovoltaic modules. Inspired by the Silicon Valley Toxics Coalition's (SVTC) 'Solar Scorecard', this criteria set was designed to address the full life cycle of a PV module. The final criteria set became ANSI standard 457 and qualified to be used in the global EPEAT ecolabel for sustainable IT and electronic products.[76]

This PV Module and Inverter standard, sets product stewardship and corporate responsibility requirements for PV modules and inverters (Figure 8). To be registered companies must be validated by a Conformance Assurance Body (CAB; accredited laboratory) ensuring they meet

[76] https://globalelectronicscouncil.org/wp-content/uploads/NSF-457-2019-1.pdf

NSF/ANSI 457 criteria. As a leadership standard, only top tier products qualify for an EPEAT label.

In 2023, new ultra-low-carbon solar criteria[77] were adopted, providing a global and standardized methodology for quantifying the carbon footprint of PV modules. These criteria are now part of the **EPEAT Climate+** designation, a new leadership level that highlights products designed with progressive climate and sustainability practices[78].



List and assessment of substances	Recycled content	PV module life cycle assessment	Energy management system	End-of-life management	Eliminate substances of concern	EH&S management systems
Reduction of substances of concern		Reduction in LCA Impacts	Water use metrics	Design for recycling	Recyclability of packaging	Corporate reporting
					Recycled content in packaging	Corporate social performance
						Conflict mineral sourcing

Figure 8. Summary of product stewardship and corporate responsibility criteria in NSF/ANSI 457

More recently, the Responsible Supply Chains Criteria (2025) introduced new requirements aimed at strengthening due diligence in supply chains with respect to forced labor[79]. Under this framework, manufacturers must ensure that both their own production facilities and supplier facilities are not located in regions where independent third-party audits cannot be conducted as part of a credible forced labor due diligence process. It defines prohibited regions as those in the annual Global Slavery Index report on state-imposed forced labor where “operating in accordance with the United Nations Guiding Principles on Business and Human Rights (UNGPs) is not possible”.[80]

NSF/ANSI 457 was developed through a balanced multi-stakeholder process over several years. The technical committee included international representatives from industry, customers and investors, and academic/NGO/regulatory bodies. After being initially developed for only PV modules, the standard was revised to include inverters as well. Another revision in the ecolabel registry is currently underway to add embodied carbon criteria for PV modules.

Getting to conformity involves interaction with multiple subject matter experts. First Solar was the first company to register PV products under this program (with Series 6 PV module) and the process took ~1 year. Beginning with identification of a CAB, documents were assembled over several months, presented to the CAB for initial review, and finalized over multiple review iterations. After establishing contractual terms and achieving CAB approval regarding conformity to NSF/ANSI 457. Due to meeting all required criteria and >50% of optional criteria, the product was registered in the “silver” category, where EPEAT has three ecolabel tiers

[77] https://globalelectronicscouncil.org/wp-content/uploads/EPEAT_ULCS_2023.pdf

[78] https://www.epeat.net/documents/EPEAT-Climate-Plus-Requirements.pdf

[79] https://globalelectronicscouncil.org/wp-content/uploads/EPEAT_RSC_2025.pdf

[80] https://www.walkfree.org/global-slavery-index/findings/spotlights/examining-state-imposed-forced-labour/

(bronze – meets all required criteria; silver – additionally meets 50% of optional criteria; gold – additionally meets 75% of optional criteria).

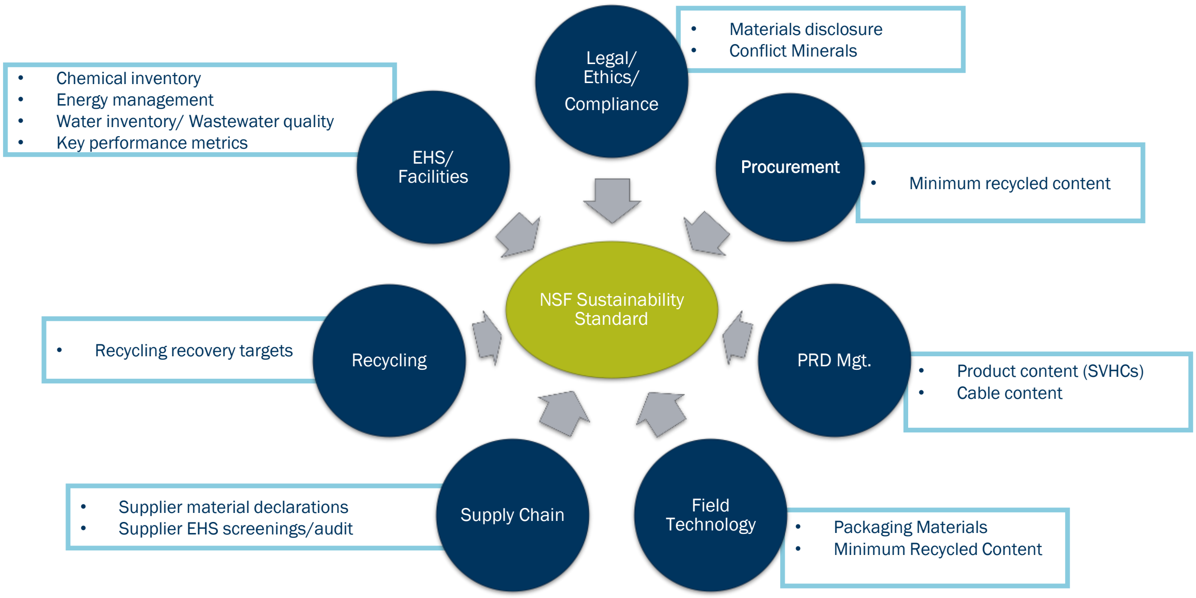


Figure 9. Summary of subject matter expertise needed to achieve conformance with NSF/ANSI 457 criteria

After registration, manufacturers undergo continuous monitoring investigations by GEC, with several criteria reviewed annually by the CAB, and have the CAB's findings reviewed by GEC. This process requires continuous maintenance by the manufacturer rather than just one-time product registration, and provides increased assurance of conformity to buyers.

As of April 19, 2024, the **Federal Acquisition Regulation (FAR)** now directs federal agencies to prioritize purchasing products that meet eco-labels listed in the **U.S. EPA's Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing**. This program is currently the only approved ecolabel for PV modules and power purchase agreements in the US EPA's Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing.[81]

2.2.3 Cradle to Cradle Standard

Cradle to Cradle Certified is a global standard for products that are safe, circular, and responsibly made. It guides the designers and manufacturers of sustainable products through a continuous process that looks at a product's health impact; circularity; air, water, and soil protection; climate change stewardship; and equity.

The Cradle to Cradle (C2C) certified standard was first developed and released in 2005 by McDonough's and Braungart's company as a program to acknowledge the high levels of sustainability achieved by its clients in developing products based on Cradle to Cradle® design principles. After the release of several versions, McDonough and Braungart created in 2010

[81] EPA Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing available at https://www.epa.gov/greenerproducts/recommendations-specifications-standards-and-ecolabels-federal-purchasing

the Products Innovation Institute[82]; a non-profit organization, to scale Cradle to Cradle certification globally. From 2012, C2CPII took over administration of the Cradle to Cradle Certified Products Program from MBDC, LLC and began to independently certify products.

The Cradle to Cradle Products Innovation Institute evaluates products for certification through a network of Cradle to Cradle Certified assessment bodies who are recognized by the Institute based on experience, qualifications, and training of their organization's staff. Assessors are trained to help companies achieve certification for their products.

For over a decade, the C2C Certified Product Standard has been used by brands, designers, retailers, and manufacturers. This standard focuses on maximizing health and wellbeing while assessing products across various sustainability performance categories. With more than 700 companies from over 40 countries participating, the program has certified over 10,000 products, ranging from building materials and automotive to cosmetics and packaging. Whether you're in need of HVAC systems or hand soap, dresses or drywall, the Cradle to Cradle Certified registry offers a wide range of options that have immediate and long-term positive impacts on companies, workers, consumers, and the planet.

The Cradle to Cradle Certified Product Standard examines five categories:

1. Material Health: ensuring materials are safe for humans and the environment
2. Product Circularity: enabling a circular economy through regenerative products and process design
3. Clean Air & Climate Protection: protecting clean air, promoting renewable energy, and reducing harmful emissions
4. Water & Soil Stewardship: safeguarding clean water and healthy soils
5. Social Fairness: respecting human rights and contributing to a fair and equitable society

The standard, now in version 4.0, helps manufacturers develop and implement change, from product innovation to operations. Companies are transforming their business models and systems, collaborating to drive sustainability and wellness up and down the value chain. Third-party verification goes beyond accredited labs evaluating individual products. Consultants helps measure a company's progress toward larger sustainability goals and ethical initiatives. C2C certification is driving transformation towards a safe, circular and equitable future.

Products are assigned an achievement level for each of the five categories: levels are Bronze, Silver, Gold, and Platinum. The overall certification level awarded by the Cradle to Cradle Products Innovation Institute corresponds to the lowest level of achievement among the five categories. Examining three C2C-certified drywall products from three different manufacturers might show that all are awarded Bronze and all will contribute to LEED credits on material ingredients disclosure. However, closer examination might reveal that one manufacturer emphasizes recycling and reuse; another focuses more on the health impacts of materials; while a third has made strides in sustainable water use and equity. By awarding overall certification on the basis of the "weakest link," and requiring certification renewal every two years, the Products Innovation Institute encourages continuous improvement over time.

C2C case studies

While many companies, governments, and organizations have embraced C2C certification, just two are from the solar industry: SunPower Inc. and JinkoSolar Holding Co. Ltd.

[82] https://c2ccertified.org/

In 2014, SunPower Maxeon direct current (DC) panels were the world's first solar panels to earn C2C certification (Silver). For this certification, panels go through a rigorous evaluation of sustainable practices in the areas of material health, material reutilization, renewable energy and carbon management, water stewardship, and social fairness. To date, the certification of SunPower modules is Bronze.

In 2017, JinkoSolar achieved the silver cradle to cradle certification[83] for its Eagle module series. JinkoSolar's decision to pursue C2C certification was driven by increasing interest from Scandinavian and EU customers for environmental topics, like carbon footprint, environmental health and safety, corporate social responsibility, and sustainability. However, from the beginning of 2023, Jinko Solar products are no longer listed in the C2C registry.

2.2.4 Horizontal standards series 4555x

The horizontal standards series 4555x refers to a set of standards that are designed to address specific aspects of sustainability in various industries or sectors. They were developed under the Standardisation Request M/543.

The Standardisation Request M/543 was issued by the European Commission on 17 December 2015. Its purpose was to request the European standardisation organizations (such as CENELEC) to develop horizontal standards for material efficiency aspects of energy-related products in support of the implementation of Directive 2009/125/EC. This directive establishes the framework for the EU Ecodesign requirements of energy-related products.

In general, horizontal standards aim to provide a common framework or set of guidelines that can be applied across multiple industries to ensure consistent sustainability practices. These standards are focused on product circularity, in areas such as repair, reuse, recycle.

These standards have a broader scope, but are envisioned to be used for energy-related products. The standards are:

- EN 45552:2020 'General method for the assessment of the durability of energy-related products';
- EN 45553:2020 'General method for the assessment of the ability to remanufacture energy-related products';
- EN 45554:2020 'General methods for the assessment of the ability to repair, reuse and upgrade energy-related products';
- EN 45555:2019 'General methods for assessing the recyclability and recoverability of energy-related products';
- EN 45556:2019 'General method for assessing the proportion of reused components in energy-related products';
- EN 45557:2020 'General method for assessing the proportion of recycled material content in energy-related products';
- EN 45558:2019 'General method to declare the use of critical raw materials in energy-related products';
- EN 45559:2019 'Methods for providing information relating to material efficiency aspects of energy-related products'.

They include several common definitions and calculation methods for aspects such as repairability, reusability, and durability for "energy-related products", a concept that includes a wide range of home appliances and ICT devices.

[83] https://jinkosolar.com.au/2017/11/jinkosolar-awarded-cradle-cradle-certification/

These new standards can be used as the methodological basis to ensure material efficiency aspects are considered in future Ecodesign regulations and product-specific EU standards.

Take this practical example: the European Commission is considering including a repairability index on the energy labels of many products in the coming years, in a similar way that it is already done for energy efficiency. But without a common method to measure “repairability”, it would be hard to put this idea into practice.

The next challenge lies in developing additional details to adapt the methods to each type of product, since measurements of durability in a washing machine might be different than for a laptop, for example. Discussions are ongoing in the CEN-CENELEC technical committee TC59X for adapting the norms to household appliances. At the same time, the standardiser for ICT, the European Telecommunications Standards Institute (ETSI), is looking into translating the horizontal standards to telecom devices such as laptops and smartphones.

2.2.5 IECRE / TEXXECURE rating scheme

IECRE is the IEC system for certifying renewable energy equipment according to standards. In other words, it is the conformity assessment system for renewable energy sources operated under IEC, the International Electrotechnical Commission.

Currently, under task force 6 of IECRE, a rating system is being developed, with the current concept as illustrated in the following Table 4.

Table 4. Rating system under development. Source: EXXERGY, TEXXECURE Rating Foundation

Criteria / Policy Tool Implementation	Life Cycle GWP / embodied carbon / carbon footprint	Life Cycle GER / Energy Payback Time (EPBT)	Hazardous Substances	Recycled Content	Recyclability & Repairability	Quality (IECRE / TEXXECURE)
Proposed Scale	A - G	A - G	A - G	A - G	A - G	A - G
Information Requirement under ED* / EL **	EL	EL	ED	ED	ED	ED
Minimum Requirement Eco-Design (ED) Energy Label (EL)	D	D	D	D	D	D
Visibility on extended Energy Label (EL)	YES	YES	NO	NO	NO	NO
GPP Award Criteria	B	B	B	B	B	B

* It is assumed that Eco-Design compliance is demonstrated through self declaration / CE marking
** It is assumed that Energy Label claims are validated through independent 3rd parties and through dedidated product group standards based on horizontal standards

The Environmental Impact Index (EII) under development will provide a unique index by which the various factors of industrial or other human activity to the environment are comprehensively condensed in a way that the impact of such activity can be reconstructed and evaluated.

The expert group, suggests the development of an EII in cooperation between the EU Commission standardization body and an industrial expert group. managed by a neutral (non-profit) entity, such as TEXXECURE Rating Foundation.

To reduce the impact of industrial and human activity on the planet, clear rules, procedures, and standards can enable conformity assessments and monitoring systems to be established. Therefore, the expert group suggests for the EII system the following terms of reference :

- To provide a consensus-based EII system of established (or to be established) methods, including but not limited to PEFCR v.1.1, NPCR 029 v.1.1, EPEAT PVMI based on NSF/ANSI 457, CSR guidelines, and IEA PVPS Task 12 Methodology Guidelines;
- To define the relevant bodies, their requirements, and their roles and responsibilities to enable an EII system;
- To define the rules of procedure to set up, operate, and maintain an EII system that includes conformity assessment and monitoring; and
- To propose the operational documents and deliverables defining the processes and requirements for establishing the EII system, reflecting with weighted final results on how to establish a final EII.

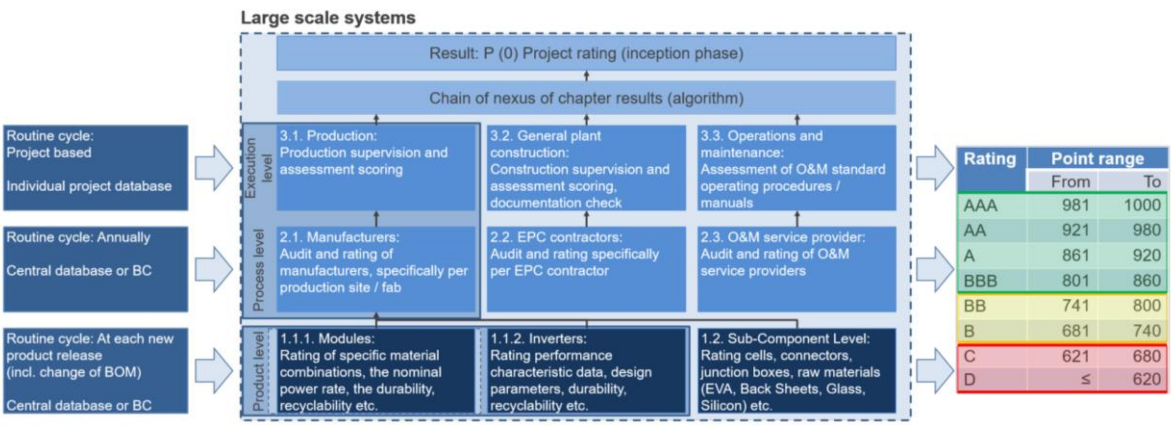
Generally, the EII could either consist of a single letter or a combination of several letters, one for each category, to differentiate declaration. In the following, the concept is explained at the example of modules and inverters.

