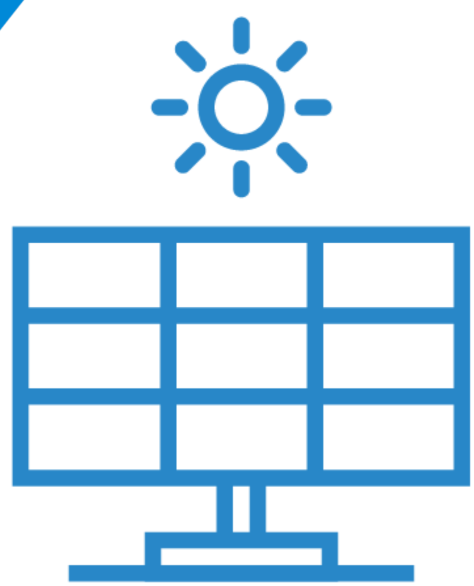
PHOTOVOLTAIC MODULES AND INVERTERS

State of Sustainability Research

FINAL

June 11, 2025



GLOBAL ELECTRONICS COUNCIL®

Sustainabilty for a Connected Future

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Acronyms

AC: alternating current

a-Si: amorphous-based silicon

ARC: anti-reflective coatings

ASC: anti-soil coatings

BIPV: building integrated photovoltaics

CFP: carbon footprint

c-Si: crystalline silicon-based

CIGS: copper indium gallium selenide

DC: direct current

EN: European Normative

EPD: environmental product declaration

EPR: extended producer responsibility

EU: European Union

EVA: ethylene vinyl acetate

FPVs: floating solar photovoltaics or 'floatovoltaics'

FU: functional unit

GHG: greenhouse gas

HDPE: high-density polyethylene

IEA: International Energy Agency

ISE: Institute for Solar Energy Systems

ITRPV: International Technology Roadmap for Photovoltaics

JRC: Joint Research Commission

LID: light-induced degradation

LCA: lifecycle assessment

NREL: National Renewable Energy Laboratory

OPV: organic photovoltaics

OSC: Organic solar cells

PERC: passivated emitter rear contact

PFAS: per- and polyfluoroalkyl substances

PET: polyethylene terephthalate

PCR: product category rule

PSCs: perovskite solar cells

PID: potential-induced degradation

PEFCR: Product Environmental Footprint Category Rules

PV: photovoltaic

PVMI: photovoltaic modules and inverters

SEIA: Solar Energy Industries Association

SSI: Solar Stewardship Initiative

SOSR: State of Sustainability Research

ULCS: Ultra Low Carbon Solar

US: United States

WEEE: Waste Electrical and Electronic Equipment Directive

1. Introduction

1.1 Overview

To address sustainability concerns in the PV sector, GEC launched its EPEAT® ecolabel in 2017, providing a framework and standardized set of performance objectives for the design and manufacture of more sustainable PV modules. Inverters were added in 2019. In 2023, GEC added low-carbon performance criteria that require PV manufacturers to meet a stringent GHG emission threshold for module production, awarding manufacturers of products that contribute to decarbonization of the supply chain.

In alignment with ISO 14024 for Type 1 ecolabels, EPEAT criteria are periodically reviewed and revised to ensure that the definition of sustainability leadership, as reflected in the performance criteria, progresses with the evolution of technology and services and sustainability/environmental improvements in the product sector. The goal of this State of Sustainability Research (SOSR) is to generate up-to-date information on PVMI technologies and sustainability issues and mitigation efforts in the sector, to inform the criteria revision process.

There has been exceptional solar photovoltaic (PV) market growth in recent years. According to estimates by the International Energy Agency (IEA), new solar capacity added between 2025 and 2030 will account for 80% of the growth in renewable power globally. In calendar year 2023, global PV shipments were approximately 564 GW—an increase of 100% from 2022. Solar PV accounted for three-quarters of renewable capacity additions worldwide in 2023 [1] and as per IEA, 6% of global electricity generation came from PV in that year [2]. As shown in Figure 1, solar PV is projected to become the main renewable electricity source, followed by wind, both of which will surpass hydropower by 2030 [3].

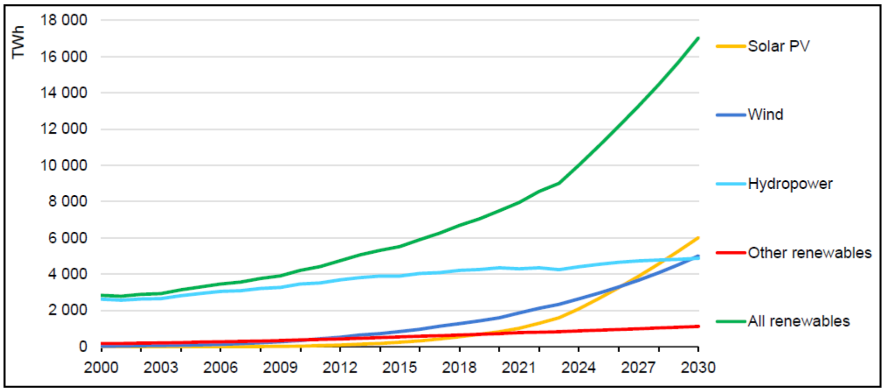

Figure 1: Global electricity generation by technology, 2000-2030 [3].

Global PV installations in 2024 were estimated by Bloomberg to be 592 GW, a 33% increase compared to 2023. Figure 2 presents global annual PV capacity additions by region. The figure highlights Mainland China as the region which contributes most to total annual PV installations globally. The annual PV installation forecast beyond year 2030 shows slight decreases in annual installations for China and Europe but increases in India and the North American & Caribbean regions. The growth in the PV industry has also had significant impacts on the job market across the globe. As per the14th Annual National Solar Jobs Census released by the Interstate Renewable Energy Council, 15,564 jobs were added in the U.S by the solar industry in 2023, amounting to a total of 280,000 workers in the sector in the country [90].

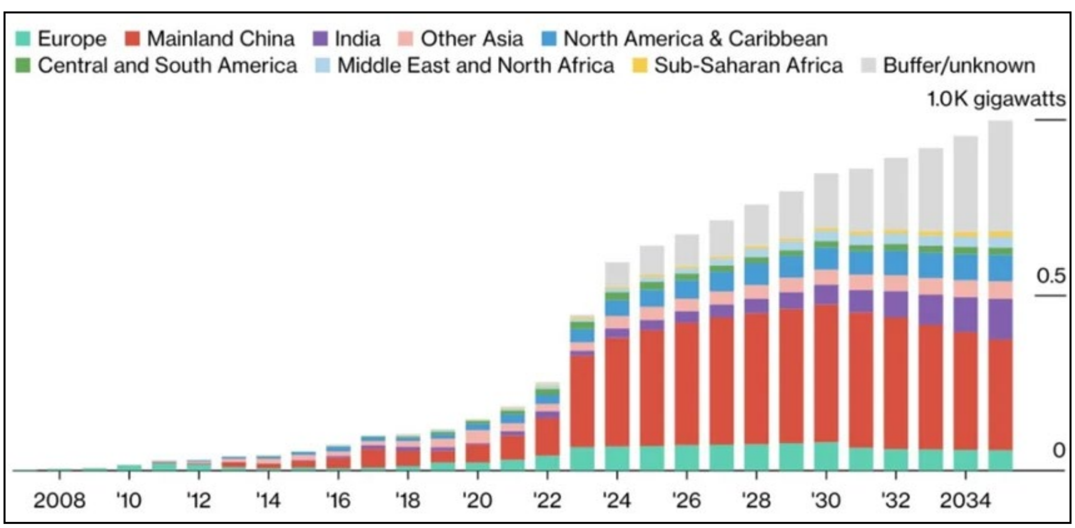

Figure 2: Solar power new build capacity by year as reported by BloombergNEF [84]

Advances in the PV industry also bring environmental and social sustainability concerns. These include use of critical and toxic materials in PV modules as well as the chemical pollution issues associated with this use. Additionally, the rapid expansion of PV module installations raises concerns about proper disposal of modules at end of life, particularly in geographic regions without waste regulations. And a lack of supply chain traceability coupled with allegations of forced labor in the Xinjiang Province of China, a key supplier of polysilicon to the PV industry, is also a major sustainability concern in the industry, which has led the U.S. to impose trade restrictions [4].

1.2 EPEAT Sustainability Impact Categories

GEC organizes its sustainability analyses and criteria into four priority areas of material importance to electronic products, as described on the right: Climate Change Mitigation, Sustainable Use of Resources (or Circularity), Chemicals of Concern, and Responsible Supply Chains. Focusing on these key sustainability impacts allows for a systematic analysis of data based on a unifying theme or metric to identify "hot spots" in the life cycle of the product, followed by a targeted examination of strategies that offer opportunities to reduce the identified impacts. The sustainability impact focus also provides a practical approach for criteria development and revisions, and simplifies product registration efforts for industry, as well as communication of results.

Sustainability Impact Categories

Climate Change Mitigation

This impact category addresses life cycle greenhouse gas (GHG) emissions associated with the production, transport, use and end of life management of electronic products. Production phase impacts include emissions from raw materials mining, component manufacturing and product assembly.

Sustainable Use of Resources

This impact category identifies priority sustainability impacts with respect to material selection and use, product design, end-of-life management, water management and packaging.

Chemicals of Concern

This impact category seeks to reduce the use of chemicals of concerns in products, packaging and manufacturing through effective management of the supply chain, chemical substance restrictions and alternatives assessment to prevent regrettable substitutions.

Responsible Supply Chains

Manufacturers leverage complex global supply chains for material sourcing and production, which can have negative labor, human rights, and environmental consequences. This impact category addresses such social risks in the supply chain and promotes best practices for labor, worker health and safety, and responsible sourcing of raw materials.