The proposed scale would be in alphabetical order from A to G, providing guidance and interpretation (Figure 10):

- Levels A, B: Pass for GPP and ED/EL requirements
- Levels C, D: Pass for ED/EL requirements, fail for GPP requirements
- Level E: Fail for GPP, ED/EL requirements with minor deficiencies
- Levels F, G: Fail for GPP, ED/EL requirements with medium/major deficiencies

The differentiation for the levels E, F, and G (all “fail to meet requirements”) would trigger staged consequences. Level E is suggested to result in a conformity re-assessment just for the category within three months to enable minimum D rating, provided that the conformity re-assessment would prove compliance. Levels F and G would suggest medium and major deficiencies that would require complete conformity re-assessments in all categories.

EII minimum classification of “B” in every single category would be recommended for Green Public Procurement and Ecolabels.



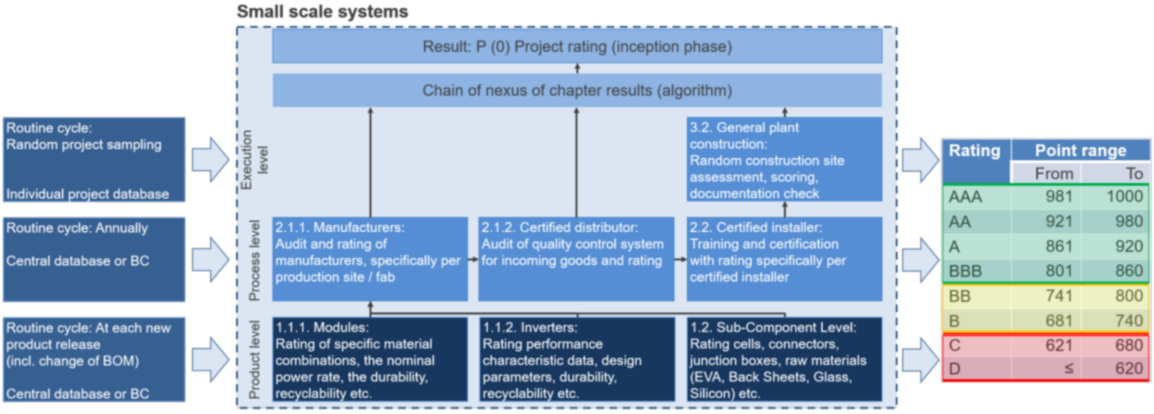


Figure 10. Proposal of scales to comply with Energy Label, Ecodesign (ED) for different proposed environmental categories (Exxergy, 2021[84]).

For PV modules, six different categories have been identified, two of which may be considered to be reflected in the Energy Label (EL), namely GWP and GER, and the others to be considered to be reflected in the Ecodesign requirements, namely HAZ (hazardous substances), RECY (recycled content), and REPA (recyclability and repairability), and QUAL (quality, IECRE, TEXXECURE, or other generally accepted international or European conformity assessment system).

2.2.6 Reemployment/reuse standard for PV modules

Repairing and reusing solar modules that fail to reach their expected lifetime offers greater environmental benefits than replacement new, more efficient PV modules. However, several challenges remain to promote reuse. A study by IEA PVPS Task 12 (Rajagopalan, y otros, 2021) analyzes barriers to economic viability, indicating that a limited number of positive business cases exist under current market conditions.

Priorities for lifetime extension could include refined accelerated testing protocols, manufacturing quality control, predictive modeling to assess the impacts of design changes, efficiency and material improvements, modules compatibility , and repair and refurbishment of system components. (Jordan, Barnes, Haegel, & Repins, 2021)

The following standards promote the reuse of PV modules:

1. **EN 50614:2020** - This existing European norm governs the reuse of electrical and electronic equipment (WEEE) and provides a framework that could be adapted for the solar sector, fostering a sustainable and legally compliant reuse business environment.
2. **IEC TR 63525** - Currently under development by IEC TC 82, this technical report aims to enhance reuse and reemployment standards specifically for PV modules. It is expected to address essential considerations related to reusability, repairability, and the extended life of PV modules, offering guidance to navigate the technical and regulatory challenges within the industry.

2.2.7 Standards on PV modules recycling

Significant barriers to PV recycling remain. According to an International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) report, “low waste volumes, limited

[84] https://etip-pv.eu/publications/etip-pv-publications/download/expert-input-paper-on-eco-design-energy-labelling

available recycling technologies, logistics challenges, and undeveloped markets for recovered materials result in a high-cost, low-revenue scenario for PV module recycling globally" (Komoto K., 2022)

PV module recycling has been mandatory in Europe since 2012 under the Waste from Electrical and Electronic Equipment (WEEE) directive. The directive requires all producers in the EU market to either operate their own take-back and recycling scheme or join producer compliance schemes[85]. All EU member states have adopted the WEEE into national law. By 2021, 31,380 tons of PV module waste were collected in EU-27 countries[86]. Countries whith stricter end-of-life requirements and obligations for PV modules (and PV inverters) report an increased number of recycled PV waste. See Table 5.

The European Committee for Electrotechnical Standardisation, CENELEC, developed a supplementary standard to the WEEE Directive (2012/19/EU) specific to PV module collection and treatment (EN50625-2-4 & TS50625-3-5) to assist recyclers. The standard provides administrative, organizational, and technical requirements preventing pollution and improper disposal, minimizing emissions, promoting increased material recycling and high-value recovery operations, and impeding PV waste shipments to facilities that fail to comply with standard environmental and health and safety requirements.

Table 5. Facts and figures of recycled PV modules waste in Europe

Country	Requirements	PV waste collected (tons)	Cummulative PV waste expected (tons)	Treatment of PV waste	Maturity
Germany[87]	Registration and specific end-of-life treatment for all PV modules. Paid take-back/collection fee for B2B PV modules; B2C PV modules free.	16,050 (2021)	400,000 tons to 1 million tons of PV waste by 2030; 4 million tons in 2050	Monocrystalline Si modules are mostly recycled by glass recycling companies First Solar operates a specific recycling line for thin-film CdTe panels in Frankfurt.	Medium/high
Fran	Registration and specific end-of-life treatment for all PV modules.	Ca. 4,000 tons of PV waste in 2021	350,000 tons of PV waste by 2030; Above 800,000 tons by 2040	Soren, a nonprofit eco-organization, is the system operator of PV module waste management, collection, and recycling.	Medium

[85] Extended producer responsibility (EPR) is mandatory in the EU within the context of the WEEE Directive, which places the responsibility for financing the collection, recycling and responsible end of-life disposal of WEEE on producers.

[86] These are the last statistics published by Eurostat: https://ec.europa.eu/eurostat/databrowser/view/env_waseleeos__custom_10825460/default/table?lang=en

[87] For extensive information check the report: Status of PV Module Recycling in Selected IEA PVPS Task12 Countries, 2022 (Komoto K., 2022)

ce	Paid take-back/collection fee for B2B PV modules; B2C PV modules free			Three new recycling facilities have started operations in 2021/22.	
Spain	Producers are obliged to manage waste according to product design and must bear the cost of the process, as well as register the products in the national producer registry of electrical and electronic equipment (RII_AEE).	1,865.87 tons of PV modules in 2021	34,000 by 2030 and 150,000 expected by 2050.	Monocrystalline Si modules are mostly recycled by WEEE recycling companies	Medium
Italy	Modules from feed-in-tariff installations have specific disposal. End-of-life modules from plants <10 kW are sent to national collection centres, while those from plants >10 kW are managed by authorized entity.	6,486 tons of PV modules in 2021	140,000–500,000 tons of PV waste by 2030, with an increase up to 2.2. million tons by 2050	Italy's energy services manager, GSE (Gestore dei Servizi Energetici SpA), sets disposal instructions for modules Monocrystalline Si modules are mostly recycled by WEEE companies, as no recycling plants are exclusively dedicated to PV modules due to low waste volumes.	Medium

In the United States, the Sustainable Electronics Recycling International (SERI) is developing criteria for the safe, secure, and sustainable reuse and recycling of PV modules. Once completed, the PV criteria will be added to the international Responsible Recycling (R2) Standard. The R2 Standard provides a common set of criteria to recognize responsible reuse and recycling practices for used electronics.

According to a complete report published by SA CSA GROUP about standards research, "Photovoltaic (PV) Recycling, Reusing and decommissioning" (2020)[88], the lack of regulations and industrial-scale recycling facilities in North America hinders PV module recycling. The report provides an overview of the current state of recycling, reusing, and decommissioning of PV modules, with a focus on North America. It highlights the challenges and opportunities in managing PV module waste streams. Landfill disposal is the primary method of PV module disposal in North America due to sufficient landfill capacity and low recycling investments. End-of-life management costs are higher in the EU where landfill disposal is banned. The report emphasizes the importance of international standards and guidelines for PV waste management. It mentions existing documents such as EU Product Environmental Footprint Category Rules, ANSI/NSF 457 Sustainability Leadership Standard for PV Modules, Responsible Recycling Standard (R2), EN 50625 Standard Series, and Silicon Valley Toxics Coalition (SVTC) Solar Scorecard. These standards promote sustainable end-of-life management decisions and responsible recycling practices. The report identifies various standardization opportunities, including harmonization of standards, guidelines for decommissioning, recycling standards, monitoring and statistics, and financial analysis

[88] https://www.csagroup.org/wp-content/uploads/CSA-Group-Research-Photovoltaic-Recycling-Reusing-and-Decommissioning.pdf

practices. Implementing these standards can improve PV waste management, increase recycling efficiency, and support a circular economy approach.

2.2.8 Blue Angel standard on PV inverters

Photovoltaic inverters product group (RAL-UZ 163)

The 2012 Blue Angel criteria for inverters apply to string and multi-string inverters with an output power up to 13.8 kVA that are designed for use in grid-connected PV power systems. The criteria seek to address key challenges of maximising inverter efficiency as part of a photovoltaic system and engaging in network management to support grid stability. The eight technical criteria areas are listed in Table 6. Excluded from the product group are inverters integrated into a module (micro-inverters) and inverters designed for use in standalone systems. The criteria are all pass or fail. There are currently no licenses awarded.

Table 6. Blue Angel photovoltaic inverters criteria overview (Germany). Source: RAL (2012).

Criteria area	Criteria	Requirement
1. Energy efficiency	Overall efficiency	Overall European weighted efficiency calculated according to EN5030 of 95%
	No-load loss	No-load loss not exceeding 0.5 watts
2.Reactive power capability	Reactive power capability	In accordance with Guideline VDE-AR-N 4105
3. Longevity	Warranty	Free-of-charge warranty of at least 5 years
	Service	Defective systems repaired or replaced within a maximum of 48h.
4. Material requirements	General requirements for plastics	Shall not contain REACH Candidate list substances Shall not contain substance with specific CLP hazard classifications (criteria document listing includes some exemptions)
	Additional requirements for plastics used in housings and housing parts	Halogenated polymers shall not be permitted. Halogenated organic compounds may not be used as additives or added to parts (with exemptions).
	Additional requirements for plastics used in printed circuit boards	PBBs, PBDEs, TBBPA or chlorinated paraffins may not be added to the carrier material of the printed circuit boards.
	Requirements for electronic components	Shall not contain lead, mercury, cadmium or hexavalent chromium. Lead-containing solder shall not be used.
5.Recycling and disposal	Recyclability	Shall be designed to allow for easy disassembly for recycling by a specialist firm using ordinary tools
	Product take-back	Free take back of the product

		Routing to reuse, recycling or professional disposal
6. Safety	Safety requirements	Product literature to integrate product into protection systems Meets minimum requirements according to EN 62109 (CE marking) Certificate of non-objection to integrated electronic load break switch
7.Electromagnetic capability	Compatibility requirements	Conformity with EN 61000-6-1/6-3 (CE marking)
8. Noise emissions	Maximum level	Maximum sound power level of 55 dB(A)

2.3 Regulatory frameworks

In the pursuit of global sustainability, regulatory frameworks play a role in shaping policies that promote environmentally friendly and socially responsible practices across the life cycle of products. This section delves into regulatory processes that have emerged on the international stage, providing frameworks for sustainable product policies that transcend geographical boundaries. Below we list the standards that relate to PV products.

Regulatory frameworks
Mandatory tools
Voluntary tools
Waste related frameworks

The following categories summarize the relevant standards related to PV products:

- **Mandatory Tools**: Regulations and requirements established by governmental bodies that must be adhered to for legal compliance and environmental responsibility.
- **Voluntary Tools**: Frameworks developed by the European Commission, such as the EU Ecolabel and EU Green Public Procurement (GPP), which promote sustainability practices but are not legally binding.
- **Waste-Related Frameworks**: Regulations and guidelines that focus on the management of products at the end of their life cycle, particularly addressing waste reduction, recycling, and the principles of the circular economy.

Sustainable product policies focus on a comprehensive range of aspects, including product design, materials, manufacturing, usage, end-of-life considerations, and resource utilization like energy, water, and chemicals. To drive the production and consumption of more sustainable products worldwide, governments and international organizations have adopted various policy instruments tailored to their unique contexts. See Figure 11.

Key regulatory tools include Ecodesign, Energy Labelling, Green Public Procurement (GPP), and ecolabeling schemes (Table 7). Ecodesign sets environmental standards for products, emphasizing resource efficiency, while Energy Labelling empowers consumers by providing information on energy efficiency, encouraging informed choices.

Green Public Procurement (GPP) advocates sustainable procurement practices in public entities, driving demand for eco-friendly goods and services. Eco-labels, such as the EU Ecolabel, certify products meeting stringent environmental criteria, helping consumers identify sustainable choices.

Table 7. Summary of nature of the provisions, scope, life cycle stage, and verification process for the four product policy instruments. Reproduced from (Polverini, Dodd, & Espinosa, 2021).

Policy instrument	Nature of the provisions	Scope	Life cycle stage	Verification
Ecodesign	Mandatory	Products	The EU Ecodesign Directive sets minimum environmental requirements across all product life cycle stages. While early requirements focused on energy efficiency during use stage, recent regulations (2019) include material efficiency. Annex V also permits using a design-to-manufacturing management system for conformity assessment.	Market surveillance is carried out at Member State level.
Energy label	Mandatory	Products, packages of products	Energy labels help customers in choosing less energy consuming products under provision of accurate, relevant, and comparable information on the specific energy consumption of products.	Market surveillance is carried out at Member State level.
EU Ecolabel	Voluntary	Products/ services	The ecolabel helps consumers in choosing products with stringent ecological criteria. Criteria can apply to any life cycle stage, including manufacturing sites and tested product performance.	Member State competent bodies verify compliance evidence and award the label.
Green Public Procureme nt (GPP)	Voluntary	Products/ services	Criteria can be set on any life cycle stage and can include manufacturing sites as well as tested product performance. The criteria must always relate to the subject matter.	Evidence-based verification submitted by tenderers.

Ensuring compliance with sustainability standards and frameworks can substantiate claims of environmental responsibility. This section explores different approaches used to assess and validate product adherence to sustainability standards, bolstering credibility for companies in the global marketplace.

Alongside an examination of regulatory processes, this section incorporates insights from a preparatory study that sheds light on the impact of these frameworks on sustainable product policies worldwide. The study highlights successes and challenges, fostering a broader understanding of global efforts to promote sustainability across industries and sectors.

Furthermore, this section overlays the standard frameworks presented in previous sections, offering a comparative analysis of international sustainability initiatives. By exploring these interconnected frameworks, we gain valuable insights into the collaborative efforts of nations and organizations in advancing global sustainability.

While regulatory frameworks have made strides towards sustainability, some regions that introduced local content requirements in solar and wind energy components have faced challenges in developing competitive export sectors. Exceptions like China and Spain demonstrate potential avenues for success, spurring further discussions on the global impact of such policies.

As global consciousness for sustainable practices grows, the need for effective regulatory frameworks becomes more pronounced. This section aims to provide a comprehensive overview of international efforts to drive sustainability, underscoring the importance of regulatory processes in shaping a more environmentally conscious and responsible world.

2.3.1 Mandatory tools

2.3.1.1 EU Ecodesign and EU Energy label

(\Regulatory Frameworks\Mandatory tools)

The European Green Deal underscores the critical role of the EU energy system in reaching climate objectives in 2030 and 2050. The REPowerEU plan emphasizes the need for newly installed PV modules in the EU to be both, affordable and environmentally-friendly. In this context, a preparatory study provided specific recommendations for PV modules, inverters, and systems, ensuring the environmental sustainability of photovoltaics by improving their environmental performance as well as their energy yield, while reducing the overall life cycle environmental footprint.

Ecodesign (European Union, 2009) and Energy Labelling (European Union, 2017) are rules of EU market that make it easier and less costly for business, citizens, and governments to contribute to the clean energy transition and deliver on the EU's 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 foster demand for and supply of more sustainable products whilst reducing energy user expenditure significantly. Indicatively, these savings exceeded EUR 120 billion in 2021 and could reach double in 2022 (European Commission, 2021).