1.3 PVMI Category Scope

The purpose of the EPEAT PVMI product category is to establish product sustainability performance criteria and corporate performance metrics that exemplify sustainability leadership in the market. The criteria provide a framework and standardized set of sustainability performance objectives for the design and manufacture of PV modules and inverters, inclusive of the supply chain.

The scope of the existing EPEAT product category covers PV modules and inverters, which include:

1) PV modules for installation on, or integral with buildings, or to be primarily used as components of free-standing power-generation systems, including, but not necessarily limited to:

- PV cells that generate electric power using solar energy
- interconnects (materials that conduct electricity between cells)
- encapsulant (insulating material enclosing the cells and cell interconnects)
- superstrate (material forming primary light-facing outer surface) and substrate (material forming back outer surface) (e.g., glass, plastic films)
- wires used to interconnect PV modules and connect junction boxes to the balance of system equipment and
- frame or integrated mounting mechanism, if present.

The following are not included in the definition of a PV module:

- balance of system equipment, such as cabling and mounting structures, equipment intended to accept the electrical output from the array, such as power conditioning units (inverters) and batteries, unless they are contained in the PV module.
- a PV cell that is a part of another device for which it produces electricity, such as consumer or industrial electronic products (e.g., calculators, lights, textiles) where the PV cell primarily provides the energy needed to make the electronic product function, and
- mobile PV cell where the inverter is so integrated with the PV cell that the solar cell requires disassembly before recovery.

2) PV inverters convert and condition electrical power of a PV module to AC. The PV inverter is all the devices necessary to implement the PV inverter function. If separate devices are required to perform this function, the PV inverter includes the totality of these discrete devices including, but not limited to:

- PV-string inverters with included maximum power point trackers
- central inverters
- micro inverters

- bi-directional inverters; and
- a combination of a DC optimizer plus the inverter in systems where both are necessary.

The following are not included in the definition of PV inverters:

- PV module
- cabling and mounting structures
- external disconnects
- communication equipment
- combiners without power conversion or conditioning equipment function
- batteries and other energy storage components
- external transformers and other devices not required to perform the PV inverter function

2. Current State of PV and Inverter Technologies

2.1 PV Technologies

Photovoltaic cells or solar cells are primarily employed to convert solar energy into a flow of electrons. PV cells produce electricity from sunlight, which can be used to power equipment or recharge batteries. Different technologies have been established and/or are in development in the photovoltaic industry (Table 1). The environmental impacts and mitigation strategies may be different for different technologies.

The main PV technologies are crystalline silicon (mono and polycrystalline silicon), thin-film PV based on Cadmium Telluride (CdTe) and the newer thin-film types such as copper indium gallium selenide (CIS/CIGS). In 2023, 98% of PV shipments were mono crystalline silicon technology, compared to 35% in 2015 (Figure 3). Semiconductor thin films made of materials such as GaAs and CdX (X=Te, S, Se) and perovskite have gained interest due to their optical and electronic properties. In thin film PV technologies, CdTe is an established technology leader. Thin film panels are known as cost-effective substitutes for silicon-based solar PV panels as they can be manufactured in bulk. They are mainly used in utility-scale and commercial applications owing to their low installation costs [5]. CIGS PV has also been developed extensively in recent years.

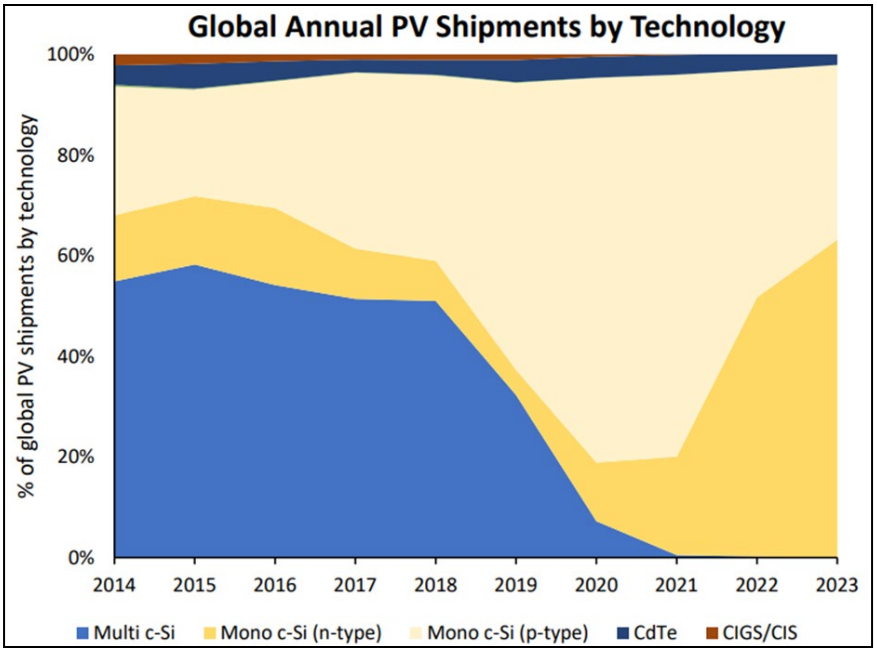

Figure 3: Global annual PV shipments by technology [2].

For crystalline silicon modules, high-purity silicon is manufactured by purifying metallurgical grade silicon from quartzite and quartz pebble at high temperatures. Purified solar-grade silicon is crystallized into silicon ingots which are then sliced and cleaned to form wafers. Silicon wafers are then transformed into solar cells using different methods. Thin-film CdTe PV technology does not use polysilicon. Instead, the process starts by extracting and refining specific minerals, in particular cadmium and tellurium as by-products of zinc and copper mining and refining, compounding Cd and Te into a stable cadmium telluride compound, and then proceeds to deposit a series of thin layers on a substrate (glass). Cells are then delimited by laser scribing or etching before being encapsulated, framed and covered. Both silicon and thin-film modules require a mounting structure, cables and inverters to be connected to the grid. Figure 4 summarizes the manufacturing processes of the two main PV technologies – crystalline silicon and CdTe solar PV systems [6]. Crystalline PV cells are more efficient in their conversion of light to electricity compared to thin films but are generally more expensive [7].

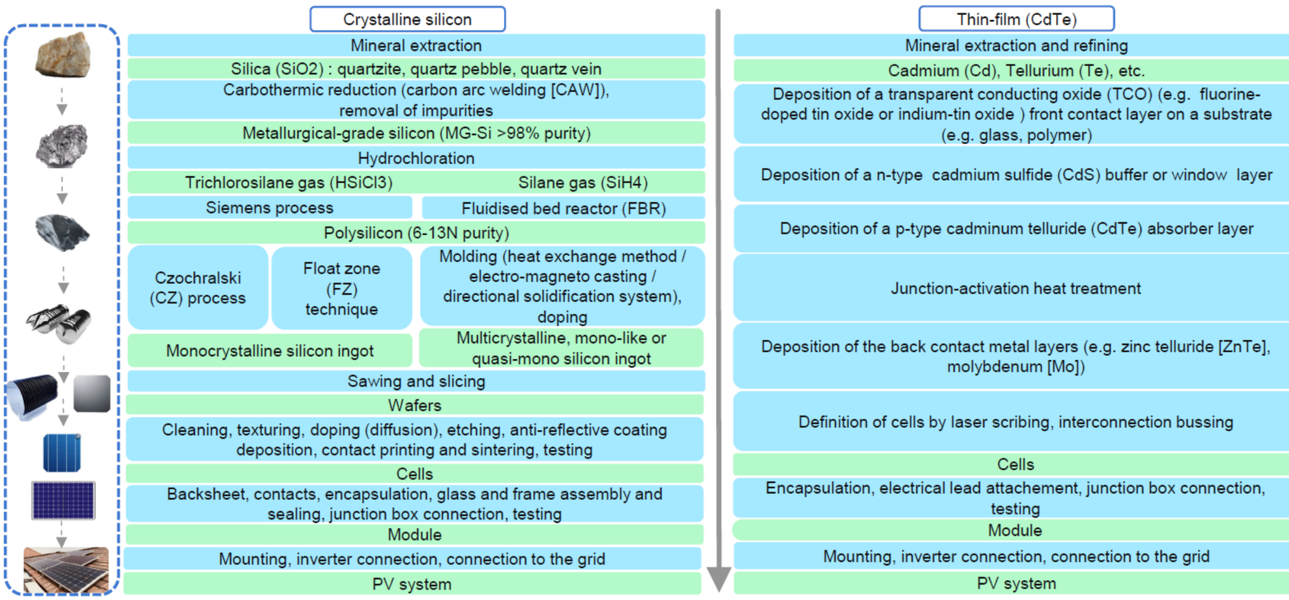

Figure 4: Simplified manufacturing from raw materials for c-Si and CdTe solar PV systems, adopted from the IEA (2022) Special Report on Solar PV Global Supply Chains [6].

Other PV technologies include [8]:

1) III-V Solar Cells

This PV technology type is named after the elements they are made of. III-V solar cells are mainly made of elements in Group III—e.g., gallium and indium—and Group V—e.g., arsenic and antimony—of the periodic table. While these solar cells are more expensive to manufacture than other technologies, they have higher sunlight to energy conversion efficiency. Therefore, III-V solar cells are often in applications that require a high ratio of power-to-weight such as in satellites and unmanned aerial vehicles [8].

2) Organic solar cells

Organic solar cells (OSC), also known as organic photovoltaics (OPV) are the emerging photovoltaic devices in the third-generation solar cell technologies [9]. The basic concept of OSCs involves the conversion of light into electricity through the absorption of photons by an organic material, followed by the separation of electron–hole pairs and the collection of charges by electrodes. OPV cells are categorized into small- molecule OPV cells and polymer based OPV cells. The wide abundance of building-block materials may reduce supply and price constraints [10].