The European Commission prioritized PV modules and inverters in its third Ecodesign Working Plan (European Commission, 2016), as one of the non-regulated product groups with the largest potential for environmental savings. Following the inclusion of PV products in an Ecodesign working plan, a preparatory study (Dodd et al. 2020) on the environmental impact of photovoltaic products was carried out by the Joint Research Centre of the European Commission. In 2024, the European Solar PV Industry Alliance (ESIA) also published their policy recommendations for these two directives. [89]

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[89] European Solar PV Industry Alliance (ESIA). (August, 2024). Recommendation Paper Series VII, Comprehensive Strategies for Carbon Footprint Assessment: Best Practices for European Sustainability Directives for PV modules. Available at https://solaralliance.eu/wp-content/uploads/2024/09/ESIA-Recommendation-Paper-Series-VII.pdf

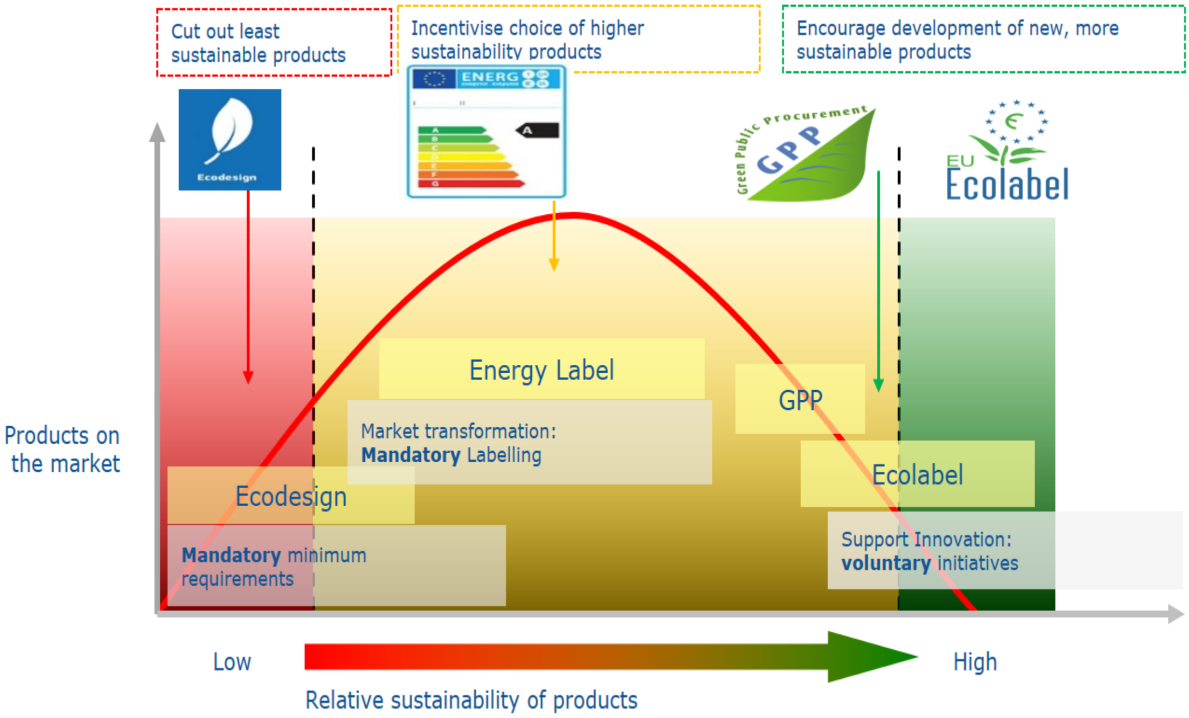

Figure 11. Products and policy tools at the European Commission showing the relative sustainability of products attained. Source: (Cordella, et al., 2020)

The two European Commission initiatives "Ecodesign" and "Energy labelling" aim to make solar PV products more energy efficient in manufacturing, extend their lifetime (i.e., make them less prone to damage) and improve their material efficiency (i.e., make them more recyclable). This would make these devices less harmful to the environment while ensuring they can still circulate freely in the single market. Only products satisfying these requirements would be able to be sold on the EU market. It would also provide accurate and comparable information to businesses and citizens when choosing solar PV products. The areas for potential regulation to be further assessed based on the outcome of this consultation and the Commission's impact assessment relate to:

- Reliable information about performance and energy yield taking into account local climate conditions
- Durability, resilience and resistance to wear and climate hazards
- Reparability and ability of the product to be disassembled
- Recyclability, declaration of the material content
- Availability of priority spare parts and product repair information
- Availability of adequate product servicing by the manufacturer (maintenance, repairs)
- Availability of appropriate information for users/purchasers, installers, repairers, and recyclers
- Carbon footprint of the manufacturing and shipment phases
- Energy label to allow comparisons on production energy consumption efficiencies.

2.3.2 Voluntary tools

2.3.2.1 Ecolabel

(\Regulatory Frameworks\Voluntary tools)

Voluntary tools and certifications guide consumers and businesses toward sustainable and environmentally responsible choices within the PV sector. These tools are designed to verify and recognize compliance with stringent ecological criteria throughout a product's life cycle, from its manufacturing to its end-of-life management and environmental performance. In this section, we explore some of the notable voluntary tools and ecolabels that promote sustainability within the PV sector.

European Union Ecolabel (EU Flower): The European Union Ecolabel, often referred to as the EU Flower, stands as a symbol of environmental excellence across the European Union. It is awarded to products that meet or exceed the demanding sustainability criteria set by EU authorities. This label assures consumers and businesses that a product aligns with high environmental and sustainability standards. Importantly, Member State competent bodies play a pivotal role in verifying compliance evidence and awarding this label.

Following a proposal for an Ecolabel specifically for PV modules made in 2016 by the European Technology and Innovation Platform for Photovoltaic (ETIPV)[90], a preparatory study was performed in 2021. It underlined the EU Ecolabel's significance in ensuring that PV products would meet stringent environmental and sustainability criteria (Dodd & Espinosa, 2021). A number of hotspots were identified to be potentially translated into EU Ecolabel criteria. For example, regarding metallisation paste, the study proposed "1) Use of less silver metallization paste, or 2) Substitute silver by copper plating". This certification could play a crucial role in guiding consumers and businesses toward environmentally responsible choices.

If awarded with an EU Ecolabel, products must comply with the Regulation, particularly Articles 6(6) and 6(7) related to Substances of Very High Concern (SVHC) under the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) and Restriction of Hazardous Substances (RoHS) directives. In the PV industry, ensuring compliance with REACH and RoHS directives can be a complex endeavor. Recognizing these challenges, some ecolabeling and certification programs collaborate with regulatory authorities to offer allowances and exemptions for specific SVHC.

Blue Angel Certification (Germany): The Blue Angel is an ecolabel established at the national level by the German government in 1978. It has been at the forefront of developing product performance criteria for a wide range of consumer products. Notably, a criteria set for PV inverters was published in 2012. Furthermore, the Blue Angel has made several attempts to develop criteria for PV modules and systems. This certification focuses on setting rigorous standards for environmental impact and energy efficiency, contributing to reducing the ecological footprint of PV systems.

EPEAT (Electronic Product Environmental Assessment Tool): globally recognized and independently validated ecolabel for sustainable electronics. It is maintained by the Global Electronics Council (GEC) and empowers purchasers to identify environmentally preferable products from socially responsible companies. While EPEAT is not exclusive to PV products, its broader scope encompasses sustainable electronics, making it a resource for those seeking

[90] https://etip-pv.eu/publications/etip-pv-publications/download/proposal-for-eu-ecolabel-for-solar-photovoltaic-pa

environmentally responsible PV-related equipment. Further details on their process can be found in Section 2.2.2: NSF457/EPEAT for Solar Ecolabel.

Other Initiatives: Additionally, various organizations, such as TÜV Rheinland, Japan Environment Association (JEA), Korea Environmental Industry & Technology Institute, NSF International, and the Cradle to Cradle Products Innovation Institute, have been actively engaged in developing ecolabel criteria related to PV products. These initiatives address specific aspects of PV products, including consumer products with PV cells, inverters, and modules. While their focus may vary, they all contribute to the broader goal of promoting sustainability and environmentally responsible practices within the PV sector.

2.3.2.2 Green Public Procurement

(\Regulatory Frameworks\Voluntary tools)

Green Public Procurement (GPP) Criteria are increasingly being adopted worldwide to guide public procurement toward environmentally friendly and sustainable PV systems. These criteria encompass various aspects including component requirements, life cycle performance indicators, and carbon footprint considerations. By incorporating GPP into their procurement processes, countries demonstrate their commitment to promoting renewable energy and reducing the environmental impact of PV systems.

Key Regulatory and Policy Contexts Impacting GPP

1. **NZIA (Net-Zero Industry Act) Criteria**: Although the NZIA work is not finalized, the European Commission has already reached an agreement on key provisions. The NZIA emphasizes the need for sustainable practices, including reduced carbon emissions and enhanced recyclability in the PV sector. It aims to strengthen Europe's clean energy manufacturing capacity, and GPP initiatives can integrate these criteria to align with future EU sustainability goals.
2. **Critical Raw Material (CRM) Act**: The CRM Act will impact the PV sector by promoting responsible sourcing and recycling of critical materials such as silicon, silver, and rare earth elements. GPP can incorporate CRM Act guidelines to ensure sustainable procurement of PV systems while addressing resource scarcity and supply chain resilience.
3. **AGEC Law (France)**: The French Anti-Waste for a Circular Economy Law (AGEC) mandates eco-design criteria for products, including PV modules, which are classified under WEEE (Waste Electrical and Electronic Equipment). This law emphasizes reducing material consumption, increasing recyclability rates, and facilitating the recycling of products. GPP in France already integrates such criteria, promoting eco-friendly PV solutions.
4. **ETIP Platform KPIs**: The European Technology and Innovation Platform (ETIP) for Photovoltaics has established key performance indicators (KPIs) for reducing the environmental impact of PV modules. These include metrics such as energy payback time (EPBT), recyclability rates, and carbon footprints. GPP frameworks can adopt these KPIs to standardize procurement practices and incentivize innovation in PV sustainability.
5. **REACH and RoHS Regulations**: These regulations, focusing on the restriction of hazardous substances (RoHS) and chemical safety (REACH), directly impact recycling and production strategies in the PV sector. GPP criteria can ensure compliance with

these regulations, especially for emerging PV technologies, by prioritizing low-toxicity materials and supporting circular economy practices.

Examples of Country-Specific GPP initiatives

Different countries have implemented specific GPP initiatives to ensure that public entities prioritize environmentally friendly PV solutions. For example, in Spain, national requirements focus on promoting energy efficiency and the use of renewable energy sources. This may involve criteria related to the environmental performance of PV modules, such as energy efficiency, carbon footprint, and adherence to sustainability standards.

In France, GPP emphasizes evaluating the life cycle performance of PV systems. This entails considering the environmental impact from raw material extraction to end-of-life management. Indicators such as carbon footprint, resource depletion, and waste generation guide French GPP criteria, directing public procurement decisions toward more sustainable and environmentally friendly PV solutions.

In the United Kingdom, GPP criteria may emphasize the use of specific components that meet sustainability standards. This can include requiring PV modules with a high percentage of recycled materials or those certified for their environmental performance. By prioritizing sustainable components, the UK promotes the use of environmentally friendly PV systems in public procurement.

In California, GPP criteria consider both component and system performance. Public entities may require the use of components that meet specific sustainability certifications, such as those demonstrating low toxicity or high energy efficiency. Additionally, the performance of the entire PV system, including energy generation capacity and efficiency, is taken into account. These criteria ensure that public procurement in California supports environmentally sustainable PV solutions.

In Korea, GPP criteria focus on evaluating the carbon footprint of PV products. Public entities may require PV modules and systems with lower carbon emissions throughout their life cycle. By prioritizing low-carbon PV solutions, Korea aims to reduce greenhouse gas emissions and promote a sustainable energy transition.

Public auctions may play a significant role in the global expansion of solar power, but newly adopting countries lack solar-specific experience and capacity. According to the International Renewable Energy Agency (IRENA), by the end of 2019, 106 countries had conducted renewable energy auctions, with a significant number being held for the first time. However, a prior study revealed widespread deficiencies in nearly 30 percent of the analyzed solar projects, hindering the growth of the sector and undermining efforts to achieve solar energy deployment targets.[91]

One potential solution lies in incorporating technical requirements based on international quality standards. A collaborative effort by several German institutions has produced a policy brief titled "Technical requirements in public auctions to make solar plants shine",[92] which offers valuable insights by synthesizing lessons learned from international experiences with technical requirements in solar PV auctions.

The policy brief puts forth three key recommendations to improve the effectiveness of technical requirements. Firstly, it highlights the importance of defining technical requirements aligned

[91] https://www.sciencedirect.com/science/article/pii/S1364032121009874?via%3Dihub

[92] https://www.ferdinand.es/integrating-international-quality-standards-in-solar-photovoltaic-auctions/

with national solar policy objectives. Considering the unique context and policy goals of each country's solar PV sector development is crucial. Additionally, the state of the national Quality Infrastructure system has bearing on ensuring local project developers can access the necessary services to meet the technical requirements.

Secondly, the Policy Brief emphasizes the promotion of international quality standards. Transparent and accessible communication of technical requirements enhance quality and ensure compliance with standards in the solar sector. By emphasizing the connection between these requirements and policy objectives, stakeholders can collaborate toward a common mission. Effective incentives can also encourage the PV industry to adapt to new quality requirements and standards.

Authorities can monitor compliance with international quality standards through in-person inspections during plant commissioning and digital monitoring of real-time generation data during operation. Such monitoring mechanisms enable evaluation of the impact of quality standards on plant performance and ensure desired outcomes.

By implementing these recommendations, countries can enhance the quality and performance of solar PV projects procured through public auctions. This not only mitigates investment risks in newcomer countries but also accelerates the development of the solar sector, contributing to the achievement of renewable energy goals.

2.3.2.3 Product Environmental Footprint Category Rules PEFCR

(\Regulatory Frameworks\Voluntary tools)

The Product Environmental Footprint (PEF) is a European Commission initiative, that uses Life Cycle Assessment (LCA) methods to quantify the relevant environmental impacts of products (goods or services). The aim of the PEF is to set the basis for better reproducibility and comparability of LCA results. However, comparability is only possible if the results are based on the same Product Environmental Footprint Category Rules (PEFCR).

For the PV sector, PEF Category Rules represent a step in evaluating the environmental performance of PV technology used in power systems for electricity generation. Unlike module-specific assessments, the PEFCR methodology provides a **system-level assessment** that encompasses not only the PV module but also extends to components within the PV system, including the mounting systems and electrical installations. This broader system boundary aligns with the PEFCR's goal of providing a holistic evaluation of environmental impacts across the full PV power system life cycle, encompassing raw material extraction, manufacturing, use phase, and end-of-life management.

However, this expanded system boundary introduces complexities when comparing the environmental performances of individual PV modules. Variability in PV system components can contribute to uncertainties in the energy yield and overall system performance, as highlighted by the findings of IEA Task 13 report[93]. This complicates direct comparisons between modules, especially when each module's performance is influenced by the specific configuration of the surrounding system components.

For module-level comparisons focused specifically on environmental performance, methodologies that define the functional unit based on **Watt peak (Wp)** output and apply a **module-only system boundary**—such as those used in the Norwegian Environmental

[93] **Uncertainties in PV System Yield Predictions and Assessments, at** https://iea-pvps.org/key-topics/uncertainties-in-pv-system-yield-predictions-and-assessments/

Product Declaration (EPD) System (adopted by the International EPD System), EPEAT, and the French tender system—are generally more suitable. These methodologies allow for a more direct assessment of the module's environmental footprint, isolating the impacts specific to the module and enabling a clearer basis for comparison across different products.

Furthermore, PEFCR facilitates the identification of hotspots and areas for improvement throughout the module's life cycle. By pinpointing the stages with the highest environmental impact, stakeholders can focus their efforts on implementing measures to mitigate these impacts. This drives innovation in cleaner production techniques, resource efficiency, and the adoption of circular economy principles within the PV industry.

The development and application of these category rules for PV modules contribute to the broader goal of achieving a sustainable energy transition. By providing a comprehensive and standardized framework, PEFCR enables a transparent and comparable assessment of the environmental footprint of PV modules. This supports the adoption of greener and more sustainable practices within the PV industry, fostering its integration into a low-carbon and resource-efficient energy system.

2.3.3 Waste related frameworks

From a regulatory perspective, the classification of PV module waste varies globally. Generally, PV modules are considered as general waste; however, regulations and classifications may evolve over time as new guidelines and standards are implemented.

Waste related frameworks
EU Directive WEEE
Extended Producer responsibility
Specific standards in PV waste
US waste related frameworks
Asian waste frameworks

In the United States, waste PV modules are generally classified as electronic waste (e-waste) under the Resource Conservation and Recovery Act (RCRA). However, it's important to check state-specific regulations as they may have additional requirements or classifications.

In China, PV modules are typically classified as electronic waste (e-waste). And aresubject to specific regulations under the country´s waste management framework. These regulations address the collection, recycling, and disposal of EoL PV modules, emphasizing sustainable practices and resource recovery. China has established detailed guidelines for managing waste electrical and electronic products through its *Solid Waste Classification and Code Catalog,* updated in 2024. In this Catalog, end-of-life PV panels are re classified as **renewable waste** under the category of general industrial solid waste, with the specific code 900-015-S17. This classification aims to streamline the recycling and resource recovery processes, ensuring that valuable materials like silicon, silver, and aluminum are reclaimed and reused.