OPV advantages include flexibility, lightweight form, potential low-cost manufacturing, and integration into various applications [11]. They also have a lower environmental impact compared to traditional inorganic solar cells, as they can be produced using non-toxic materials and solvents and have a lower carbon footprint due to their lower energy requirements during manufacturing. However, organic solar cells have lower efficiencies compared to silicon-based cells. Some of the challenges in the practical implementation of organic solar cells are stability, durability, and scalability [12].

3) Quantum dot solar cells

Quantum dots are semiconducting nanocrystals with typical dimensions ranging from several to tens of nanometers, capable of controlling photoelectric properties based on their particle size. They have gained great attraction for the development of high efficiency solar cells due to their remarkable properties such as tunable bandgap, multiple exciton generation and higher relaxation time. Quantum dots can be synthesized from different semiconductor materials; commonly used materials are CdX, ZnX, PbX, SnX (X=S, Se, Te), HgTe, InP, InAs, GaAs, GaP, CuInS2. Carbon quantum dots and graphene quantum dots are considered eco-friendly while As and P based quantum dots are sometimes avoided due to the toxicity of the reactants and their high reactiveness [13].

4) Perovskite solar cells

Perovskite solar cells (PSCs) are a third-generation solar cell technology that has been attracting extensive attention in recent years due to their rapidly boosted power conversion efficiency and low fabrication cost. PSCs are a type of thin-film solar cell made from a class of man-made materials with a unique crystallographic structure, called perovskites. Different types of PSCs include organic–inorganic hybrid perovskites and all-inorganic perovskites [14].

Tandem perovskite is a technology that may involve perovskites combined with traditional silicon or CIGS cells to create a compound solar cell with benefits from both types of photovoltaic technology [14]. Tandem solar cells have gradually attracted more attention due to their great potential to reduce thermalization losses. Among various kinds of perovskite-based tandems, all perovskite tandem cells offer great promise with the advantages of solution processability, low cost, and flexibility. A combined tandem solar cell of PSC and OPV has advantages in terms of flexibility and reduction of Pb usage [15]. The British perovskite solar company Oxford PV has completed the world's first commercial sale of perovskite-silicon tandem solar modules to a U.S company for deployment in a utility-scale project. The perovskite-on-silicon cells being sold are reported to have a conversion efficiency of 24.5% [16].

PV Cell Technologies	Cell Types
Crystalline Si Cells	Single crystal (non-concentrator)
Crystalline Si Cells	Multicrystalline
Crystalline Si Cells	Single crystal (concentrator)
Crystalline Si Cells	Thin-film crystal
Crystalline Si Cells	Silicon heterostructures (HIT)
Emerging PV	Dye-sensitized cells
Emerging PV	Organic cells
Emerging PV	Organic tandem cells
Emerging PV	Inorganic cells (CZTSSe)
Emerging PV	Quantum dot cells
Emerging PV	Perovskite cells
Emerging PV	Perovskite Tandems
Hybrid Tandems	Perovskite/Si tandem (monolithic)
Hybrid Tandems	Perovskite/CIGS tandem (monolithic)
Hybrid Tandems	Perovskite Tandems
Hybrid Tandems	III-V/Si
Hybrid Tandems	Perovskite/Organic
Multijunction Cells	Two-junction (concentrator)
Multijunction Cells	Two-junction (non-concentrator)
Multijunction Cells	Three-junction (non-concentrator)
Multijunction Cells	Three-junction (concentrator)
Multijunction Cells	Four-junction or more (concentrator)
Multijunction Cells	Four-junction or more (non-concentrator)
Single-Junction GaAs	Single crystal
Single-Junction GaAs	Concentrator
Single-Junction GaAs	Thin-film crystal
Thin-Film Technologies	Amorphous Si:H (stabilized)
Thin-Film Technologies	CdTe
Thin-Film Technologies	CIGS
Thin-Film Technologies	CIGS (concentrator)

Table 1: Detailed list of solar PV technologies and types within each technology as reported by the NREL in their cell efficiency data file and chart, 2024[85].

Another technological development in the PV industry is the floating solar photovoltaics (FPVs) or 'floatovoltaics'. They typically consist of an array of PV modules mounted upon a series of floats, moored into position on the surface of a water body. Material composition of floaters used in FPVs include HDPE (High-density polyethylene) floaters and steel/HDPE floaters [17].

FPVs avert the need for land-use change when compared to conventionally deployed PVs which require ground-mounted systems, a key benefit in land-scarce countries and regions with high land prices. FPVs have also been shown to reduce evaporative losses, potentially providing water savings for drought-stricken areas. FPV systems are also reported to have higher efficiencies, compared with land-based systems [18]. A recent study led by the European Commission's Joint Research Centre, which explored the benefits of installing FPVs on existing hydropower reservoirs in Europe, reported that coupling FPV with hydropower can be a great solution for limited land availability while providing solar electricity, leveraging water bodies, and reducing water evaporation losses. The study highlighted that pairing FPV with hydropower can be a unique energy aid with water savings for countries such as Spain, Greece, Italy and Portugal which face high water scarcity issues [19]. However, the introduction of floating photovoltaic arrays into aquatic ecosystems are also associated with environmental impacts such as shading, impacts on hydrodynamics and water-atmosphere exchange, energy emissions, impacts on benthic communities, and impacts on mobile species [91].

Building-integrated and built-environment-integrated photovoltaic systems

The Architectural Solar Association defines building integrated photovoltaics (BIPV) as a photovoltaic generating component which forms an integral and essential part of a permanent building structure without which a non-BIPV building material or component would be required to replace it [20]. The most competitive current BIPV products on the market are roofing products (solar panel frames, PV shingles), glass products (solar windows, glazing) and conventional solar modules on building façades [21]. Roof-mounted systems are currently the dominant design. BIPV solar panels currently available on the market use either crystalline silicon-based (c-Si) solar cells or thin-film technologies such as amorphous-based silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) [22].

2.2 Inverter technologies

Solar power inverters convert the direct current (DC) energy produced by a solar panel into alternating current (AC). The different inverter types available in the market are central inverters, string inverters, micro inverters, smart inverters and battery-based inverters. Central inverters are centrally connected to all solar power module arrays, while string inverters are smaller inverters connected to a single array or string of solar modules. Central inverters have simple connections and lower per unit power cost. String inverters offer modularity but have more interconnections and high per unit cost. Nowadays, with the use of sensors and weather monitoring tools, string inverters have been modified as energy management systems. While capital expenditure is higher, reduced breakdown time, higher generation yield, replaceability and lower operating and maintenance costs have resulted in greater uptake of string inverters [23].

As opposed to central and string inverters, microinverters are connected to multiple solar modules or panels of a PV system. A key advantage of microinverters is that even a complete module failure will not reduce the output of the entire array. However, microinverters have higher initial equipment cost per peak watt compared to central inverters since each inverter needs to be installed adjacent to a panel, making maintenance tough and replacement costlier [23].

Smart inverters work autonomously and use voltage and frequency sensors to detect grid abnormalities enabling two-way communication with utility operators. Battery-based inverters are used in storage systems in solar installations. In such systems, the battery bank is charged by a PV array connected through a charge controller or a battery inverter via AC coupling [23].

3. PV Supply Chain & Market Overview

As per the IEA, China's solar capacity has almost quadrupled since 2020 and its share in all the manufacturing stages of solar panels (such as polysilicon, ingots, wafers, cells and modules) exceeded 80% [3]. The reduction in module prices, which almost halved in 2023, has been a contributor to China's utility scale PV additions. The Chinese government has also enacted policies to speed up the construction of large-scale solar PV electricity generation plants in deserted areas. From 2022 to 2023, the United States government also initiated efforts to expand their PV module manufacturing market, and the US reported the second-largest increase in utility PV installations, almost doubling the installations.

China is forecasted to continue its leadership by maintaining over 80% PV manufacturing capacity in all segments through 2030. However, the IEA reports that industrial policies and trade measures have stimulated diversification in PV manufacturing. While China has limited competition in wafer production, Southeast Asian countries such as Vietnam, Malaysia and Thailand now have considerable cell and module manufacturing capacity (Figure 5).

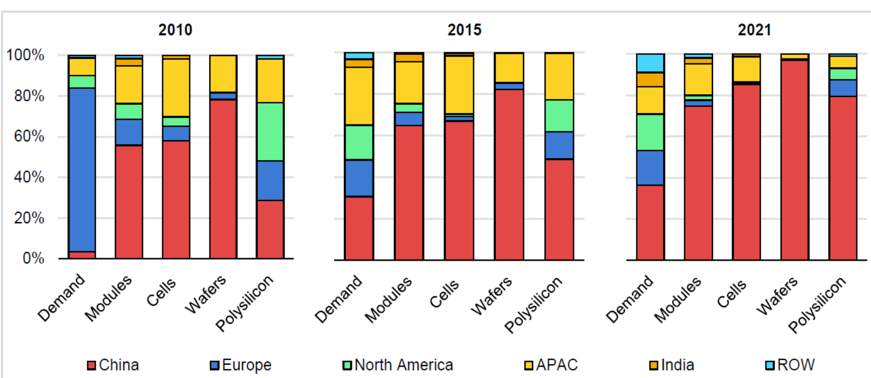

Figure 5: Solar PV manufacturing capacity by country and region from 2010 to 2021, adopted from the IEA (2022) Special Report on Solar PV Global Supply Chains [6].

Germany is a major supplier of polysilicon for the c-Si modules industry. While the U.S and Japan have significant polysilicon capacity the production is currently focused on semiconductor-grade products [6]. The solar cell and module manufacturing capacity in the United States and India is forecasted to triple in the coming years. However, the cost of manufacturing cells and modules in these countries is expected to remain 2 to 3 times higher than that in China. Figure 6 illustrates China's growing share of total PV module shipments from 2004 to 2023.

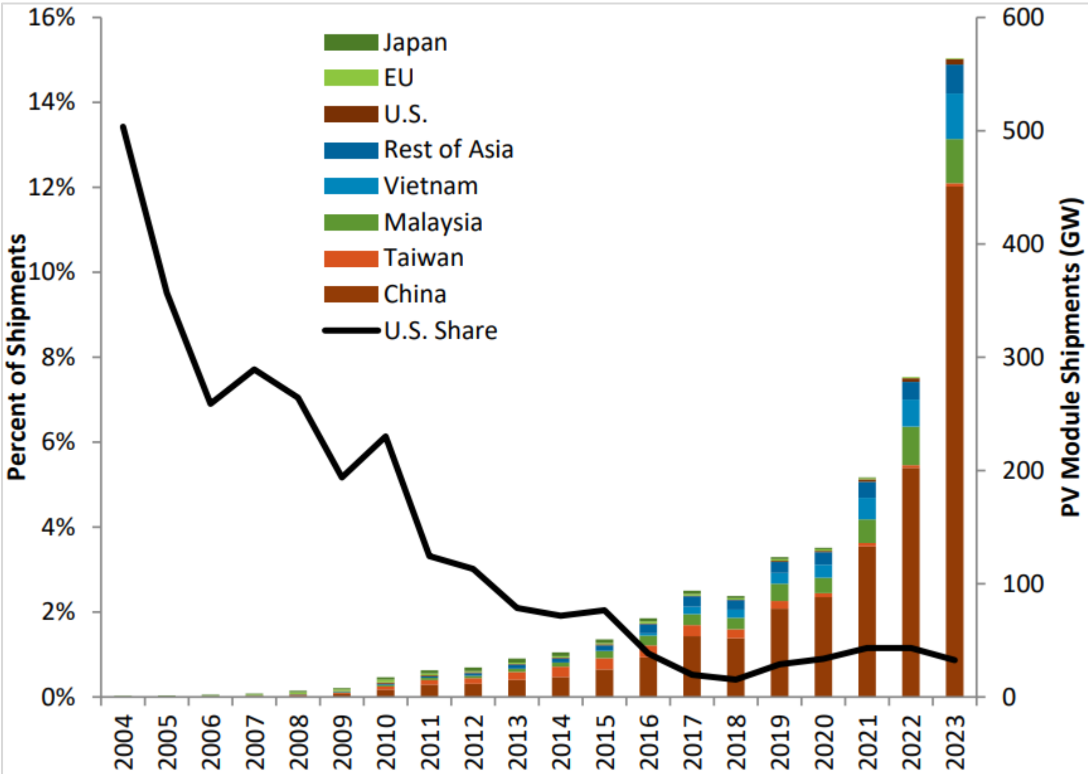

Figure 6: Global annual PV shipments by region [2].

At a company level, approximately fifty percent of PV shipments came from five top companies in 2023. Tongwei (11.6%), Jinko Solar (10.7%), LONGi (10.4%), Trina Solar (9.9%) and JA Solar (9%) together contributed 51.6% of total PV shipments in 2023 (Table 2). The shipments from the top 10 PV manufacturers totaled 414 GW in 2023, with some companies shipping more than 60 GW annually.

Ranking	2017	GWdc	2022	GWdc	2023	GWdc
1	JA Solar	6.5	Tongwei	38.1	Tongwei	65.5
2	Canadian Solar	5.4	JA Solar	36.2	Jinko Solar	60.2
3	Zhongli Talesun	5.0	Aiko	30.7	LONGi	58.4
4	Jinko Solar	4.9	LONGi	29.2	Trina Solar	55.9
5	Trina Solar	4.8	Jinko Solar	23.9	JA Solar	51.2
6	LONGi	4.5	Canadian Solar	16.8	Aiko Solar	36.8
7	Hanwha Q Cells	4.2	Trina Solar	14.5	Canadian Solar	30.7
8	Tongwei	3.8	SolarSpace	11.6	Astroenergy	19.5
9	Motech	3.2	Zhongli Talesun	9.8	Risen	18.5
10	Aiko	3.1	First Solar	9.1	Runergy	17.0
Total Above		**45.5**		**220.0**		**413.7**
Total Shipped		**93.9**		**283.1**		**564.0**

Table 2: Global Leading PV Manufacturers by Shipment [2].

A key challenge faced by the global solar PV industry currently is the financial turbulence due to supply overcapacity. The prices of PV components such as polysilicon, wafers, cells and modules fell almost 50% from 2023 to 2024 (Figure 7). The IEA predicts that the prospects of global demand catching up with supply are low, exposing smaller manufacturers to financial risks. The supply over capacity is expected to result in a drop in average manufacturing capacity utilization rates from about 55-80% in 2023 to 50-65% in 2024.

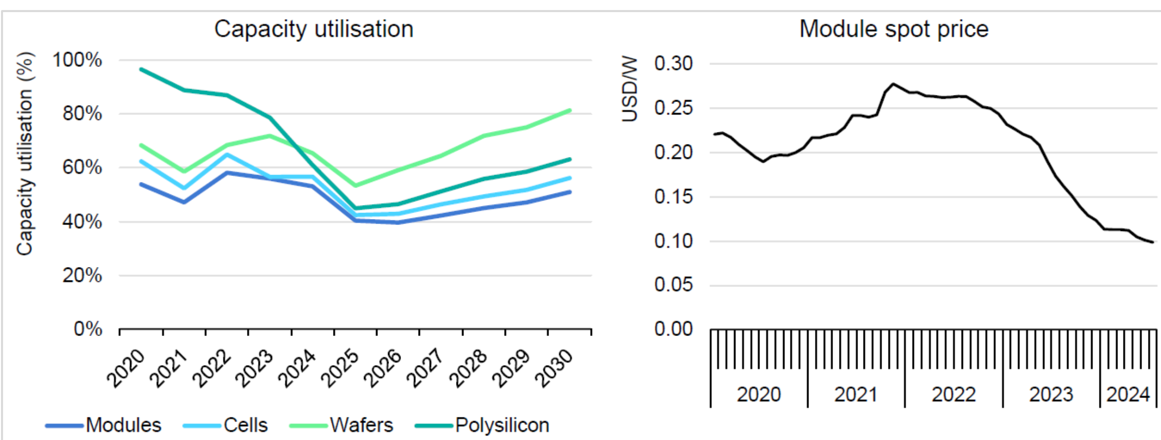

Figure 7: Manufacturing capacity utilization rate, 2020-2030, and average monthly solar PV module spot prices, 2020-2024 [3].

4. Sustainability Impacts

The major environmental issues identified in the production of solar PV are:

- Energy consumption
- Greenhouse gas emissions associated with production
- Toxic chemical use. For example, thin film PV modules contain toxic substances such as cadmium and crystalline silicon technologies use lead. Indium tin oxide (ITO) may also be found in thin film PV modules
- Heavy metal and pollutant emissions from manufacturing plants
- Water use in production and operation of PV modules as well as wastewater generation during manufacturing
- Land use and biodiversity. PV installations may directly impact ecosystems and species through habitat change and loss, mortality, behavior alteration or population displacements [24].
- End of life management, since PV modules are often not recycled at the end of life

Table 3 below shows the latest PV system environmental impact data reported by the IEA. The carbon footprint per kWh of solar electricity is reported to vary from 25.2 to 43.6 g CO_2 equivalent for different technologies. The other impacts presented include resource use of fossil fuels (0.35 to 0.52 MJ per kWh), resource use of minerals and metals (4.6 to 5.3 mg Sb equivalent per kWh), particulate matter (1.0 to 4.0 incidences per kWh), and acidification (0.18 to 0.36 mmol H+ equivalent per kWh) [25]. The study considered a 3 kWp roof mounted PV system in Europe, with a 30-year service life for panels and 15 years for inverters. The scope included panel, cabling, mounting structure, inverter and system installation [26].

	UNIT	Mono-Si	Multi-Si	CIS	CdTe
Greenhouse gas emissions	g CO_2 eq	35.8[4]	43.6	35.5	25.2
Resource use, fossil fuels	MJ	0.44	0.52	0.51	0.35
Resource use, minerals and metals	mg Sb eq	5.04	5.30	4.64	5.22
Particulate matter	10^{-9} disease incidences	2.87	3.97	1.34	1.04
Acidification	mmol H^+ eq	0.29	0.36	0.21	0.18
Module efficiency	%	20.9	18.0	17.0	18.4
Data	reference period	2020 - 2023	2019 - 2021	2010 / 2020	2020 - 2022

Table 3: The environmental impacts associated with generating 1 kwh of solar electricity from PV systems as reported in the IEA PVPS 2023 Factsheet [26].

Some of the key environmental issues are discussed in detail below.

4.1 Energy use in PV production

The majority (80%) of the total energy used in solar PV manufacturing is provided by electricity. A large portion of the electricity consumption is to produce polysilicon, ingots and wafers which require heat at high and precise temperatures. Since PV production is concentrated in provinces of China like Xinjiang and Jiangsu where coal accounts for majority of power supply, 60% of the electricity used for global solar PV manufacturing becomes coal powered. This share is significantly more than the solar PV share in global power generation [6].

However, energy payback time or the time in years required by a PV system to produce the same amount of energy equal to the energy consumed during its life cycle, has been decreasing with improving production technologies [27]. As per a study published by NREL in 2004, the energy payback estimates for rooftop PV systems ranged from 1 to 4 years. As shown in Figure 8, the estimated energy payback time for current multi-crystalline-silicon PV modules was 4 years and current thin-film modules was 3 years. Future projections by the study showed the energy payback of multi-crystalline modules to decrease to 2 years and thin-film modules to decrease to 1 year [28]. However, more recent research reports much lower energy payback time for PV modules. For example, a study published by Leccisi et al. in 2016 reported the energy payback times for fixed-tilt ground mounted installations to range from 0.5 years for CdTe PV at high-irradiation to 2.8 years for single crystalline Si PV at low-irradiation [86]. In their 2024 Sustainability Report, PV manufacturing company *First Solar* has reported the energy payback time of their *Series* 6 & *Series* 6 *Plus* CdTe PV modules to be 4 months and their *Series 7* CdTe PV modules to be 1.9 months [87].