In the European Union (EU), waste PV modules are commonly classified as electronic waste (e-waste) under the Waste Electrical and Electronic Equipment (WEEE) Directive. The WEEE Directive sets out requirements for the collection, recycling, and disposal of e-waste, including

PV modules. The EU has specific regulations for the management of PV module waste to ensure proper handling, recycling, and recovery of valuable materials.

Proper management of discarded PV modules offers environmental benefits across different impact categories (Leccisi & Fthenakis, 2021). For instance, it can lead to a reduction of up to 7% in terms of human toxicity (Herceg, Pinto Bautista, & Weiß, 2020). A recent[94] study by the IEA suggests that if solar panels were consistently recycled, the recovered raw materials could meet over 20% of the solar PV industry's needed input of aluminium, copper, glass, and silicon, as well as nearly 70% of the silver demand globally between 2040 and 2050 (Grijelmo, Molina, & Sanz, 2022).

While recycling technologies for PV modules are still relatively recent and not yet fully mature commercially, they hold significant potential (Ardente, Latunussa, & Blengini, 2019) (Lunardi, Alvarez-Gaitan, Bilbao, & Corkish, 2018) (Weckend, Wade, & Heath, 2016), (Lunardi, Alvarez-Gaitan, Bilbao, & Corkish, 2018), (Grijelmo, Molina, & Sanz, 2022). Apart from high-purity glass and silicon recovery, valuable materials such as indium and gallium, tin, aluminium, copper, silver, and germanium have a high recycling potential. There are studies that indicate that more than 95% of these materials could eventually be recycled at no net cost or even with a profit, which would also reduce the EU's reliance on material imports (Mathieux, 2017). The silicon in the cells can be extracted with various qualities (ferro-Si, metallurgical-grade Si, or solar-grade), with a higher revenue but more complicated recycling process for the purer products. The recycling rate of silicon metal could reach up to 95%, an output comparable to metallurgical-grade silicon metal (Ardente, Latunussa, & Blengini, 2019).

However, the recycling of PV modules is a young technology and still relatively costly (there is only one specialised facility in the EU for PV module recycling (Grijelmo, Molina, & Sanz, 2022)); the cheaper and legally feasible landfilling of modules (after decontamination[95]) constitutes the most common practice and is set to persist. Even when preventative measures are taken, landfilling is known to cause small amounts of heavy metals and other hazardous materials still contained in modules to leach and contaminate the soil or groundwater. These contaminations, e.g., lead and tin present in crystalline silicon (c-Si) PV modules, or fluoropolymers present in the back-sheet, result in significant environmental pollution (Deng, Chang, Ouyang, & Chong, 2019); (Ayran & Maga, 2017); and (Nain & Kumar, 2020). For emerging technologies, the problem is likely to persist or worsen, e.g., silicon-perovskite tandem technologies may include lead in the perovskite absorber layer (Leccisi & Fthenakis, 2021).

Moreover, common manufacturing and information practices impede the development and expansion of recycling. The separation of the glass and aluminium frame from the other components of the module is too complicated (Heitmann & Pohl, 2019); the standard product information sheets accompanying solar PV modules do not at all or only very rarely provide information on the type of silicon doping, the solder used nor the exact structure of the back-sheet foil, nor on the raw material content. Furthermore, the back-sheet films typically consist of a composite of different polymers and can therefore not be treated with a polymer-specific recycling technology. Also, information on silicon impurities is currently lacking, which would facilitate the re-use of recovered silicon (Heath, et al., 2020).

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[94] IEA (2021). Special Report on Solar PV global Supply chain.

[95] Under the WEEE directive, to qualify for landfill disposal the modules must be collected separately and be non-hazardous (e.g., under the EPA's regulated levels on toxic metals), as otherwise they are precluded from being treated as solid waste.

2.3.3.1 EU Directive WEEE

(\Regulatory Frameworks\Waste related frameworks)

The 2012/19 Directive on Waste Electrical and Electronic Equipment (WEEE), classifies PV panels as category 4 (large equipment), and requires producers to collect separately and recover PV modules at their own cost. It also recommends setting cost contribution rates of producers based on modules' recyclability. However, currently the end-of-life management of PV modules is based on silicon wafer technology, the main technology on the market, excludes recovering silicon from the sandwich layer (backsheet plus cells plus encapsulant, typically ethyl vinyl acetate), nor the glass. For cadmium-telluride modules, the main manufacturer runs a take-back program for treating end-of-life modules, recovering up to 90% of materials[96].

The Directive also states that Member States shall encourage cooperation between product manufacturers and recyclers in order to facilitate the re-use, dismantling, and recycling of WEEE at product, component, and material level. It is understood that some Member States are considering specific references in legislation to the treatment of photovoltaic modules.

The Waste Electrical and Electronic Equipment (WEEE) Directive includes targets for the recovery and recycling/preparing for reuse for photovoltaic panels: recovering 85% of the collected PV panel waste and reusing/recycling 80% of it from 2018 onwards. However, only 6 of the 12 countries that reported this data met this target in 2021 as shown in Figure 12.

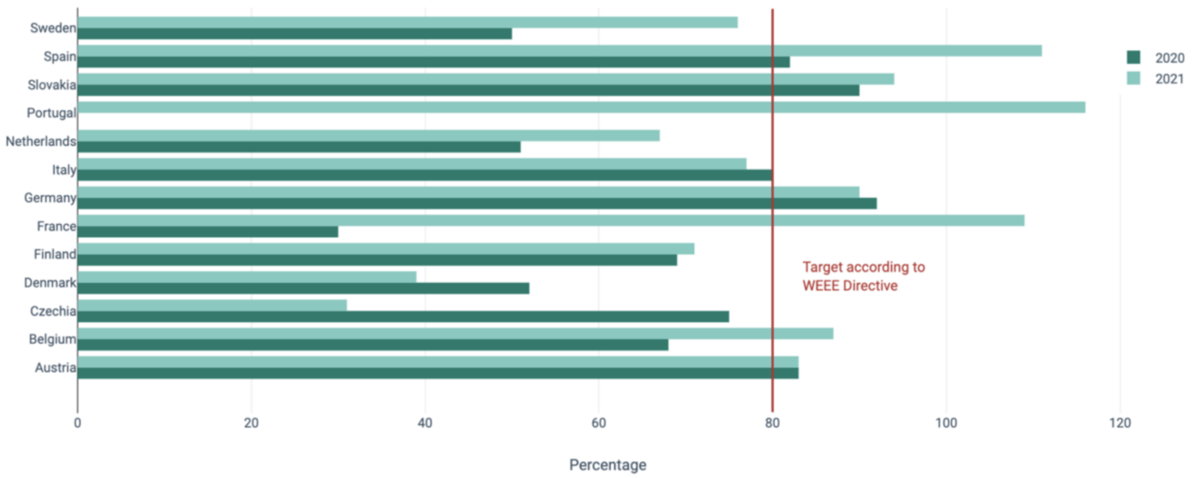

Figure 12. *Percentage of photovoltaic (PV) panels waste recycled or prepared for reuse in 2020 and 2021. From: EEA website[97].*

According to WEEE forum[98], making EN 50625 standards legally binding is part of the solution (WEEE FORUM, 2018). Verification of proper treatment and depollution is supported by the EN 50625 series which defines WEEE collection logistics and treatment requirements. Annex

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96 Cadmium and tellurium separation and refining are carried out by a third party. For pre-2013 sales customers, First Solar, the main manufacturer for this technology, has a prefunded collection and recycling programme for end-of-life modules. With the sale of each module, First Solar historically set aside sufficient funds to meet the estimated future collection and recycling costs of its modules. Individual modules are labelled with information for the owner on how to return the end-of-life module.

97 https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/recycling-from-green-technology?activeTab=8a280073-bf94-4717-b3e2-1374b57ca99d

98 The WEEE Forum, set up in 2002, is a Brussels-based international not-for-profit association speaking for 36 not-for-profit electrical and electronic equipment waste (WEEE) producer compliance schemes – alternatively referred to as 'producer responsibility organisations' (PRO)

A of EN 50625-1 identifies specific components of equipment that shall be removed for depollution purposes. Parts 2–4 and 3–5 focusing on treatment requirements and a specification for depollution for PV panels are in the final stages of development.

PV Cycle is one producer responsibility organization that manages the collection and recycling of PV modules in compliance with the WEEE Directive in the European Union. They do cover PV module waste, electrical/electronic equipment waste, battery waste, and industrial and packaging waste.

With a membership base across the EU, PV Cycle recently published a position paper (Cycle, 2023) that evaluates the WEEE Directive and provides recommendations specifically related to photovoltaic panels. Their evaluation highlights the need for a separate Extended Producer Responsibility (EPR) legislative framework dedicated to all renewable energy equipment. This separate framework addresses the unique characteristics and challenges posed by PV panels in waste management and recycling. The recommendations also advocate for a differentiated approach that recognizes the unique characteristics of renewable energy products:

- Exclusion from Collection Targets: PV modules should be excluded from the collection targets of the WEEE Directive due to their long lifespan, investment nature, and limited contribution to waste during the first 15 years of operation.
- Introduction of Key Performance Indicators (KPIs): Instead of rigid collection rates or targets, KPIs should be implemented to reflect the unique characteristics and long lifetime of PV modules. These KPIs should consider factors such as waste prevention, societal contribution, and performance over time.
- Dedicated Waste Treatment Requirements: Minimum waste treatment requirements should be defined specifically for renewable energy products, including PV modules. These requirements should take into account the composition and nature of PV modules, which differ from traditional electrical and electronic equipment (EEE).
- Harmonization of Recycling and Recovery Targets: Recycling and recovery targets for PV modules should be reasonable and aligned with their specific composition, such as flat glass laminated products. The interpretation of definitions related to recycling and recovery should be harmonized across Member States.
- Financing Mechanism: A realistic and secure financing mechanism should be established for PV modules, considering their long lifespan and distinct market dynamics. This mechanism should ensure that provisions are in place for future costs and prevent a race to the bottom in terms of compliance fees.

In addition to these recommendations, the paper also highlights the need for harmonized implementation of the authorized representative requirement and the removal of the distinction date of 13 August 2005 for PV modules.

PV inverters are very different from modules and their end-of-life situation is not comparable. Inverters are e-waste, and while not mentioned explicitly in the WEEE Directive, are still understood to fall under its scope.[99] With an expected lifetime between 10 and 15 years (Richter, et al., 2017), inverter failures are mostly related to its main circuit board, AC contactors, fuses, capacitors, and fans. Such kind of failures frequently lead to the replacement of the equipment.

99 Frequently Asked Questions on Directive 2012/19/EU

2.3.3.2 Extended Producer Responsibility (EPR)

(\Regulatory Frameworks\Waste related frameworks)

Extended Producer Responsibility (EPR) is a policy approach that embodies a significant responsibility, both financial and physical, for producers in the treatment or disposal of post-consumer products. This concept aims to provide incentives for waste prevention at the source, promote environmentally friendly product design, and contribute to the attainment of public recycling and materials management objectives. In recent years, there has been a growing trend within the Organisation for Economic Cooperation and Development (OECD) toward expanding the scope of EPR to encompass new products, product groups, and waste streams, particularly in the realm of electrical appliances and electronics.

In the context of PV modules, the implementation of EPR could be promising for module recyling. As PV technology gains traction worldwide and the number of decommissioned modules increases, responsible management of end-of-life PV modules becomes crucial. EPR can play a role in ensuring that producers of PV modules assume responsibility for the proper treatment and disposal of these post-consumer products.

By imposing a shared responsibility on PV module manufacturers, EPR encourages them to adopt sustainable practices throughout the product life cycle. This includes not only the production phase but also the end-of-life stage. Manufacturers are incentivized to design PV modules with recyclability and resource efficiency in mind, fostering a circular economy approach. The integration of EPR in the PV industry promotes the development of collection and recycling infrastructure, facilitating the recovery of valuable materials and reducing environmental impacts associated with waste disposal.

Moreover, the extension of EPR to PV modules aligns with broader sustainability objectives. By shifting the burden of waste management onto producers, EPR encourages them to take proactive measures to minimize the environmental footprint of their products. This can drive innovation and the adoption of cleaner production technologies, leading to improvements in energy efficiency, reduction in hazardous materials usage, and overall product sustainability.

Collaboration among stakeholders can ensure the effective implementation of EPR for PV modules,. This includes government entities, industry associations, recycling facilities, and consumers. Clear guidelines and regulations can delineate the roles and responsibilities of each stakeholder, while also providing necessary support and incentives for compliance. Robust monitoring and reporting mechanisms can help track the progress of EPR implementation, ensuring transparency and accountability.

In conclusion, the adoption and expansion of EPR represents a significant step forward in the responsible management of end-of-life PV modules. By making producers accountable for the treatment and disposal of these products, EPR fosters a circular economy approach, encourages sustainable product design, and supports the achievement of recycling and materials management goals. The implementation of EPR for PV modules requires collaboration, clear regulations, and monitoring mechanisms to ensure its effectiveness and maximize environmental benefits.

In the United States, EPR programs for electronic waste, including PV modules, are primarily regulated at the state level. Currently, 26 states have implemented EPR laws that require manufacturers to take responsibility for the collection and recycling of electronic products at the end of their life. These laws typically involve establishing recycling programs, funding mechanisms, and reporting requirements. However, the specifics of EPR implementation can vary from state to state[100].

China has also adopted EPR measures for electronic waste, including PV modules, as part of its broader waste management strategy. The country introduced the Regulation on the Management of the Disposal of Waste Electrical and Electronic Products in 2011, which places the responsibility for product recycling on manufacturers. Producers are required to establish collection and recycling systems, meet recycling targets, and report their recycling activities to the government.

Several countries in Asia have implemented EPR programs for electronic waste. For example, Japan has a well-established EPR system for electronics, known as the Home Appliance Recycling Law. South Korea also has an EPR system for electronic waste, including PV modules, under the Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles. These programs require manufacturers to manage the collection and recycling of their products.[101]

In India, the E-Waste (Management) Rules were introduced in 2016 to address the growing challenge of electronic waste. The rules impose Extended Producer Responsibility on manufacturers, importers, and brand owners of electronic products, including PV modules. They are required to establish collection centers, arrange for the recycling of e-waste, and file annual reports with the government.

The EU has established the most comprehensive framework for EPR, encapsulated in the Waste Electrical and Electronic Equipment (WEEE) Directive. This Directive (see section 2.3.3.1) mandates that producers of electrical and electronic equipment, including PV modules, are responsible for the collection, recycling, and proper treatment of their products at the end of their life cycle. Producers must either join collective schemes (by adhering to a Producer responsibility organization, such as PV Cycle) or set up their own take-back and recycling systems to comply with the directive.

There are two main financing models for EPR fees:

i) *Pay-as-you-go (PAYG) system*, where producers pay for the waste generated in a specific year, and

ii) *Deferred payment system*, where producers pay in advance to cover the future management costs of waste.

Member States predominantly use the PAYG financing model. EPR fees in Europe vary widely, from 4.8 €/ton in Austria, to 160 €/ton in Hungary[102], based on the tons placed on market. This cost seems to be more closely related to the size of the PV market than to the actual tons of PV module waste collected. However, these fees would ideally cover the cost of the waste generated. Additionally, since the cost is typically expressed as "tons placed on the market", it does not reflect accurately the amount of waste generated.

Meeting the EPR obligations for PV modules under the WEEE Directive presents several challenges. PV modules fall under the large equipment category, the collection targets based on the average weight of EEE placed on the market (POM) methodology are not feasible for

[100] https://www.ncsl.org/environment-and-natural-resources/extended-producer-responsibility?utm_source=chatgpt.com

[101] Status of PV Module Recycling in Selected IEA PVPS Task12 Countries, 2022, available at https://iea-pvps.org/key-topics/status-of-pv-module-recycling-in-selected-iea-pvps-task12-countries/

[102] Figures collected by the author through interviews. Not published yet.

PV panels. This is due to their long lifespans, which mean they do not yet generate significant amounts of waste. Furthermore, the lack of a specific category for PV panels in the legislation leads to reporting difficulties, as they are often reported mixed with other category 4 waste types.

According to a WEEE Forum report[103], there are five recommendations regarding EPR schemes:

- Stop applying collection targets based on the POM methodology to PV modules.
- Support research to understand the flow of PV panels at the EU level and establish realistic collection targets
- Consider alternatives such as *service upon demand* schemes or a derogation of the POM collection target until sufficient volumes of waste PV panels arise
- Introduce a separate category for PV panels in the legislation and enforce the reporting of PV panels placed on the market and collected in a separate category
- Urgently request harmonized specific legislative measures at the EU level to ensure fair and realistic compliance with the extended producer responsibility principle for PV panels.