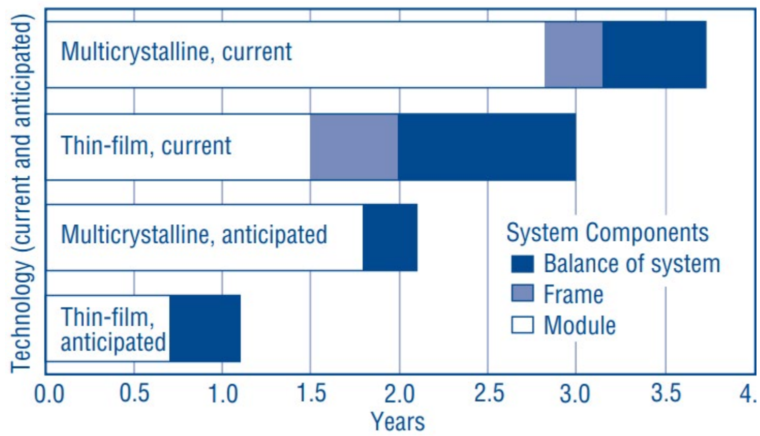

Figure 8: Energy payback time for rooftop PV systems estimated in 2004 [28].

4.2 Climate Impact

The global carbon emissions from PV manufacturing increased four times to more than 51,900 kilotonnes of carbon dioxide in the past decade due to a sevenfold production increase and manufacturing capacity shift to China [6]. However, the emissions intensity of solar PV manufacturing has decreased almost 45% in the last decade. The IEA attributes this reduction to material and energy efficiency improvements in addition to the use of renewable energy in manufacturing. Figure 9 adopted from an IEA report on PV supply chains presents the PV manufacturing emissions reduction achieved through the aforementioned strategies in the year 2021. Over 65% of emissions reduction is achieved through material efficiency in polysilicon manufacturing, 20% from low carbon electricity use, and the remaining from energy efficiency improvements in producing polysilicon.

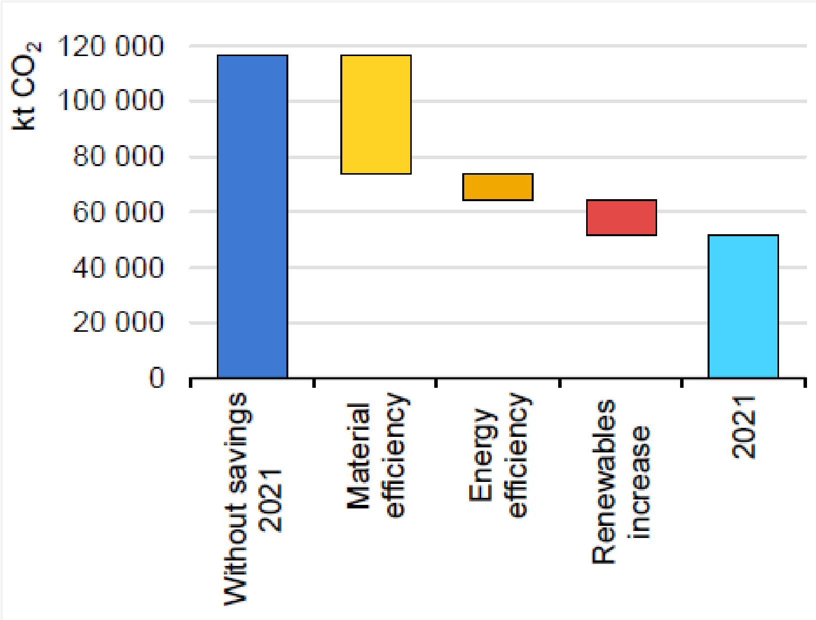

Figure 9: Solar PV manufacturing CO2 emissions savings in 2021 [6].

The changes in global PV manufacturing emissions over time are presented in Figure 10. The figure shows PV manufacturing emissions at three levels: the absolute emissions by segment, segment level emissions intensity and emissions from manufacturing by country. Among the four supply chain segments, polysilicon and wafer production are significant contributors to overall emissions. In the past decade, the absolute emissions from both polysilicon and wafer production have increased. The emission intensity of polysilicon, however, decreased over the same time due to improvements in material efficiency, energy efficiency and low carbon energy use for production [6].

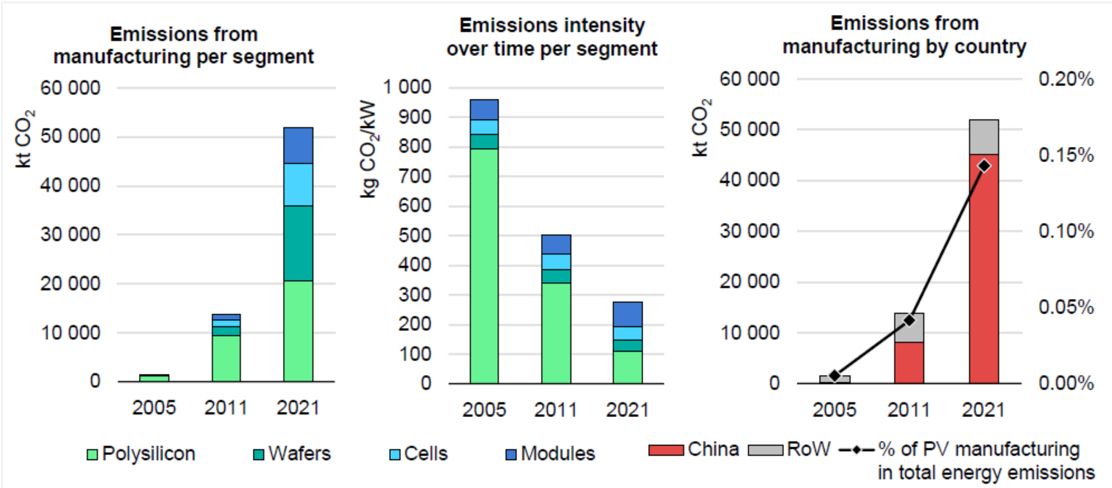

Figure 10: Absolute emissions and emission intensity of PV manufacturing globally as reported by the IEA [6].

The total life cycle footprint of the solar module is dominated by the upstream raw materials and manufacturing emissions, and to a lesser extent end-of-life emissions associated with the decommissioning of used PV modules. That is, almost 70% of the total life cycle carbon footprint of a PV module is due to the carbon intensity of the module's raw materials and underlying manufacturing processes [29]. Fluorinated gases with high global warming potential such as sulfur hexafluoride (SF6) and nitrogen trifluoride (NF3) are used in the manufacturing of some PVs. For example, SF6 and NF3 are known to be used for reactor cleaning after deposition of silicon nitride or film silicon and CF4 is used in edge isolation [30]. Recent studies indicate that the manufacturing process of thin-film technologies, such as cadmium telluride (CdTe), does not involve the use of such gases [88][89].

Different life cycle impact assessment methods can be used for carbon footprint calculations of PV modules which may lead to variations in results. Studies show that PV module parameters such as module lifetime, degradation rate, and purchased renewable electricity certificate allowance limit can significantly influence the carbon footprint calculation. Two prevalent methodologies for PV carbon footprint calculations are EPEAT and the Ecodesign adaptation of the Product Environmental Footprint Category Rules (PEFCR), both of which are referenced by the European Commission for PV modules carbon footprint calculation guidelines for Ecodesign Directive 2009/125/EC. The table below (Table 4) presents a summary of carbon footprint data for different PV technologies calculated as per PEFCR 2019 version by Polverini et al (2023) [31]. The carbon footprint for different PV technologies presented in Table 4 shows that, for all of these technologies, use phase carbon emissions are much lower than all other PV life cycle stages. The Norwegian product category rule (PCR) for photovoltaic modules (NPCR 029: 2020 Part B) defined for environmental product declarations (EPD) of PV modules has also developed a universal and easily comparable methodology for product environmental impact assessment and declaration [32]. Other PCRs for PV modules include the PEFCR (Product Environmental Footprint Category Rules) for photovoltaic electricity generation and the Italy PCR (EPDItaly 014: Core PCR for PV Panel).

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

Table 4: Carbon footprint values corresponding to the climate change impact category, calculated as per the Product Environmental Footprint Category Rules 2019 version [31].

Recent research by Khan et al (2024) from the Fraunhofer Institute for Solar Energy Systems (ISE) presents a comparison of the two methodologies to emphasize the implications of carbon footprint method selection [33]. Table 5 shows a summary of comparison between the PEFCR and EPEAT methodologies as reported by Khan et al (2024). The EPEAT approach uses a functional unit (FU) of kgCO2-Eq. per kilo watt peak (kWp) while the PEFCR approach uses kgCO2-Eq. per kilo watt hour (kWh) as the FU. kWp refers to the maximum power output capability of a solar panel or solar system under optimal conditions while a kWh measures how much energy is being used or produced during a period of time [34]. The Norwegian PCR for PV modules also use Wp as the functional unit for PV modules. The system boundary considered by EPEAT is cradle to gate which is through production of the module. The PEFCR methodology also considers the system boundary to the module, but also includes transportation to the European market, i.e., cradle-to-European market with default transport scenario. The module frame is included in the system boundary in both approaches [33].

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

Table 5: Differences between PEFCRs for PV modules in Ecodesign legislation and EPEAT guidelines for the carbon footprint estimation [33].

The EPEAT methodology calculates Watt peak kWp as the product of module area, maximum efficiency and irradiance and does not involve relying on warranties for parameters such as lifetime/power warranty and degradation rate. But the EPEAT approach does include minimum requirements such as a 25-year product lifetime and less than 20% lifetime performance degradation over lifetime. The functional unit Watt peak is independent of local solar irradiation, shade, temperature etc. [35]. The PEFCR approach calculates energy yield based on PV module lifetime which is assumed as a fixed 30 years for all modules and PV module lifetime performance degradation assumed as 1%. Khan et al (2024) points out that the overall energy yield of a module can vary up to 140% based on lifetime increase, degradation rate improvement and module peak power improvement. In addition, the fixed 30-year assumption equalizes lifetime and does not consider differences in module performance quality. Under this assumption, the use of module power warranty to represent product lifetime may disincentivize modules with warranties longer than 30 years. The fixed degradation rates assumption also does not consider product specific degradation which may vary among modules of the same technology [33]. The EPEAT approach offers two pathways for carbon footprint calculations. Path A allows the use of lookup tables for carbon values for component manufacturing by geography. The carbon values used are based on the LCI from the IEA's Technology Collaboration Programme on PV Power Systems Sustainability (PVPS) Task 12. Path B allows the use of site specific LCA using verified primary data. Currently, 630 kg CO2-Eq./kWp is the required threshold for EPEAT Low Carbon Solar while 400 kg CO2-Eq./kWp is the threshold for EPEAT Ultra Low Carbon. The low carbon threshold value of 630 kg CO2-Eq./kWp is 20% lower carbon emissions than the global average for PV module production. The ultra-low carbon solar represents the lowest reported emissions. The thresholds were established based on data from the IEA photovoltaic task group [36]. Installing EPEAT registered solar modules is estimated to reduce up to 45,700 metric tons of CO_2e, equivalent to removing over 10,000 gasoline powered cars from the road for one year for a 100 MW project.

The European Commission's JRC Technical Report has highlighted the life cycle hotspots in PV module and inverter production. For Si-based technology modules, ingot manufacturing or wafer production is identified as having the highest environmental impact contribution while for thin-film technology modules, the metal deposition together with flat glass production have been pointed out as the process/component having the largest impact in module manufacturing. For all modules irrespective of the technology, the electricity consumption in aluminum and copper production is reported to have a high environmental impact contribution. In the case of inverter products, the main contributor to environmental impact is the integrated circuits on printed circuit boards [30].

4.3 Sustainable Use of Resources

Material Consumption

The raw materials required for solar PV manufacturing include metals, metalloids, non-metallic minerals and polymers, with differences in material needs across technologies. Table 6 presents a list of key materials and their use in two major PV technologies - crystalline silicon and CdTe PV. The materials include silicon, aluminum, antimony, copper, cadmium, indium, molybdenum, selenium, silver, tellurium, tin, zinc, lead and glass. Aluminum, copper and cobalt are the critical minerals used in PV and inverter technologies, among which cobalt is identified as having low importance in these technologies (Figure 11) [37].

Technology	Material	Main uses
c-Si	Aluminium	Module frame; mounting structure; connectors; back contact; inverters
	Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
	Copper	Cables, wires, ribbons, inverters
	Glass	Module cover
	Indium	Transparent conducting layer (indium tin oxide [ITO]) in silicon heterojunction (SHJ)
	Lead	Soldering paste and ribbon coating in c-Si modules
	Silicon	c-Si wafers; in the form of high-purity quartz (HPQ), for crucibles to grow monocrystalline silicone ingots via the Czochralski process
	Silver	Electronic contacts: silver paste, busbars and soldering
	Tin	Solder, ribbon coating in c-Si modules
	Zinc	Galvanized steel in mounting structures
Technology	**Material**	**Main uses**
Thin-film CdTe	Aluminium	Module frame; mounting structure; connectors; inverters
	Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
	Cadmium	Absorber layer
	Copper	Cables, wires, ribbons, inverters
	Glass	Module cover
	Indium	Transparent conducting layer (indium tin oxide [ITO])
	Molybdenum	Back contact layer
	Selenium	Absorber layer in some CdTe cells
	Silver	Electronic contacts: silver paste and soldering
	Tellurium	Absorber layer (CdTe) and back contact (ZnTe)
	Tin	Solder; transparent conducting oxide (indium tin oxide)
	Zinc	Galvanized steel in mounting structures; back contact (ZnTe)

Table 6: Key materials and their use in crystalline silicon and CdTe solar PV manufacturing [6].

	Copper	Cobalt	Nickel	Lithium	REEs	Chrominum	Zinc	PGMs	Aluminium*
Solar PV	High	Low	Low	Low	Low	Low	Low	Low	High
Wind	High	Low	Moderate	Low	High	Moderate	High	Low	Moderate
Hydro	Moderate	Low	Low	Low	Low	Moderate	Moderate	Low	Moderate
CSP	Moderate	Low	Moderate	Low	Low	High	Moderate	Low	High
Bioenergy	High	Low	Low	Low	Low	Low	Moderate	Low	Moderate
Geothermal	Low	Low	High	Low	Low	High	Low	Low	Low
Nuclear	Moderate	Low	Moderate	Low	Low	Moderate	Low	Low	Low
Electricity networks	High	Low	Low	Low	Low	Low	Low	Low	High
EVs and battery storage	High	High	High	High	High	Low	Low	Low	High
Hydrogen	Low	Low	High	Low	Moderate	Low	Low	High	Moderate

Importance: High ● Moderate ● Low ●

Figure 11: Key material needs for clean energy technologies [37].

IEA reports that significant improvements in material intensity have been achieved in PVs in the past two decades. For example, cell efficiency improvements, thinner diamond wire sawing and wafers, and larger ingots have resulted in a six times reduction in the polysilicon intensity of crystalline silicon cells (in g/W) since calendar year 2004. Similarly, improvements in screen printing processes have reduced silver intensity of crystalline silicon cells (in g/cell) by a third during the time period 2009-2018. Despite these material efficiency improvements, the PV industry's demand for minerals is projected to continue to expand. For example, IEA projects the demand for silver for solar PV manufacturing in 2030 could exceed 30% of total global silver production in 2020 [6]. In order to limit global warming to less than 2 degree C by 2030, it is estimated that renewable energy generation will increase 44%. To meet this increased use of renewable energy, the World Bank has forecasted a 300% increase in demand for key minerals used in PV panels, including aluminum, copper, indium, iron, lead, molybdenum, nickel, silver, and zinc [38]. Figure 12 shows the material composition shares of the two major PV technologies, crystalline silicon and CdTe thin film, by weight and average value. The figure highlights the intensity of expensive materials in PVs and hence the need for sustainable use of resources in PV technologies. Value-based compositions are based on average 2021 market prices of materials; for example: Al- USD 2 500/Mt, Cu: USD 9 408/Mt, Ag: USD 803/kg; crystalline Si: USD 34/kg, and solar-grade glass: USD 590/Mt [6].

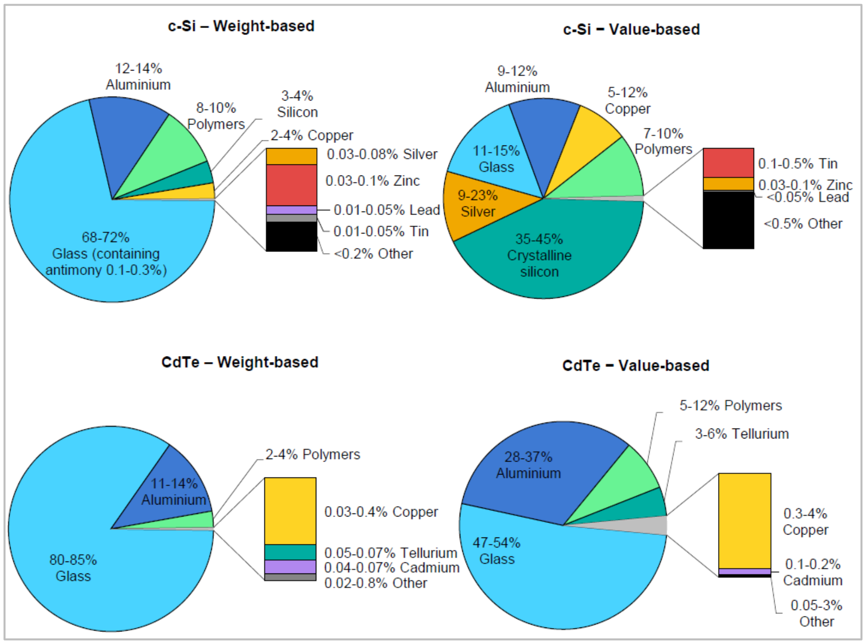

Figure 12: Material composition shares of crystalline silicon and CdTe thin-film solar PV modules by weight and average value as reported by IEA [6].

Product Lifetime

In terms of product life expectancy, the expected lifetime of PV systems has increased significantly over the last decades. That is, PV systems' life expectancy improved from approximately 21 years to over 32 years between 2007 and 2019. Module warranties have increased from 1 year in 1977 to approximately 30 years in 2019. Figure 13 shows the continued increase in PV lifetimes and module warranties observed since the calendar year 1977. An NREL study on PVs indicates that PV systems can now be expected to last beyond module performance warranties by many years. Projections by the International Technology Roadmap for Photovoltaics (ITRPV), as reported by NREL, indicate that by 2026, the performance warranty of crystalline-silicon modules will rise to 30 years.