In Australia, the Product Stewardship Act 2011 provides the legal basis for EPR. While EPR programs for electronic waste, including PV modules, are not mandatory at the national level, the government encourages voluntary industry-led schemes to promote responsible product management. Several industry-led programs exist, facilitating the collection and recycling of electronic waste, including PV modules.

2.3.3.3 Specific standards in PV waste treatment in EU

(\Regulatory Frameworks\Waste related frameworks)

In 2017, Sinha et al. (Sinha, Raju, Drozdiak, & Wade, 2017), conducted a study on life cycle management and the recycling of PV systems listing PV panel specific collection standards. According to Sinha, CENELEC, the European Committee for Electrotechnical Standardization, has developed a supplementary standard (EN50625-2-4 & TS50625-3-5) to assist treatment operators in the PV panel collection and treatments. The standard specifies various administrative, organizational, and technical requirements aimed at preventing pollution and improper disposal, minimizing emissions, promoting increased material recycling and high-value recovery operations, and impeding PV waste shipments to facilities that fail to comply with standard environmental and health and safety requirements. The standard includes specific depollution requirements whereby the content of hazardous substances in output glass fractions shall not exceed the limit values defined in Table 8.

Table 8. Limit values for cadmium, selenium, and lead specified in EN50625-2-4 standard.

	Si-based-PV	Non-Si based PV
Cadmium	1 mg/kg (dry matter)	10 mg/kg (dry matter)
Selenium	1 mg/kg (dry matter)	10 mg/kg (dry matter)
Lead	100 mg/kg (dry matter)	100 mg/kg (dry matter)

[103] Issues associated to photovoltaic panels and compliance with EPR legislation, WEEE Forum, 2021. https://weee-forum.org/wp-content/uploads/2021/06/WEEE-Forum-PV-Panels-Issue-Paper-2021-Final.pdf

Specific conditions apply in Germany for the disposal of PV module waste, where the WEEE Directive, is implemented through the German Electrical and Electronic Equipment Act (ElektroG). The ElektroG provides specific conditions for the handling and disposal of PV module waste. Here are some key points:

1. Collection and Take-Back Obligations: PV module manufacturers and distributors are obligated to collect and take back end-of-life modules when they reach the waste stage. They are required to establish or join a collective take-back system to ensure proper collection and recycling of the modules.
2. Recycling and Recovery Targets: The ElektroG sets specific recycling and recovery targets for PV module waste. These targets aim to ensure that a certain percentage of the materials used in the modules, such as glass, metals, and other components, are recycled or recovered. This helps to minimize the environmental impact of waste disposal and promotes resource conservation.
3. Treatment and Disposal Standards: The ElektroG establishes standards for the treatment and disposal of PV module waste. It outlines requirements for environmentally sound processing methods and ensures that hazardous substances present in the modules are handled safely to prevent harm to human health and the environment. These standards help to minimize the potential risks associated with the disposal of PV module waste.
4. Producer Responsibility: Similar to the EPR approach, PV module manufacturers have a significant responsibility for the treatment and disposal of their products. They are required to finance the collection, treatment, and recycling of end-of-life modules. This encourages manufacturers to design products with end-of-life considerations in mind and promotes their active involvement in the recycling and circular economy initiatives.
5. Reporting and Compliance: The ElektroG also includes reporting requirements for PV module manufacturers and distributors. They must provide information on the quantities of modules placed on the market, collected for recycling, and treated or disposed of. This reporting ensures transparency and helps regulatory authorities monitor compliance with the regulations. By implementing the WEEE Directive through the ElektroG, Germany has established a robust framework for the management and disposal of PV module waste. These specific conditions ensure that PV modules are properly collected, recycled, and disposed of in an environmentally responsible manner, minimizing their impact on the environment and contributing to the sustainable management of electronic waste.

2.3.3.4 U.S. waste related frameworks

(\Regulatory Frameworks\Waste related frameworks)

In the United States, several standards and regulations address PV waste management and disposal. It’s important to note that regulations and standards related to PV waste management may vary at the state level in the United States. Here are some of the key frameworks:

Resource Conservation and Recovery Act (RCRA): The RCRA is a federal law that governs the management of hazardous waste in the United States. PV modules may contain hazardous substances such as lead and cadmium, which fall under the RCRA regulations. Producers and handlers of PV waste must comply with the RCRA requirements, including proper identification, storage, transportation, and treatment of hazardous waste.

Electronics Waste Recycling: Several U.S. states have implemented their own electronics waste recycling programs, which cover PV modules among other electronic products. These programs typically require manufacturers to finance or participate in the collection and recycling of end-of-life PV modules. The specifics of these programs vary by state, with some mandating recycling targets and others promoting industry-led initiatives.

UL 2703 Standard: The UL 2703 standard, developed by Underwriters Laboratories, provides requirements for mounting systems, connectors, and grounding for PV modules. While not directly focused on waste management, this standard includes provisions for ease of disassembly and recycling, encouraging environmentally friendly practices in the design and manufacturing of PV systems.

Global Electronics Council (GEC): The Global Electronics Council manages the EPEAT program (see section 2.2.2), which includes environmental performance criteria for electronic products, including PV modules. The registration indicates compliance with specific environmental standards, including requirements for recycling and end-of-life management.

Industry Best Practices: The U.S. PV industry has developed voluntary initiatives and best practices for managing PV waste. Organizations such as the Solar Energy Industries Association (SEIA) and the Solar Energy Industries Association of America (SEIAA) provide guidance on responsible end-of-life management, including recommendations for recycling, proper disposal, and adherence to applicable regulations.

2.3.3.5 Asian waste frameworks

(\Regulatory Frameworks\Waste related frameworks)

In Asia, several countries have implemented frameworks and regulations to address the management and disposal of PV waste. These frameworks aim to promote sustainable waste management practices, establish extended producer responsibility (EPR) systems, and reduce the environmental impact of PV waste. Here are some examples:

China has implemented the *Management Measures for the Recycling and Disposal of Waste Electrical and Electronic Products* (also known as China WEEE Regulations). These regulations require PV module manufacturers and importers to establish collection and recycling systems for end-of-life modules. They also encourage the use of eco-design principles and promote the development of recycling technologies.

In addition, China released the **Guidance on Promoting the Recycling of End-of-Life Wind Power and Photovoltaic Equipment** in 2023. This is the country's first comprehensive guidance document with detailed regulations on the recycling of end-of-life equipment for wind power and photovoltaics. The guidance mandates that:

- **PV module manufacturers**, **PV plant owners**, and **government bodies** establish systems for the collection and recycling of end-of-life PV modules.
- Eco-design principles be integrated into product development to enhance recyclability.
- Advanced recycling technologies be developed and deployed to improve material recovery rates and minimize environmental impact.

Japan has established the *Act on the Promotion of Effective Utilization of Resources*, which includes provisions for the recycling of PV modules. The act requires PV module manufacturers and importers to establish a recycling system and achieve certain recycling targets. It also promotes eco-design and provides guidelines for proper recycling practices.

South Korea has implemented the *Act on Resource Recycling of Electrical and Electronic Equipment and Vehicles*, which covers the recycling and disposal of PV modules. The act sets recycling targets and requires PV module manufacturers and importers to finance the collection and recycling of end-of-life modules. It also promotes eco-design practices and encourages the development of recycling technologies.

In **India**, the *E-Waste (Management) Rules*, 2016, cover the recycling and disposal of PV modules as part of electronic waste. The rules require PV module manufacturers and importers to obtain an Extended Producer Responsibility (EPR) authorization and establish collection and recycling systems. They also specify recycling targets and promote environmentally sound recycling practices.

Southeast Asia (Thailand, Vietnam, Malaysia)

Thailand has implemented the *Hazardous Substance Management Act (HSMA)* to regulate the management of hazardous substances, including PV modules classified as e-waste. Manufacturers and importers are required to fulfill their EPR obligations, by establishing systems for collection recycling and disposal of PV modules.

Vietnam has adopted the *Law on Environmental Protection*, which obliges manufacturers and importers to set up EPR systems and ensure proper recycling and disposal of PV modules to minimize environmental impacts.

Malaysia has introduced the *Environmental Quality (Scheduled Waste) Regulations*. They classify PV modules as scheduled waste. EPR obligations include establishing collection systems and ensuring proper recycling to enhance sustainable waste management practices.

3 EFFECTS AND IMPACTS OF THE SUSTAINABILITY STANDARDS

3.1 Effectiveness of Sustainability Standards & Frameworks

Evaluation methodologies assess the sustainability of PV standards, ensuring they align with environmental goals and promote sustainable development. This section evaluates the effectiveness of PV sustainability standards, focusing on their impact on improvement, influence on purchase decisions, benefits for producers, support for due diligence requirements, and achievement of higher sustainability goals. By using these evaluation methodologies, stakeholders can gain a comprehensive understanding of the sustainability of PV standards and make informed decisions to drive positive environmental outcomes.

Assessing the effectiveness of a specific sustainability standard drives improvement within the PV industry. Such evaluations provide insights into how standards address environmental and social challenges, promoting adherence to best practices throughout the supply chain.

An important aspect of sustainability standards is their influence on consumer purchase decisions. For example, initiatives such as Ecolabels play a key role in encouraging consumers to choose products with higher sustainability credentials. By analyzing consumer behavior and preferences, stakeholders can better understand how these standards shape market dynamics and promote demand for sustainable products.

From the producers' perspective, sustainability standards can significantly impact their ability to leverage marketing strategies and secure finance. These standards support due diligence requirements within the PV industry by addressing social and environmental risks throughout the supply chain. By evaluating how effectively standards promote responsible sourcing practices, stakeholders can ensure alignment with broader sustainability objectives.

The ultimate goal of sustainability standards and frameworks is to drive the PV industry toward higher sustainability. Evaluating their effectiveness involves examining whether they achieve intended goals such as promoting sustainable practices, reducing environmental impacts, and fostering a circular economy. Additionally, the transparency provided by sustainability standards in the PV supply chain, empowers customers to make informed decisions, reinforcing their preference for sustainable PV products.

Among the available options for evaluating the effectiveness of sustainability standards and frameworks in the PV industry, the OECD 6 Principles and the 2degree initiative have been chosen as the primary evaluation methodologies:

- The OECD 6 Principles offer a broad understanding of sustainability standards, helping stakeholders make informed decisions that drive positive environmental outcomes and support sustainable development within the PV sector.
- In contrast, the 2degree initiative is specifically focused on the environmental performance of PV standards, offering detailed insights into how these standards contribute to reducing greenhouse gas emissions. By prioritizing this aspect, stakeholders can evaluate and improve the environmental footprint of PV standards, ensuring alignment with global climate goals.

3.1.1 OECD six criteria

The Organisation for Economic Co-operation and Development (OECD) has established common definitions for six evaluation criteria—relevance, coherence, effectiveness, efficiency, impact and sustainability—to support consistent, high-quality evaluation. These criteria provide a normative framework used to determine the merit or worth of an intervention (policy, strategy, programme, project, or activity). They serve as the basis upon which evaluative judgements are made.

The key concepts for each of the criterion are defined as follows:

- *Relevance* entails examining the extent to which the intervention's objectives and design respond to beneficiaries' needs and priorities, as well as alignment with national, global and partner/institutional policies and priorities. Understanding gendered power dynamics and reflecting on the commitment to "leave no one behind" are crucial in understanding relevance. If circumstances change, evaluations should also look at whether interventions remain relevant.
- *Coherence*, the new criterion, examines the extent to which other interventions (particularly policies) support or undermine the intervention and vice versa. This includes internal coherence (within one institution or government) including compatibility with international norms and standards, and external coherence (with other actors' interventions in the same context). Coherence includes concepts of complementarity, harmonisation, and coordination, and the extent to which the intervention is adding value while avoiding duplication of effort. In line with the 2030 Agenda, greater attention must be paid to coherence, with an increased focus on the synergies (or trade-offs) between policy areas. This new criterion encourages an integrated approach to understanding complex interventions and their results.
- Effectiveness looks at the extent to which the intervention achieved, or is expected to achieve, its objectives and its results, while taking into account the relative importance of the objectives. The new definition encourages analysis of differential results across groups and the extent to which the intervention contributes to or exacerbates equity gaps. Effectiveness is the most commonly evaluated criteria and is often used as an overall measure of success.
- *Efficiency* helps evaluators ask questions about the extent to which the intervention delivers or is likely to deliver results in an economic and timely way. "Economic" is the conversion of inputs (funds, expertise, natural resources, time, etc.) into results, in the most cost-effective way possible, as compared to feasible alternatives in the context. The new definition includes the dimension of "timely delivery". This criterion is an opportunity to check whether an intervention's resources can be justified by its results, which is of major practical and political importance. Many stakeholders, including beneficiaries, care about efficiency because it can support better use of limited resources to achieve more.
- *Impact* is the extent to which the intervention has generated or is expected to generate significant positive or negative, intended or unintended, higher-level effects. Impact addresses the intervention's ultimate significance and potentially transformative effects i.e., holistic and enduring changes in systems or norms. The impact criterion goes beyond effectiveness and encourages consideration of the big "so what?" question. This is where evaluators look at whether or not the intervention created change that really matters to people.
- *Sustainability* is the extent to which the net benefits of the intervention continue or are likely to continue. Depending on the timing of the evaluation, this may involve analysing the actual flow of net benefits or estimating the likelihood of net benefits continuing over the medium and long term. While the underlying concept of continuing benefits remains unchanged, the new definition encompasses several elements for analysis—financial,

economic, social, and environmental—and attention should be paid to the interaction between them.

3.1.2 2degree Investing Initiative

The 2° Investing Initiative (2DII) is a non-profit think tank and international collaboration working towards aligning the financial sector with climate goals. It was founded in 2012 with the aim of promoting sustainable finance and transitioning investment practices to support the goal of limiting global warming to 2 degrees Celsius or below.

The 2° Investing Initiative provides research, analysis, and policy recommendations to financial institutions, policymakers, and regulators to help them understand and integrate climate-related risks and opportunities into their decision-making processes. They work on various areas, including climate scenario analysis, carbon footprinting, impact assessment, and sustainable finance policy development.

While the 2° Investing Initiative primarily focuses on the financial sector, their research and methodologies can be valuable for evaluating the sustainability of PV standards. Their expertise in climate-related analysis and impact assessment can provide insights into the environmental performance of PV modules and their contribution to mitigating climate change. By applying the methodologies and tools developed by the 2° Investing Initiative, stakeholders can assess the alignment of PV standards with climate goals and make informed decisions to support sustainable investment and development of photovoltaic technologies.

3.2 Portraits

Two initiatives have been portrayed against the established OECD six criteria framework: the NSF 457 Sustainability Leadership Standard/EPEAT Ecolabel and the Extended Producer Responsibility Directive.

3.2.1 NSF 457 Sustainability Leadership Standard/ EPEAT Ecolabel

To illustrate the effectiveness of sustainability standards and frameworks, the NSF/ANSI 457 sustainability leadership standard presented in Section 2.1.2. is evaluated with respect to the OECD's six evaluation criteria.

Relevance: In order to determine NSF/ANSI 457's relevance, the standard's criteria (Figure 3) can be compared to stakeholder priorities. In the case of First Solar which has registered products in the EPEAT registry in conformance with NSF/ANSI 457, the company's stakeholder priorities are summarized in an annual corporate materiality assessment[104]. The topics of highest stakeholder importance in First Solar's materiality assessment are sustainable products and innovation, energy and emissions, circular economy, responsible sourcing and human rights, governance and accountability, supply chain resilience, and public policy. Because all of these stakeholder priorities are addressed in NSF/ANSI 457 (aside from public policy), the standard is relevant to the manufacturer's stakeholders.

Coherence: There are several megatrends affecting the PV industry such as climate change, circular economy, and labour and human rights. Coherence with these issues in a multi-criteria sustainability standard can simplify the decision-making process for buyers. In addition to addressing the megatrends in a single multi-criteria standard, NSF/ANSI 457 makes reference to external standards in its verification requirements, such as standards for declarable substances (IEC 62474), environmental health and safety (ISO 14001 and ISO 45001), energy

[104] https://www.firstsolar.com/-/media/First-Solar/Sustainability-Documents/FirstSolar_Sustainability-Report_2022.ashx

management (ISO 50001), and social responsibility (RBA VAP and SA 8000). These external references enable coherence with the single issues being managed in a multi-criteria standard.

Effectiveness: The objective of NSF/ANSI 457 is to recognize and promote sustainability leadership in the PV industry. To evaluate the standard's effectiveness in achieving this objective, it can be informative to compare its outcomes with an independent evaluation of sustainability leadership conducted in the EU. In 2020, the EU Commission's Joint Research Centre (JRC) conducted a techno-economic and environmental preparatory study[105] to inform four PV policy instruments - Ecodesign, Energy Label, Ecolabel, and Green Public Procurement. In this study, CdTe PV modules were identified as the best available technology (BAT) from an environmental and economic point of view for commercial and utility-scale applications. This technology is also the first to be registered in conformance with NSF/ANSI 457, indicating the standard's success at recognizing sustainability leadership.