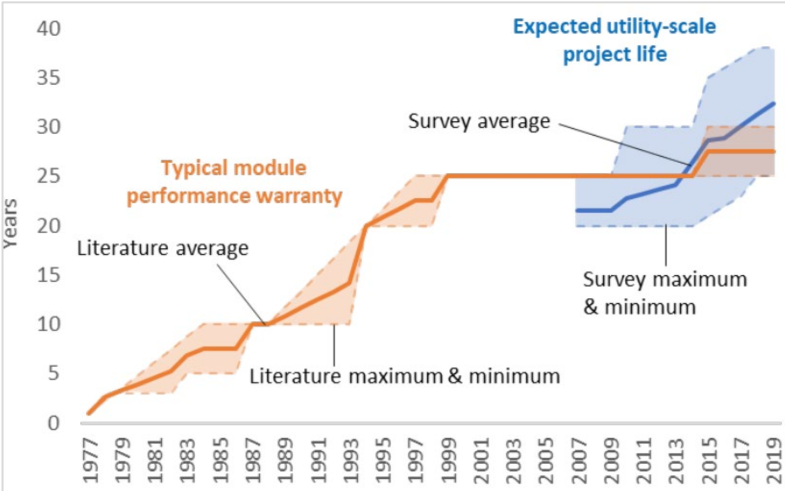

Figure 13: PV system lifetimes [2].

They also project that the initial degradation after the first year of module operation will fall to 1.0% in 2026 and the annual degradation will decline to 0.38% by 2034 (Figure 14) [2]. Module degradation is the reduction in solar PV output over time and can be caused by a variety of factors such as cracking and breakages, discoloration of the encapsulating material EVA (ethylene vinyl acetate), hotspots, light-induced degradation (LID), potential-induced degradation (PID), delamination, and corrosion. Understanding module degradation is important for improving PV life expectancy [39].

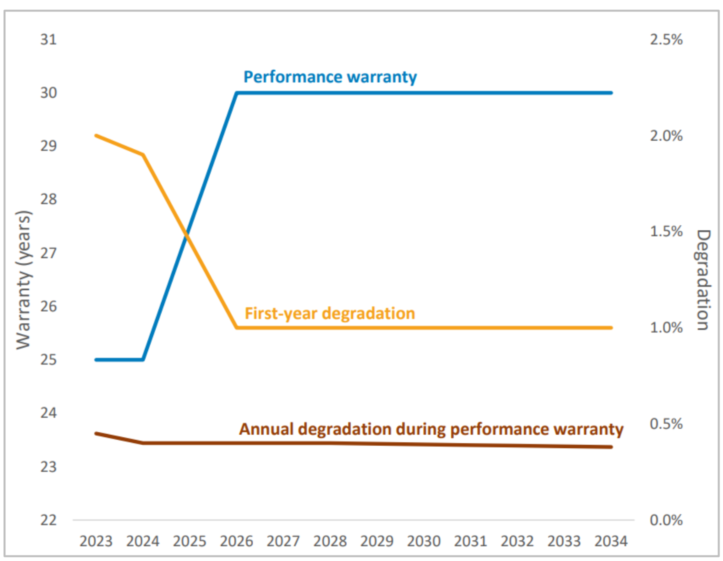

Figure 14: Silicon module warranty and degradation projections by ITRPV as reported by NREL [2].

<u>End of Life Management</u>

As per the Global E-waste Monitor 2024 report, 0.6 billion kg of end-of-life photovoltaic panels was generated globally in 2022, out of which 0.1 billion kg was collected (17% collection rate) [40]. A 2023 IEA report on the status of PV module recycling predicts 2.5 to 3.5 million tons of PV module waste in 2040 in comparison to 6.5 million tons in new PV module installations in the year [41]. However, the technology, infrastructure, and processes associated with recycling PV modules are still not optimized for cost-effective recovery of high value materials [42].

As per a report by the NREL, less than 10% of modules are being recycled in the U.S and only two recyclers in the U.S recover high-purity bulk and trace materials from PV modules - *We Recycle Solar* and *First Solar* [43]. The recycling rates of PV panels are much higher in European Union (EU) member states due to the Waste Electrical and Electronic Equipment (WEEE) Directive which has established targets for the recovery and recycling/preparation for reuse of photovoltaic panels. The Directive has mandated recovering 85% of PV panel waste generated annually and reusing/recycling 80% of it. But, as of year 2021, less than 50% of EU member states have met the target recycling rate [44]. Figure 15 shows as a percentage, the amount recycled or prepared for reuse out of the amount of solar photovoltaic panel waste collected in 12 EU member states in the years 2021 and 2022. It can be seen that Spain, Slovakia, Portugal, Germany, France, Belgium and Austria met the WEEE Directive target in 2021. It is to be noted that the reported recycling rate is above 100% when stored PV waste from previous years is recycled in the reporting year.

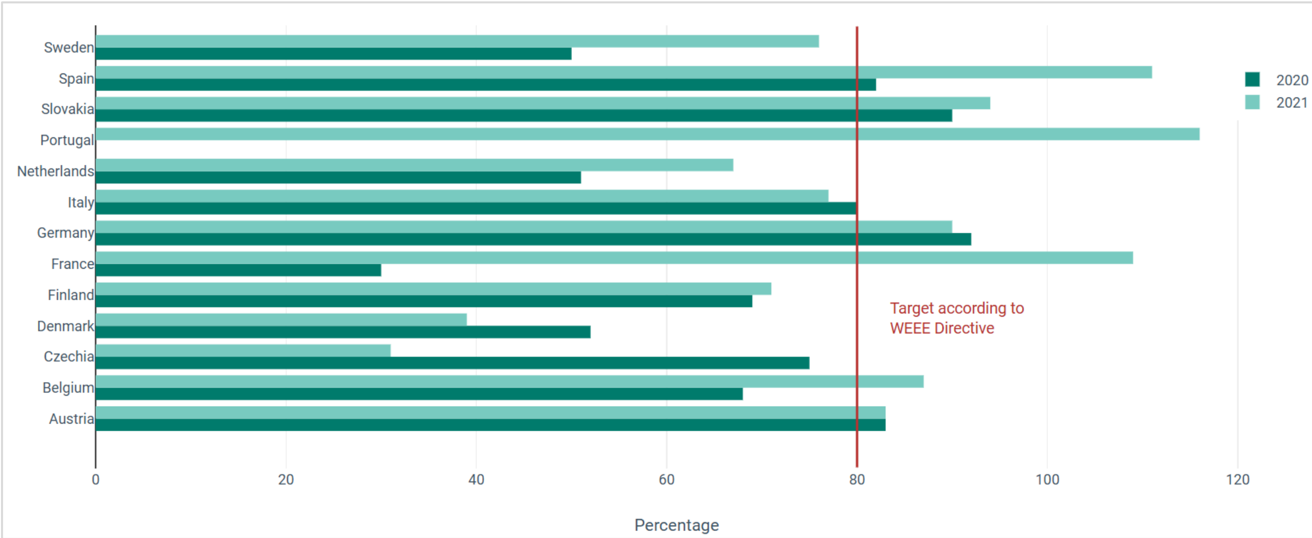

Figure 15: Percentage of photovoltaic (PV) panels waste recycled or prepared for reuse in 12 EU member states [44].

Recycling companies can easily separate the aluminum frame and external copper wires in PV modules for recycling. But since the PV cells are encapsulated in layers of ethylene vinyl acetate (EVA) plastic and bonded to the glass, additional processes are needed to recover the silver, copper or high-purity silicon in the silicon wafers. Another factor that can complicate end-of-life management of solar panels is hazardous metal content. For example, some end-of-life panels are considered hazardous waste under the U.S Federal Resource Conservation and Recovery Act (RCRA) due to lead, cadmium, selenium or silver content. Panels which haven't exceeded acceptable lead or silver levels, may exceed state copper or zinc limits under California standards.

Here is some information on technology specific toxic material content [45]:

- CDTe solar panels: some can be hazardous due to possible cadmium content.
- Gallium arsenide (GaAs) panels: some can be hazardous due to possible arsenic content
- Silicon solar panels: some may be hazardous waste if hexavalent chromium coatings are used.
- Thin-film CIS/CIGS solar panels: some may be hazardous due to possible copper and/or selenium content.

PV Packaging: Large cardboard boxes and wood crates are common packaging materials for solar panels [92]. Plastic pallets are also used for ease of handling and transportation. Foam inserts, bubble wraps, aircushions, plastic shrink wraps etc. are used in packaging, to prevent damage to the modules during handling and transportation. Strapping materials like polyester or steel straps are also used to secure modules to pallets or within packaging to prevent movement during transportation [94]. PV packaging is generally used one time and is then disposed of in landfills or is burned [95]. A key challenge in enabling end of life recycling of PV packaging is the use of mixed materials in packaging. For example, plastic straps with metal staples and wood with large metal pieces are hard to recycle due to difficulty of material separation. Metal brackets in wood pallets can damage woodchippers and complicate the recycling process [92]. Improving reusability and recyclability of PV packaging will reduce resource consumption and waste in the PV industry.

4.4. Chemicals of Concern

Silicon PV manufacturing uses a variety of hazardous chemicals including sulfuric acid, hydrogen fluoride, hydrochloric acid, nitric acid, 1,1,1-trichloroethane, and acetone. Thin film PV technology uses toxic materials including indium, gallium, arsenic, selenium, cadmium and tellurium [77]. Table 7 presents a list of materials used in PV industry which are classified as hazardous by the Department of Transportation (DOT) in the U.S.