However, it is noteworthy that, to date, two manufacturers, one crystalline and one thin-film, have achieved this registration, representing a relatively limited market share. Broader industry participation in NSF/ANSI 457 could strengthen the standard's impact. As the standard is still new, this limited uptake is not yet a concern, but future adoption trends will be important to monitor. Interest from other manufacturers in registering additional PV technologies would further support the standard's objective and bolster its effectiveness in driving industry-wide sustainability leadership.

Efficiency: The efficiency of a sustainability standard can be assessed with respect to minimizing costs and resources and maximizing benefits. From a PV purchaser's perspective, NSF/ANSI 457 is efficient as adopted in the EPEAT registry because there is no cost to use the registry, it is available internationally, includes third-party verification, and can be easily specified in the purchasing process as a single ecolabel. From the manufacturer's standpoint, costs and resources are needed as the product registration process includes conformity assurance taking place over a year, and requires fees for the conformity assurance body and the registry. Additionally, the manufacturer must dedicate internal staff to establishing governance and documentation spanning multiple areas of expertise (Figure 4). These costs and resources borne by the manufacturer are necessary to assure conformity with the NSF/ANSI 457 standard.

Impact: With regards to transformative effects, the impact of NSF/ANSI 457 is still in progress. Once at least three PV products are added to the EPEAT registry in conformance with NSF/ANSI 457, U.S. federal government agencies are mandated to buy EPEAT-registered products, creating an incentive for additional products to be added and continuous improvement to maintain standing in the registry. Aside from the U.S. federal agencies, use of the EPEAT ecolabel in the purchasing requirements of PV buyers internationally will also signal greater impact of NSF/ANSI 457. For example, the ecolabel requirements are illustrated in model Request for Proposal (RFP) guidance developed by Salesforce and the Clean Energy Buyers Alliance (formerly the Renewable Energy Buyers Alliance)[106]. Use of this ecolabel is also part of RFP guidance from the Clean Energy Buyers Institute for sourcing PV modules with low embodied carbon.[107] In 2022, solar developer Lightsource BP was recognized by GEC for sustainability leadership due to its large-scale purchasing of EPEAT-registered PV modules.[108]

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[105]https://op.europa.eu/en/publication-detail/-/publication/5b8c4730-3450-11eb-b27b-01aa75ed71a1/language-en
[106] https://c1.sfdcstatic.com/content/dam/web/en_us/www/assets/pdf/sustainability/sustainability-more-than-megawatt.pdf
[107] https://cebi.org/programs/disc-e/
[108] https://www.lightsourcebp.com/us/2022/07/lightsource-bp-recognized-by-global-electronics-council-for-leadership-in-sustainability/

Sustainability: The NSF/ANSI 457 standard as adopted in the registry requires continuous maintenance. After a product is initially registered, it is subject to multiple conformity assurance rounds annually that involve detailed investigation of the current year's documentation for a given criterion. Therefore, a product's documentation and sustainability performance must be maintained over time, rather than just an initial qualification. Continuous maintenance provides a second tier of verification beyond the initial product conformity assurance review, and also ensures that the product's leadership attributes are sustained over time.

Overall, NSF/ANSI 457 aids individual purchasers with the complex task of defining sustainability performance by providing a multi-criteria framework for the sustainability assessment of PV modules with regards to product stewardship and corporate responsibility. The adoption of the standard in the registry has resulted in a global Type 1 (third-party validated; ISO 14024) ecolabel. The impact of the standard will depend on additional PV products being added to the registry and use of the ecolabel in the PV procurement process.

3.2.2 Extended Producer Responsibility Scheme

By evaluating EPR applied to the PV sector against these OECD criteria, stakeholders can gain insights into its strengths and weaknesses. This evaluation can inform policymakers and industry players about areas of improvement and guide the implementation of more effective and sustainable approaches to managing PV waste.

Relevance: EPR is relevant to the PV sector as it addresses the specific needs and priorities related to managing PV waste. It aligns with national, global, and industry-specific policies and priorities aimed at reducing the environmental impact of electronic waste. EPR in the PV sector responds to the growing concern over the proper disposal, recycling, and recovery of PV panels, ensuring the responsibility of producers in managing the entire life cycle of their products.

Coherence: Coherence examines the extent to which EPR in the PV sector aligns with other interventions and policies, assessing its compatibility with international waste management norms and standards. Evaluating coherence includes examining the internal coherence within the PV industry, such as the coordination between EPR schemes and other waste management initiatives. In practice, the coherence of EPR implementation in the PV varies significantly. For example, some EPR implementations closely align with EU waste directives, such as the Waste Electrical and Electronic Equipment (WEEE) Directive, which promotes shared collection and recycling systems across industries. This alignment supports smoother integration with broader waste management efforts. In contrast, other programs such as in the US or Australia, operate with less coordination, leading to isolated recycling streams that may be less efficient and hinder a unified approach to waste management.

Effectiveness: The effectiveness of EPR in the PV sector can be measured by evaluating its success in achieving key objectives, such as improving collection, recycling, and Figure 12.s of PV waste, along with assessing producer compliance and participation levels. These indicators help determine whether EPR effectively reduces the environmental impact of PV waste and supports sustainable waste management.

In practice, the effectiveness of EPR schemes varies across regions and implementations. For example, again in the EU, where PV waste is regulated under the WEEE Directive, collection and recycling rates for PV have shown marked improvement, with certain countries achieving high compliance and recovery rates (Germany, France, Spain). However, in other regions where EPR programs are newer or less comprehensive, rates are often lower, and challenges like limited infrastructure or lack of producer accountability hinder effectiveness. In the US, EPR has proven less successful, with Washington State deciding to delay and modify its solar panel stewardship and takeback program.[109]

Efficiency: Efficiency evaluates the economic and resource implications of implementing and complying with EPR in the PV sector. This involves assessing the costs of PV waste collection, recycling, and disposal processes, as well as the economic benefits derived from recovered materials. Evaluating efficiency helps determine whether EPR optimizes resource use, minimizes waste generation, and provides cost-effective solutions for PV waste management. Germany is often cited as a country with a successful EPR system for electronic waste, including PV panels, achieving high recycling rates. France and Japan have also made efforts to establish collection and recycling systems for PV waste, but the specific efficiency of the EPR system in the PV sector may vary. Despite the European framework for EPR implementation in the PV sector, its efficiency can vary among member states, depending on the establishment of collection and recycling infrastructure. Evaluating the overall success of EPR in the PV sector requires ongoing monitoring of recycling rates, compliance levels, and environmental outcomes, along with collaboration among stakeholders and continuous improvement of recycling technologies.

Impact: The impact criterion assesses the broader effects of EPR in the PV sector. This includes evaluating the reduction of hazardous substances in PV waste, the promotion of circular economy principles, and the overall improvement in environmental outcomes. It also involves considering the social and economic impacts, such as job creation and sustainable development. Assessing the impact of EPR helps determine the extent to which it contributes to positive changes and addresses environmental and social challenges in the PV sector.

Sustainability: Evaluating sustainability in the context of EPR in the PV sector, involves analysing its long-term benefits, viability and capacity for enduring impact. This requires a balance assessment of financial, economic, social, and environmental dimensions in PV waste management. Key factors include financial sustainability—ensuring that the costs of waste management are manageable for producers and ultimately support the longevity of EPR programs—and environmental benefits, such as reducing landfill waste and promoting resource recovery.

A sustainable EPR approach also considers trade-offs between these dimensions. For instance, while the financial costs of recycling PV materials are often high, they can be offset by significant environmental gains, such as reducing emissions and conserving natural resources. Social factors, including job creation in recycling industries and public health benefits from better waste management, are additional considerations that contribute to a holistic view of sustainability.

3.3 Case studies

In this section, we present a comprehensive analysis of key initiatives and standards within the renewable energy sector, evaluating them applying the 2DII methodology, which emphasizes aligning financial flows with climate goals. This combined approach provides a holistic view of how these initiatives and standards perform in addressing critical challenges within the PV industry.

Five comparisons have been made that encapsulate diverse aspects of sustainable business practices, ranging from compliance and accountability to environmental impact and societal

[109] State of Washington, Department of Ecology, Solar Panel Stewardship and Takeback Program https://apps.ecology.wa.gov/publications/documents/2407033.pdf

responsibility. These comparisons offer insights into the varying approaches and outcomes of initiatives that shape the renewable energy landscape.

The comparisons include:

1. EU Nonfinancial Reporting Directive (via CSRD) vs. European Sustainable Corporate Governance Directive
2. Solar Energy Sustainability Accounting Standard (SASB) vs. Global Reporting Initiative (GRI) standards
3. Uyghur Forced Labor Prevention Act and EU Forced labour ban
4. Renewable electricity criteria (RE100 Criteria) vs. Solar Industry Commitment to Environmental & Social Responsibility (Solar Commitment)
5. EU Sustainable Finance Taxonomy vs. Industry benchmark, ISO 14067:2018

3.3.1 EU Nonfinancial Reporting Directive (via CSRD) vs. European Sustainable Corporate Governance Directive

The 2DII focuses on aligning financial flows with climate goals. While the EU Nonfinancial Reporting Directive and the European Sustainable Corporate Governance Directive contribute to sustainability reporting and corporate governance, their direct alignment with the 2DII's mission may not be evident. However, these directives can indirectly support the goal of aligning corporate practices with climate objectives.

Table 9. Comparison of EU Nonfinancial Reporting Directive (via CSRD) vs European Sustainable Corporate Governance Directive across the 2DII's aspects

	EU Nonfinancial Reporting Directive	EU Corporate Governance Directive
Climate Actions	Encourage companies in the PV sector to measure and disclose their environmental impacts. This action aims to create transparency and awareness of the PV sector's contribution to climate change mitigation.	Enhance the environmental and social responsibility of companies by promoting sustainable corporate governance practices. It encourages companies to consider environmental and social aspects in their decision-making processes.
Outputs	Increased transparency and disclosure of environmental performance by PV companies, better understanding of emissions and resource use in the sector. Identification of improvement opportunities.	Adoption of sustainable governance practices by companies, integration of environmental and social considerations into corporate decision-making, and increased accountability towards stakeholders.
Outcomes	Changes in the behavior and practices of PV companies in response to disclosure requirements. This may lead to improved environmental performance, adoption of sustainability measures, and potentially reduced emissions in the PV sector.	Enhanced environmental and social responsibility of companies, strengthened stakeholder engagement, and a positive impact on corporate behavior and practices.
Impact	Potential reduction of GHG emissions in the PV sector. By promoting transparency and encouraging companies to improve their environmental performance, the guidelines contribute to identifying	Potential reduction of GHG emissions as companies integrate environmental considerations into their decision-making processes and implement sustainable governance practices.

	emission reduction opportunities and fostering sustainable practices.	
Example metrics	Percentage change in investees' capex plans; number of companies in high-carbon sectors engaged by FIs; GHG emissions reductions achieved by investee companies.	Number of companies complying with CSRD requirements and reporting nonfinancial information; Transparency and disclosure levels of environmental and social performance by companies; Adoption of sustainable governance practices by companies; Integration of environmental and social considerations into corporate decision-making; Stakeholder engagement and accountability measures; Reduction in GHG emissions and other environmental impacts by companies as a result of sustainability initiatives; Investments in companies with strong nonfinancial reporting and sustainable governance practices.

Time Horizon: The EU Nonfinancial Reporting Directive and the European Sustainable Corporate Governance Directive have long-term time horizons, as they aim to establish sustainable reporting and governance practices.

Characteristics: Both directives focus on improving corporate transparency, accountability, and sustainability practices.

Research Questions: These directives can help answer questions related to the integration of sustainability into corporate reporting and governance, the disclosure of climate-related information, and the alignment of corporate practices with sustainability goals.

Limitations: Some limitations may include the need for consistent implementation across member states, the potential for greenwashing or inadequate disclosure, and the challenge of assessing the actual impact of these directives on companies' sustainability performance.

Example Metrics: Metrics could include the number of companies reporting in line with the directives, the level of climate-related disclosures, the adoption of sustainable governance practices, and the integration of sustainability considerations into corporate decision-making.

In summary, both directives aim to improve sustainability practices and reporting in European companies, but they focus on different aspects. The former focuses on nonfinancial reporting, while the latter focuses on sustainable corporate governance.

3.3.2 Solar Energy Sustainability Accounting Standard (SASB) vs. Global Reporting Initiative (GRI) standards

The 2DII emphasizes climate-related financial disclosures and aligning investments with a low-carbon future. Both SASB and GRI standards provide frameworks for sustainability reporting, including climate-related disclosures. Comparing these standards against the 2DII can help assess the extent to which they incorporate climate-related financial metrics and support the transition to a low-carbon economy.

Time Horizon: SASB and GRI standards have a long-term time horizon, as they provide frameworks for sustainability reporting and disclosure.

Characteristics: Both standards aim to guide organizations in reporting their ESG performance.

Research Questions: These standards can help answer questions about how companies measure and report on their sustainability impacts, their alignment with ESG goals, and the transparency of their sustainability practices.

Limitations: Limitations may include variations in the application and interpretation of the standards, the need for consistent reporting practices across industries and regions, and the potential lack of specific climate-related financial metrics in the frameworks.

Example Metrics: Metrics could include the percentage of companies adopting SASB or GRI standards, the level of climate-related disclosures, the integration of ESG factors into financial decision-making, and the comparability of sustainability performance across companies.

Applying both standards to the PV sector can lead to benefits and an understanding of the industry's sustainability performance. Combining both SASB and GRI standards in the PV sector allows for a more comprehensive approach to sustainability reporting. It enables companies to address sector-specific sustainability issues and metrics outlined by SASB while adhering to the globally recognized reporting framework provided by GRI. This combination offers PV companies an opportunity to showcase their environmental and social performance, facilitate stakeholder engagement, attract responsible investment, and contribute to the global transition toward a sustainable and low-carbon energy system.

Table 10. Comparison of Solar Energy Sustainability Accounting Standard (SASB) vs. Global Reporting Initiative (GRI) standards.

	Solar Energy Sustainability Accounting Standard	**Global Reporting Initiative (GRI) standards**
Climate Actions	Provide guidance for solar energy companies to measure, manage, and report their ESG performance. They encourage companies to take climate actions such as reducing GHG emissions, improving energy efficiency, and promoting renewable energy deployment.	Provide a comprehensive framework for organizations, including solar energy companies, to report on their sustainability performance, including climate actions. These standards guide companies to measure and disclose their greenhouse gas emissions, energy consumption, renewable energy use, and climate change strategies.
Outputs	Enhanced transparency and disclosure of ESG metrics specific to the solar energy sector. This can include metrics related to carbon emissions, energy generation, water use, waste management, and community engagement.	Standardized sustainability reports that disclose environmental, social, and economic impacts. Solar energy companies can disclose information such as their carbon footprint, renewable energy projects, energy efficiency initiatives, and engagement with stakeholders on climate-related issues.
Outcomes	Improved environmental performance, better risk management, increased	Increased transparency, accountability, and comparability of sustainability performance

	stakeholder trust, and enhanced sustainability practices in the PV industry. This leads to reduced environmental impacts, improved efficiency, and positive social and economic influence.	across companies. It can also lead to improved decision-making, stakeholder engagement, and the identification of opportunities for innovation and continuous improvement in climate-related initiatives.
Impact	Promoting the transition to a more sustainable and low-carbon energy system. By driving better ESG performance and disclosure in the solar sector, SASBs contribute to climate change mitigation, resource efficiency, and the advancement of renewable energy technologies.	Driving sustainability practices, including climate change mitigation, within the solar energy sector and beyond. By providing a globally recognized reporting framework, these standards contribute to informed decision-making, responsible investment, and the transition to a low-carbon economy.
Example metrics	Reduction in GHG per unit of energy generated; Percentage of energy generated from renewable sources; Level of community engagement and benefit sharing; Integration of sustainability practices into business strategies.	Percentage reduction in GHG emissions over time; Proportion of energy derived from renewable sources; Implementation of energy efficiency measures; Level of stakeholder engagement on climate-related topics; Integration of climate change considerations into corporate governance structures.

3.3.3 Uyghur Forced Labor Prevention Act vs. EU Forced Labor Ban

The 2DII primarily focuses on climate-related aspects of investment and finance. While the Uyghur Forced Labor Prevention Act (UFLPA) and the EU Forced Labor Ban address human rights and supply chain transparency, their direct alignment with the 2DII's mission may be less apparent. However, ensuring responsible business conduct and supply chain practices can be important considerations within climate-conscious investments.

Time Horizon: The Uyghur Forced Labor Prevention Act and the EU Forced Labor Ban share a continuous time horizon, addressing forced labor and human rights abuses within their respective jurisdictions.

Characteristics: The Uyghur Forced Labor Prevention Act is a U.S.-specific legislation that primarily targets forced labor concerns within the solar supply chain, focusing on a specific industry. In contrast, the EU Forced Labor Ban is a broader regulatory framework applicable across various industries, addressing forced labor, modern slavery, and related human rights violations.

Table 11. Comparison of Uyghur Forced Labor Prevention Act vs. EU Forced Labor Ban

	Uyghur Forced Labor Prevention Act	EU Forced labor ban
Climate Actions	Focuses primarily on human rights issues rather than direct climate actions. However, it indirectly contributes to climate change mitigation by promoting responsible business conduct and supply chain transparency. By addressing forced labor practices in supply chains, the Act encourages companies to adopt ethical and	The EU Forced Labor Ban does not directly address climate change but indirectly promotes sustainability by discouraging products associated with forced labor, which can impact environmentally responsible practices.

	sustainable practices, which can have positive environmental implications.	
Outputs	Increased awareness and attention to forced labor issues in supply chains, improved due diligence processes by companies to identify and address forced labor risks, and enhanced transparency in supply chain disclosures related to labor practices.	Legal bans on products linked to forced labor. Enhanced due diligence requirements for companies.
Outcomes	IEliminating forced labor from supply chains, improving working conditions, and promoting human and labor rights, contribute to more ethical and sustainable global supply chains, indirectly enhancing environmental and social sustainability.	Reduced importation of goods linked to forced labor. Increased awareness and efforts to combat forced labor globally.
Impact	Significant in terms of combatting forced labor and human rights abuses. By addressing these issues, it contributes to a more ethical and sustainable global supply chain, which in turn can have positive environmental and social impacts.	The EU Forced Labor Ban seeks to have a significant impact on global supply chains by reducing the demand for products linked to forced labor and promoting responsible sourcing practices.
Example metrics	Number of companies conducting supply chains due diligence to mitigate forced labor risks; Transparency level in labor-related disclosures; Reduction in reported forced labor incidents.	Number of products banned from the EU market due to suspected forced labor involvement. Reduction in forced labor practices in countries exporting to the EU.

Research Questions: Researchers can utilize the Uyghur Forced Labor Prevention Act to investigate labor conditions, worker rights, and safety within the solar supply chain, offering insights into industry-specific issues. The EU Forced Labor Ban will prompt questions such as How can the EU prevent the importation of goods linked to forced labor?, or What are the economic and social impacts of the EU Forced Labor Ban on both the EU and countries exporting to the EU?

Limitations: Limitations may include challenges in monitoring and enforcing compliance, the complexity of global supply chains, and the need for collaboration between governments, companies, and civil society organizations to address forced labor effectively. The UFLPA may face limitations in terms of its enforceability and the challenges of verifying compliance across global supply chains. It may require international cooperation and coordination among governments, companies, and civil society organizations to effectively combat forced labor. On the other hand, implementing the EU Forced Labor Ban globally may be challenging and may require cooperation from non-EU countries. Enforcement of the ban outside the EU;s jurisdiction may be limited as well.

Applying the Uyghur Forced Labor Prevention Act and the EU Forced Labor Ban to the PV sector can have significant implications. The Uyghur Forced Labor Prevention Act focuses on eradicating forced labor within supply chains, aiming to ensure ethical and responsible sourcing practices. By implementing this act, PV companies can enhance transparency, traceability, and due diligence processes, ultimately reducing the prevalence of forced labor in the industry. On the other hand, adopting the EU Forced Labor Ban, signals a rigorous stance on ensuring that products linked to forced labor do not enter the EU market. PV companies exporting to the EU would need to rigorously audit their supply chains, taking steps to eliminate forced labor. This can lead to a significant transformation in global PV supply chains, with companies compelled to invest in responsible sourcing, thus creating a more sustainable and ethically sound industry. Moreover, it can trigger a ripple effect, encouraging other regions and industries to follow suit, ultimately contributing to a more responsible and transparent global supply chain ecosystem.

In conclusion, both the Uyghur Forced Labor Prevention Act and the EU Forced Labor Ban present opportunities for the PV sector to become a leader in ethical and sustainable supply chain practices. By adhering to these regulations, PV companies can enhance their reputations, mitigate risks, and contribute to the global efforts to combat forced labor and promote responsible business conduct.

3.3.4 Renewable electricity criteria (RE100 Criteria) vs. Solar Industry Commitment to Environmental & Social Responsibility (Solar Commitment)

The 2DII promotes renewable energy and a low-carbon transition. Both the RE100 Criteria and the Solar Industry Commitment contribute to sustainability and environmental responsibility within the solar sector. Evaluating these initiatives against the 2DII can provide insights into their alignment with renewable energy goals and their potential to contribute to decarbonization efforts.

Time Horizon: The RE100 Criteria typically operates with a long-term time horizon as companies commit to sourcing 100% renewable electricity over an extended period. This reflects a concerted effort to transition away from fossil fuels and promote sustainability in the long run. On the other hand, the Solar Commitment may have varying time horizons depending on the specific commitments made by solar companies, which could encompass both short-term and long-term goals related to environmental and social responsibility within the solar industry.

Characteristics: Both initiatives aim to drive the adoption of renewable electricity and enhance environmental and social responsibility within the solar industry. The RE100 Criteria is characterized by its emphasis on renewable electricity sourcing. It seeks to drive the adoption of renewable energy among companies across sectors, aiming to reduce greenhouse gas emissions and mitigate climate change. In contrast, the Solar Commitment focuses specifically on the solar industry and addresses the unique environmental and social impacts associated with solar operations. It aims to promote responsible practices within the industry, encompassing various aspects such as sustainable manufacturing, project development, and community engagement.

Research Questions: These initiatives help answer questions about the renewable energy capacity and generation of companies, their commitment to reducing carbon emissions, and their efforts to address environmental and social impacts throughout the solar value chain. The RE100 Criteria can provide insights into several research questions, including the effectiveness of renewable energy adoption in reducing GHG, the scalability and feasibility of renewable energy projects, and the barriers and opportunities for companies transitioning to renewable energy sources. On the other hand, the Solar Commitment can help answer research questions specific to the solar industry, such as the environmental impact of solar panel manufacturing, the social implications of solar projects in local communities, and the effectiveness of sustainability initiatives throughout the solar value chain.

Table 12. Comparison of Renewable electricity criteria (RE100 Criteria) vs. Solar Industry Commitment to Environmental & Social Responsibility (Solar Commitment)

	RE100 Criteria	Solar Commitment
Climate Actions	Taken by companies committing to sourcing 100% of their electricity from renewable sources. By joining the RE100 initiative, companies demonstrate their commitment to reducing GHG emissions and promoting the transition to renewable energy.	Solar companies committing to environmental and social responsibility, including measures to minimize environmental impacts, support local communities, and promote sustainable practices.
Outputs	Increased demand for renewable electricity, the development of renewable energy projects, and the procurement of renewable energy certificates or guarantees of origin to demonstrate compliance.	Implementation of environmental management systems, adoption of sustainable supply chain practices, and transparency in reporting environmental and social performance.
Outcomes	Expansion of renewable energy infrastructure, increased investment in renewable energy projects, and a decrease in greenhouse gas emissions associated with electricity consumption.	Reduction of environmental impacts of solar operations, promotion of social responsibility within the solar industry, and improvement of sustainability practices throughout the solar value chain.
Impact	Significant increase in renewable energy deployment and the displacement of fossil fuel-based electricity generation. This leads to a reduction in GHG, increased renewable energy capacity, and a positive contribution to global climate change mitigation efforts.	Promotion of environmental sustainability and social responsibility within the solar industry. It drives the adoption of sustainable practices, supports local communities, and contributes to the overall positive image and reputation of the solar sector.
Example metrics	Number of companies joining the RE100 initiative, the percentage of renewable electricity consumed by participating companies, the amount of renewable energy capacity installed or contracted, and the reduction in carbon emissions resulting from the commitment.	Adoption of environmental management systems by solar companies, the implementation of sustainable supply chain practices, the number of community engagement projects initiated, and the transparency and quality of environmental and social reporting by solar companies.

Limitations: Limitations of the RE100 Criteria may revolve around the challenges associated with sourcing renewable electricity, particularly in regions with limited renewable energy infrastructure. Companies operating in such areas may face difficulties in meeting the commitment due to availability constraints or higher costs of renewable energy. As for the Solar Commitment, potential limitations could stem from variability in the implementation and enforcement of sustainable practices across different solar companies. The voluntary nature of the commitment may result in varying levels of engagement and adherence to sustainability standards. Furthermore, while the Solar Commitment primarily addresses environmental impacts, additional attention and development may be required to fully incorporate social aspects of sustainability within the solar industry.

The RE100 Criteria drives the adoption of renewable electricity sources, ensuring that PV companies rely solely on clean energy for their operations. This commitment not only reduces greenhouse gas emissions but also fosters the growth of the renewable energy market. By meeting the RE100 Criteria, PV companies can demonstrate their dedication to sustainable energy practices and contribute to global efforts in mitigating climate change.

Simultaneously, the Solar Commitment emphasizes broader environmental and social responsibility within the PV sector. It encourages companies to adhere to sustainable business practices, including supply chain transparency, respect for human rights, and engagement with local communities. This commitment ensures that PV companies operate in an ethical and responsible manner, considering the well-being of both people and the planet.

The combination of these two standards strengthens the sustainability credentials of the PV sector. It promotes the adoption of renewable energy sources while ensuring that the entire value chain, from production to end-of-life management, operates in an environmentally and socially responsible manner. This integrated approach aligns economic growth with sustainability goals, fostering a more resilient and sustainable PV industry.

3.3.5 EU Sustainable Finance Taxonomy vs. Industry benchmark, ISO 14067:2018

The 2DII advocates for sustainable finance and the integration of climate-related risks and opportunities. The EU Sustainable Finance Taxonomy provides a classification system for sustainable economic activities, while industry benchmarks and best practices guide sustainability performance within specific sectors. Assessing these initiatives against the 2DII can help determine their contribution to climate-related financial analysis, risk assessment, and investment decision-making.

Time Horizon: The EU Sustainable Finance Taxonomy and ISO 14067:2018 have different time horizons. The EU Sustainable Finance Taxonomy is a framework that aims to promote sustainable investments and guide financial decision-making in the long term. It provides criteria and disclosure requirements for economic activities that contribute to environmental objectives. On the other hand, ISO 14067:2018, which is part of the ISO 14060 family of standards, focuses specifically on quantifying the carbon footprint of products. Its time horizon is typically shorter-term, as it provides guidelines for companies to measure and disclose the carbon footprint of their products.

Characteristics: The EU Sustainable Finance Taxonomy is characterized by its comprehensive approach to sustainable investments, covering various environmental objectives such as climate change mitigation, adaptation, and biodiversity conservation. It provides a classification system that helps investors identify sustainable economic activities. ISO 14067:2018, on the other hand, focuses specifically on carbon footprint assessment. It provides principles, requirements, and guidelines for quantifying the greenhouse gas emissions associated with a product throughout its life cycle.

Table 13. Comparison of EU Sustainable Finance Taxonomy vs. Industry benchmark, ISO 14067:2018

	Industry benchmark: ISO 14067:2018	EU Sustainable Finance Taxonomy
Climate Actions	Establish a framework for quantifying and reporting the carbon footprint of products. This involves defining principles, requirements, and guidelines for measuring	Classification and labelling of economic activities that contribute to environmental sustainability. It provides a framework for identifying investments that align with climate change mitigation goals.

	GHG emissions throughout the life cycle of products.	
Outputs	Quantification and disclosure of the carbon footprint of products. This involves collecting data on GHG emissions, conducting calculations based on specified methodologies, and reporting the results.	Classification and labelling of economic activities based on their environmental sustainability. It creates a standardized system for identifying and communicating investments that contribute to climate change mitigation.
Outcomes	Increased awareness and understanding of the carbon footprint of products, identification of emission hotspots within product life cycles, and potential opportunities for emission reductions. It can also lead to improved product design, supply chain optimization, and adoption of more sustainable practices.	Increased investment in economic activities that meet the sustainability criteria outlined in the Taxonomy. This can lead to the growth of green industries, innovation in environmentally sustainable technologies, and a shift towards a low-carbon economy.
Impact	Reduction of GHG emissions associated with products. By quantifying and disclosing the carbon footprint, organizations can identify areas for improvement, set reduction targets, and implement strategies to mitigate their environmental impact.	Reduction of GHG emissions. By guiding investment decisions towards sustainable economic activities, the Taxonomy contributes to financing projects and companies that actively work towards climate change mitigation.
Example metrics	Number of products assessed for their carbon footprint; Total GHG emissions measured and reported; Percentage reduction in carbon footprint over time; Adoption rate of carbon footprint standards by organizations; Integration of carbon footprint considerations into product design and development processes.	Amount of investment directed towards economic activities classified as environmentally sustainable based on the EU Taxonomy; Growth of green industries and technologies supported by investments aligned with the Taxonomy; Reduction in GHG emissions resulting from investments made in line with the EU Taxonomy.

Research Questions: The EU Sustainable Finance Taxonomy can help answer research questions related to the impact of sustainable investments on environmental objectives, the effectiveness of the taxonomy in guiding investment decisions, and the alignment of financial flows with climate change mitigation and other sustainability goals. ISO 14067:2018 can contribute to answering research questions about the methodologies and approaches used to quantify product carbon footprints, the comparability and reliability of carbon footprint assessments, and the potential for carbon footprint information to drive product-level emissions reductions.

Limitations of the Initiatives: The EU Sustainable Finance Taxonomy may face limitations in terms of the complexity and subjectivity involved in defining and categorizing sustainable economic activities. There may be challenges in determining the thresholds and criteria for different environmental objectives, as well as ensuring consistent interpretation and application across various sectors and regions. ISO 14067:2018 may have limitations related to its focus solely on carbon footprint assessment. It does not provide a comprehensive assessment of other environmental impacts, such as water usage, land use, and resource depletion, which may be relevant in evaluating the overall sustainability of a product. Additionally, the implementation and adoption of ISO 14067:2018 by companies may vary, leading to inconsistencies in reporting and comparability of product carbon footprint data.

The ISO 14060 family of standards (incl. 14067:2018), provide a framework for quantifying and reporting the carbon footprint of products. These standards, when applied to the PV sector, enable PV companies to measure and disclose their environmental impacts, particularly greenhouse gas emissions, energy use, and other relevant metrics. By implementing the ISO 14060 family of standards, PV companies can enhance transparency, identify emission hotspots, and potentially implement mitigation strategies to reduce their carbon footprint.

On the other hand, the EU Sustainable Finance Taxonomy focuses on classifying and labeling economic activities that contribute to environmental sustainability. When applied to the PV sector, the taxonomy can help identify investments in PV projects and companies that align with sustainability criteria. This, in turn, can attract increased investment towards PV initiatives that actively work towards climate change mitigation and promote the growth of green industries.

By combining both the ISO 14060 family of standards and the EU Sustainable Finance Taxonomy in the PV sector, companies can benefit from a comprehensive approach to environmental sustainability. The ISO standards enable PV companies to measure and disclose their carbon footprint, facilitating internal awareness and identification of improvement opportunities. Simultaneously, the EU Taxonomy attracts investment towards sustainable PV projects, fostering the transition towards a low-carbon economy and promoting the long-term environmental sustainability of the sector.

3.4 Mapping the connections of the standards with the SDGs

Countries around the world are facing immense challenges in developing their economies and societies in a sustainable way. The 2030 agenda set by the United Nations provides a roadmap to guide these actions. However, the Agenda's complexity, with its 17 Sustainable Development Goals (SDGs) and numerous targets and indicators, can make it difficult for policymakers to prioritize efforts.

To visualize the extent to which policies address these goals and targets, the SDG Mapper tool can be utilized. This web application automatically analyzes a document's text, identifying keywords that relate to specific goals and targets.

The tool presents the results through simple yet effective visualizations, giving users a quick overview of the goals and targets identified in the documents. The tool provides a structured framework that captures the complexities and interactions both within individual SDGs and across multiple goals. Ultimately, the SDG Mapper ultimately facilitates the mainstreaming of the SDGs into policy and other decision-making processes.

The bubble chart in Figure 12 show the relevance of Goals and targets in the PV sustainability standards. The main SDG detected is 12 Responsible consumption and production, with 43%. Then SDG 7 Affordable and clean energy with 25%, followed by SDG 13 Climate action, 14%.

Relevant indicators and potentially interlinked goals and targets are highlighted in Table 14. Indicators are sorted in descending order regarding their relevance.

Table 14. Relevant SDG Indicators sorted in descending order according to the respective target relevance within the documents

Indicator	
12.5.1 National recycling rate, tons of material recycled	
7.2.1 Renewable energy share in the total final energy consumption	
12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement	
12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment	
9.2.1 Manufacturing value added as a proportion of GDP and per capita	
9.2.2 Manufacturing employment as a proportion of total employment	
12.7.1 Degree of sustainable public procurement policies and action plan implementation	
13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change	
13.2.2 Total greenhouse gas emissions per year	
12.6.1 Number of companies publishing sustainability reports	

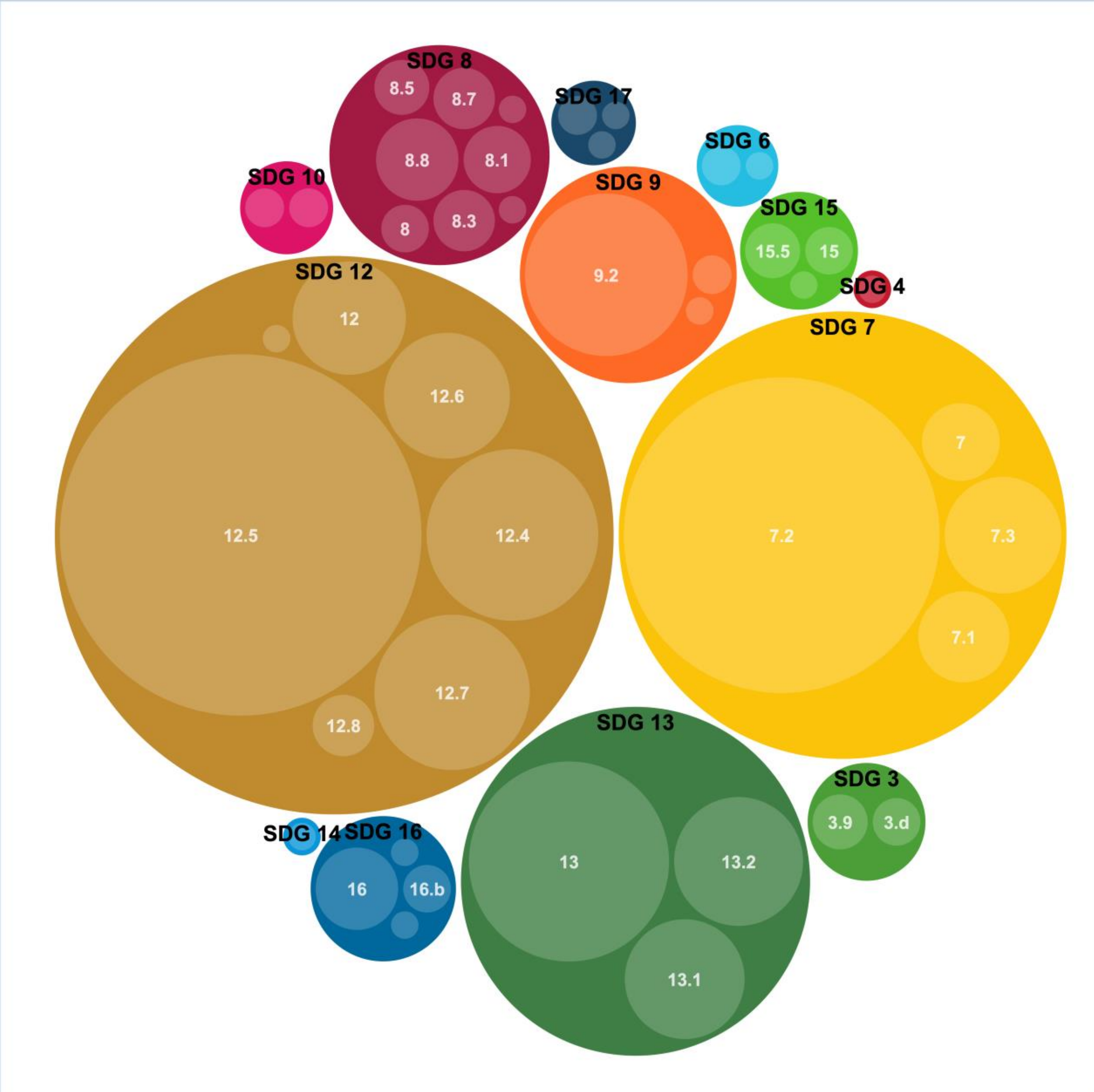

Figure 13. Bubble chart of SDGs and targets detected in PV sustainability standards. SDG Mapper tool of the European Commission

4 CONCLUSIONS

This report provides a detailed analysis of sustainability standards and frameworks within the photovoltaics (PV) sector, aimed at assessing their effectiveness in promoting sustainability and aligning with global sustainability goals. The primary motivation behind this review is to offer a comprehensive evaluation of how these standards impact the PV industry and to identify opportunities for improvement in light of the Sustainable Development Goals (SDGs).

Motivation and Categorization

The impetus for this assessment stems from the need to understand how existing standards influence the sustainability of the PV sector. Given the rapid evolution of both technology and regulatory environments, these standards bear with broader sustainability objectives and contribute to environmental, social, and economic benefits.

To structure this review, we categorized the standards into three main sections:

1. **Sectoral Reporting and Disclosure**: This category focuses on standards that govern the reporting and disclosure of environmental and social performance, such as corporate reporting obligations and environmental performance declarations. These standards are crucial for ensuring transparency and accountability in how PV companies report their sustainability efforts.

2. **Product-Related Standards**: This section includes standards that pertain to the production and performance of PV products, such as ecolabels and performance benchmarks. These standards set requirements and rules for the design, production, and recycling of PV products, aiming to enhance their environmental and social performance.

3. **Regulatory Frameworks**: This category encompasses both mandatory and voluntary regulatory measures that govern various aspects of the PV industry. It includes frameworks like the EU Ecodesign Directive and the WEEE Directive, which set out requirements for product design, recycling, and waste management.

Evaluating Effectiveness

Assessing the effectiveness of sustainability standards is inherently challenging due to the diverse and often complex nature of these standards and their impacts. To address these challenges, we employed two key evaluation methodologies:

1. **OECD Criteria**: The OECD's six criteria provide a multi-dimensional framework that is especially useful for evaluating standards´ effectiveness, coherence, and sustainability. However, enhancing this tool with more specific social and labor rights metrics would increase its relevance to a sector like PV, where ethical considerations are relevant to sustainability.

2. **2DII Methodology**: The 2 Degrees Investing Initiative (2DII) focus on climate-aligned flows assesses environmental performance but could benefit from integrating additional social and governance metrics to capture a more comprehensive view of PV sector standards.

Portraits and Case Studies

We analyzed specific standards and frameworks through the OECD criteria and 2DII methodology to gain insights into their effectiveness. For instance:

- **Sectoral Reporting and Disclosure Standards (SASB vs. GRI)**: Both SASB and GRI standards effectively support transparency in ESG reporting within the solar sector, each bringing unique advantages. SASB's sector-specific metrics promote relevance for PV companies, while GRI's global standardization facilitates comparability. However, a gap remains in the integration of social and labor-related metrics, which can provide a holistic view of sustainability in the PV sector, especially given the international supply chain and labor dynamics.
- **Product and Supply Chain Standards (RE100 vs. Solar Commitment)**: The RE100 and Solar Commitment standards underscore the importance of renewable energy sourcing and responsible supply chain practices, respectively. RE100 drives corporate commitment to 100% renewable electricity, advancing climate goals through demand-side influence. In contrast, the Solar Commitment addresses environmental management, sustainable supply chains, and community support within the PV industry. While both initiatives contribute to sustainable practices, broader adoption of comprehensive supply chain standards could enhance sector-wide social responsibility, aligning with goals such as SDG 12 (Responsible Consumption and Production).
- **Environmental and Climate Impact Standards (ISO 14067 vs. EU Sustainable Finance Taxonomy)**: The EU Sustainable Finance Taxonomy and ISO 14067 are both instrumental in promoting climate-conscious investments and carbon footprint transparency. ISO 14067 provides a structured approach for quantifying product carbon footprints, which can drive emission reductions and improve lifecycle management. The EU Taxonomy, on the other hand, classifies investments that meet specific sustainability criteria, effectively channeling capital toward green projects. However, integrating both standards within PV supply chains could amplify impact by encouraging both climate-smart product design and sustainable financial flows.
- **Labor and Human Rights Standards (Uyghur Forced Labor Prevention Act vs. EU Forced Labor Ban)**: Both of these frameworks address critical social sustainability issues by preventing products linked to forced labor from entering markets, indirectly encouraging responsible supply chain practices in the PV sector. The Uyghur Forced Labor Prevention Act emphasizes due diligence in U.S. supply chains, while the EU ban enforces legal restrictions on forced labor-linked products. Although these frameworks are impactful, there remains an opportunity to integrate labor rights more broadly across other environmental and product standards to create a more unified approach to social and environmental sustainability.

Mapping Connections with SDGs

We used the SDG Mapper tool to visualize how PV sustainability standards align with the SDGs. This tool helps in identifying relevant goals and targets within the standards and provides a visual representation of their contributions to sustainability objectives. The analysis revealed that the most prominently addressed SDGs are:

- **SDG 12 (Responsible Consumption and Production**): 43%
- **SDG 7 (Affordable and Clean Energy):** 25%

- **SDG 13 (Climate Action):** 14%

This mapping highlights the sector's focus on responsible production and clean energy, while also identifying areas where further alignment with SDGs could be beneficial.

Overall Performance and Recommendations for Improvement

The PV standards evaluated perform well in promoting environmental transparency and accountability, especially concerning climate-related actions. However, several improvements could strengthen their impact and ensure a more balanced sustainability framework:

- **Expand Circular Economy and Social Practices**: Standards such as ISO 14067 and the Solar Commitment could incorporate more circular economy principles (e.g., reuse and remanufacturing) and stronger social responsibility elements, like worker welfare, to provide a fuller sustainability model that aligns with SDG 8 (Decent Work) and SDG 12 (Responsible Production).
- **Integrate Labor and Human Rights into Broader Standards**: Building on frameworks like the Uyghur Forced Labor Prevention Act and EU Forced Labor Ban, adding labor rights protections and due diligence metrics to product and environmental standards could create a more unified approach to ethical sourcing and environmental responsibility across the PV sector.
- **Enhance Evaluation Tools for Comprehensive Coverage**: Strengthening the OECD and 2DII evaluation tools with additional social and economic metrics would allow a fuller assessment of PV sustainability standards. For example, incorporating social impact assessments could complement the strong focus on environmental performance and capture a broader range of sustainability impacts.

Concluding insights

In summary, this report underscores the importance of a diverse yet cohesive framework of PV sustainability standards. By categorizing standards, employing robust evaluation methodologies, and mapping connections with SDGs, we provide a detailed assessment of their effectiveness and impact.

Current standards and evaluation methodologies effectively support environmental goals and transparency but could be enhanced through:

- **Strengthening social and ethical criteria** across environmental and product standards to support a balanced approach to sustainability.
- **Encouraging the adoption of circular economy principles** that address lifecycle sustainability and resource efficiency.
- **Refining evaluation tools** to comprehensively cover social, environmental, and economic impacts for a more holistic view of PV sector sustainability.

These findings offer insights for stakeholders seeking to enhance the sustainability of the PV sector and align with global sustainability goals. Future assessments can help track progress and adapt to emerging challenges and opportunities in the landscape of PV sustainability.

REFERENCES

Reise, C., & Farnung, B. (2017). *Uncertainties in PV System Yield Predictions and Assessments.* Report IEA-PVPS T13-12.

Dodd, N., & Espinosa, N. (2020). *Preparatory study for solar photovoltaic modules, inverters and systems – Task 8 Policy recommendations.* European Commission - Joint Research Centre.

Wade, A., Sinha, P., Drozdiak, K., Mulvaney, D., & Slomka, J. (2018). Ecodesign, Ecolabeling and Green Procurement Policies – enabling more Sustainable Photovoltaics? *WCPEC-7, Proceedings of the 7th World Conference on Photovoltaic Energy Conversion.* Hawaii.

IEA PVPS Task 1. (2017). *Trends in Photovoltaic Applications (IEA PVPS T1-32:2017).* IEA PVPS.

World Commission on Environment and Development. (1987). Report of the World Commission on Environment and Development: Our Common Future. Bruntland report.

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science, 14*, 681-695.

Norge, E. (n.d.). National Product Category Rules - . *Photovoltaic modules used in the building and construction industry(029:2020 Part B Version 1.1).*

Italy, E. (n.d.). (Product category CR EPDItaly014 – Photovoltaic modules) .

Commission, E. (n.d.). PEFCR, EU. *((DOI: 10.1002/pip.2956))*.

Urbina, A. (2022). Sustainability of photovoltaic technologies in future net-zero emissions scenarios. *Progress in Photovoltaics*, 1-15.

European Committee for Standardization. (2019). Greenhouse Gases-Carbon Footprint of Products-Requirements and Guidelines for Quantification. Brussels.

Solarcentury. (2021). *Solar: a force for good ESG expectations for the solar sector.*

Rajagopalan, N., Peeters, K., Rommens, T., Wang, K., Stolz, P., Frischknecht, R., . . . Regel, S. D. (2021). *Preliminary Environmental and Financial Viability Analysis of Circular Economy Scenarios for Satisfying PV System Service Lifetime.* IEA PVPS Task 12: PV Sustainability.

Jordan, D., Barnes, T., Haegel, N., & Repins, I. (2021). Build solar-energy systems to last—save billions. *Nature*(600), 215-217.

WEEE FORUM. (2018). *Why making EN 50625 standards legally binding is part of the solution.*

Cycle, P. (2023). *Photovoltaic panels versus EEE: 8 years' experience under WEEE regulations across Europe.* Brussels.

Sinha, P., Raju, S., Drozdiak, K., & Wade, A. (2017). Life cycle management and recycling of PV systems. *PV-Tech Power, 13*, 47-50.

Venturelli, A., Fasan, M., & Pizzi, S. (2022). Guest editorial Rethinking non-financial reporting in Europe: challenges and opportunities in revising Directive 2014/95/EU. *Journal of Applied Accounting Research, 23*(1), 1-7.

Commission, E. (n.d.). EU Product Environmental Footprint Categroy Rules.

Dodd, N., & Espinosa, N. (2021). *Solar photovoltaic modules inverters and systems Options and feasibility of EU ecolabel and green public procurement criteria : preliminary report.* European Commission.

Cordella, M., Alfieri, F., Sanfelix, J., Donatello, S., Kaps , R., & Wolf, O. (2020). Improving material efficiency in the life cycle of products: a review of EU Ecolabel criteria. *The International Journal of Life Cycle Assessment, 25*, 921.

Ardente, F., Latunussa, C., & Blengini, G. (2019). Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. *Waste Management, 91*.

Grijelmo, T., Molina, L., & Sanz, J. (2022). *Wind, PV and batteries recycling in Europe: an opportunity for the recovery of critical raw materials.* EIT InnoEnergy.

Deng, R., Chang, N. L., Ouyang, Z., & Chong, C. M. (2019). A techno-economic review of silicon photovoltaic module recycling . *Renewable and Sustainable Energy Reviews, 109*, 532-550.

Ayran, V., & Maga, D. e. (2017). *End-of-Life Pathways for Photovoltaic Backsheet.* Fraunhofer UMSICHT.

Nain, P., & Kumar, A. (2020). Initial metal contents and leaching rate constants of metals leached from end-of-life solar photovoltaic waste: an integrative literature review and analysis. *Renewable and Sustainable Energy Reviews, 119*, 109592.

Leccisi, E., & Fthenakis, V. (2021). Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV. *Progress in Photovoltaics: Research and Applications, 29*(10), 1078-1092.

Heitmann, B., & Pohl, R. (2019). *Aufarbeitung von altmodulen und rückführung von wertstoffen in den stoffkreislauf (eol-cycle) abschlussbericht : laufzeit des vorhabens: 01.09.2016 bis 31.08.2019.* Reiling Glas Recycling GmbH & Co KG.

Heath, G., Silverman, T., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., . . . Wade, A. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. *Nature Energy, 5*, 502–510.

Herceg, S., Pinto Bautista, S., & Weiß, K.-A. (2020). Influence of Waste Management on the Environmental Footprint of Electricity Produced by Photovoltaic Systems. *Energies, 13*(9), 2146.

Lunardi, M. M., Alvarez-Gaitan, J. P., Bilbao, J. I., & Corkish, R. (2018). Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules. *Applied Sciences, 8*(8).

Weckend, S., Wade, A., & Heath, G. (2016). *End-of-Life Management: Solar Photovoltaic Panels.* IRENA & IEA-PVPS.

Mathieux, F. A. (2017). *Critical raw materials and the circular economy - Background report.* Publications Office of the European Union.

Richter, M., Tjengdrawira, C., Vedde, J., Green, M., Frearson, L., Herteleer, B., . . . Köntges, M. (2017). *Technical Assumptions Used in PV Financial Models. Review of Current Practices and Recommendations.* IEA-PVPS.

Komoto K., M. H. (2022). *Status of PV Module Recycling in Selected IEA PVPS Task12 Countries.* International Energy Agency.

Frischknecht, R., Stolzt, P., Heath, G., Raugei, M., Sinha, P., & Wild-Scholten, M. d. (2020). *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity.* IEA PVPS.

Polverini, D., Dodd, N., & Espinosa, N. (2021). *Potential regulatory approaches on the environmental impacts of photovoltaics: Expected improvements and impacts on technological innovation.* Progress in Photovoltaics, 29, (1), 83.

Solar Power Europe. (2021). *Solar Sustainability – best practices benchmark.* Brussels.

Wade, A., Stolz, W., Frischknecht, R., & Heath, G. a. (2017). The Product Environmental Footprint (PEF) of Photovoltaic Modules: Lessons Learned from the Environmental Footprint Pilot Phase on the Way to a Single Market for Green Products in the European Union. *Progress in Photovoltaics, 26*(8), 553-564.

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