Material	Source	DOT hazard classification	Critical effects
Arsenic	GaAs	Poison	Cancer, lung
Arsine	GaAs (CVD)	Highly toxic gas	Blood, kidney
Cadmium	CdTe, CdS, CdCl2	Poison	Cancer, kidney, bone
Diborane	a-Si dopant	Flammable gas	Pulmonary
Diethyl silane	a-Si deposition	Flammable liquid	
Diethyl zinc		Pyrophoric liquid	
Dimethyl zinc		Spontaneously combustible	
Hydrochloric acid	a-Si, GaAs, Cu2S/CdS	Corrosive material	
Hydrofluoric acid	a-Si	Corrosive material	
Hydrogen	a-Si	Flammable gas	Fire hazard
Hydrogen selenide	CIS	Highly toxic gas	Irritant
Hydrogen sulfide	CIS, Cu2S/CdS	Flammable gas	Irritant, Fire hazard
Indium	CIS, CIGS	Not regulated	Pulmonary, bone
Methane	GaAs	Flammable gas	Fire hazard
Molybdenum hexafluoride		Toxic and corrosive gas	
Oxygen	x-Si	Gaseous oxidizer	
Phosphine	a-Si dopant	Highly toxic and pyrophoric gas	Irritant, fire hazard
Phosphorus oxychloride	x-Si	Corrosive material	Irritant, kidney
Selenium	CIS, CZTS	Poison	Irritant
Silane	a-Si deposition	Pyrophoric gas	Irritant, fire, explosion hazard
Silicon tetrafluoride	a-Si deposition	Toxic and corrosive gas	
Tellurium	CdTe	Not regulated	Cyanosis, liver
Tertiarybutyl arsine		Pyrophoric and highly toxic liquid	
Tertiarybutyl phosphine		Pyrophoric liquid	
Trimethyl aluminum		Pyrophoric liquid	
Trimethyl gallium	GaAs	Pyrophoric liquid	
Tungsten hexafluoride		Toxic and corrosive gas	

Table 7: Hazardous chemicals used in PV module manufacturing [77].

There are concerns regarding lead leaching from solder joints in solar panels and the potential presence of per- and polyfluoroalkyl substances (PFAS) in module back sheets [46]. PFAS are a group of substances which are toxic, persistent and bio accumulative and can cause harm to human health and the environment. PFAS in solar panels are considered a waste problem. PFAS use in anti-reflective coatings (ARC) and anti-soil coatings (ASC) of solar panels and associated electrical equipment are of concern due to risk of landfill contamination from decommissioned panels [47]. They may go through degradation to produce microplastics or get absorbed on the surface of microplastics causing harm to aquatic species. Recent academic studies have pointed out the lack of consideration of emerging contaminants like PFAS and microplastics in PV waste regulations in the EU and the U.S [48]. Traditional PET-based material for solar panel outer layers is considered a safer PFAS-free alternative [49]. Recently, Boviet Solar, a prominent solar PV manufacturer confirmed that their PV modules are free from harmful PFAS chemicals by achieving the Per- and Polyfluoroalkyl Substances (PFAS)-free certification from TUV SUD, a testing and certification body [50].

It is recommended that material declarations for PV modules and inverters be done in accordance with IEC 62474 at the time the product is placed on the market [35].

4.5 Social Impacts

A priority social issue in the PV supply chain is allegations of the use of state imposed forced labor. It is reported that over 30% percent of global polysilicon and metallurgical-grade silicon production takes place in the Xinjiang autonomous region in China. However, China's polysilicon production share in the Xinjiang region is reported to be in decline, with production being shifted to Ningxia and Inner Mongolia. Transparency is pivotal to addressing forced labor risks for solar modules and cells. While traceability is reported to be increasingly achievable for polysilicon production, which is dominated by a small number of companies, Tongwei being the dominant player, metallurgical-grade silicon production lacks visibility into the supply chain. Some of the major polysilicon producers such as Daqo, Hoshine, East Hope and GCL are on the list of companies identified by the U.S. government as using forced labor involving Uyghurs and other ethnic minorities in China and therefore are subject to U.S. import restrictions under the Uyghur Forced Labour Prevention Act [51].

The mining of minerals from conflicted affected and high-risk areas has been associated with risks of contributing to significant human rights abuses [78]. Among conflict minerals identified in U.S. and European legal text, i.e., tin, tantalum, tungsten and gold (3TG); tin and tantalum are known to be used in different PV technologies [30].

5. Sustainability Impact Mitigation Strategies

This section discusses potential strategies for mitigating the aforementioned sustainability impacts associated with PV technologies. It is to be noted that strategies below can help in alleviating more than one impact category. For example, circularity strategies such as use of recycled content can not only reduce resource consumption but also result in avoiding climate impacts associated with extraction and use of virgin materials. Similarly, the reduction of toxic materials in products reduces chemical impacts and enables circularity.

5.1. Decarbonization

As discussed in Section 4.2, the carbon footprint of PV modules is dominated by upstream or embodied carbon related to its manufacturing. Therefore, the differences in PV supply chain emissions can have a significant influence on the carbon benefits of solar projects. GEC Low Carbon Solar State of Sustainability Research reports that the use of materials with lower embodied carbon and energy efficient manufacturing processes in PV modules can reduce the life cycle carbon footprint of solar systems by 40 percent. The report highlights that the reduction is primarily dependent on the carbon intensity of the electricity grid, powering the production process of where module components are produced [29].

In general, the decarbonization of the power sector is seen as a major approach to mitigate electricity demand for solar PV manufacturing and associated emissions. The IEA reports that Europe holds the highest potential in reducing energy related emissions in PV manufacturing due to the high shares of renewables and nuclear in the country's electricity grid mix. Countries in Latin America and sub-Saharan Africa which have significant hydropower in the electricity mix are also highlighted as potentially less carbon intensive PV manufacturing locations [6].

Some of the decarbonization strategies that PV manufacturers can employ at the facility level include using renewable energy sources in manufacturing facilities and improving energy efficiency in manufacturing processes to reduce energy consumption [52]. Using sustainable material inputs such as recycled steel, glass etc. can also reduce GHG equivalent emissions associated with raw material extraction and processing. Section 5.2 below details the potential of such material circularity measures to reduce production impacts.

A recent IEA report highlighted reductions in GHG emissions achieved through improvements in manufacturing and increase in module efficiencies, for certain PV technologies. The report showed that in the case of mono-Si, for which the average module efficiency increased from 14% to 20% from 2007 to 2023, the emissions decreased from 76 g CO2 eq/kWh to 36 g CO2 eq/kWh. The reduction in emissions is attributed to increases in efficiency and improvements in the manufacturing process of the studied residential rooftop mono-crystalline PV system in Switzerland [26].

Inverter Efficiency

Enabling improvements in inverter efficiency is also seen as a strategy for reducing PV system impacts. For example, the Joint Mission Group (JMP) of solar industry experts and researchers proposed setting minimum requirements for inverter euro efficiency (Tier 1 at 94% and Tier 2 at 96%) and measuring the same according to European Normative (EN) 50530, in their expert input paper on eco-design & energy labelling for PV modules, inverters and systems [35]. The California Energy Commission's Solar Equipment Lists Program publishes a list of equipment that meets established national safety and performance standards. The program also requires public reporting of PV inverter power and efficiency [53].

5.2 Circularity

As the PV module market matures, increasing numbers of modules will reach end-of-life annually. A PV module waste volume of 100 000 tons was estimated for the year 2020 and is forecasted to increase to 1.7 million tons by 2030 (Figure 16) [41].

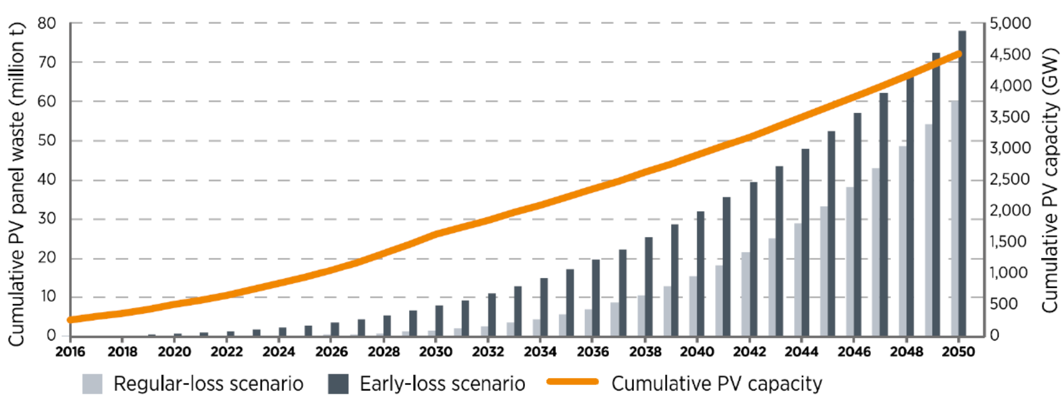

Figure 16: Estimated cumulative global waste volumes of EOL PV modules 2016 to 2050 [41].

A recent study forecasted the list of top five countries expected to generate the highest volumes of PV waste by 2050 (Figure 17). China is on top with a forecasted PV waste of 20 million tonnes, followed by the U.S (10 Mt), India (7.5 Mt), Japan (7.5 Mt) and Germany (4.3 Mt) [83].

Figure 17: The projected cumulative mass of PV waste (in million tonnes, Mt) in the top 5 countries in 2050 [83].

The IEA states that, if end-of-life PV panels were systematically collected and recycled, recovered materials could meet over 20% of the solar PV industry's demand for aluminum, copper, glass, silicon and almost 70% for silver by 2050 [6]. At present, physical, thermal and chemical recycling processes are being used for end-of-life PV panel recovery. The different recycling technologies used for silicon solar modules and thin-film solar module processing along with their advantages and disadvantages are presented in Table 8 and Table 9 [54].

Silicon solar module recycling processes.			
Technology	**Process**	**Advantages**	**Disadvantages**
Delamination	Physical disintegration	➢ Efficient waste handling	➢ Other materials mix with EVA. ➢ Solar cells damage. ➢ Apparatus decomposition.
	Thinner dissolution (Organic Chemistry)	➢ Organic layer removal from glass ➢ Waste chemical reuse ➢ Simple removal of EVA	➢ Time necessary for delamination depends on area. ➢ Expensive equipment. ➢ Hazardous for human health.
	Nitric acid dissolution	➢ Complete removal of EVA and metal layer from the wafer ➢ Possible recovery of the whole cell	➢ Dangerous emissions. ➢ Cell defects due to inorganic acid.
	Thermal treatment	➢ EVA fully eliminated. ➢ By reusing wafers, possible to regain whole cell	➢ Involves high energy consumption. ➢ Dangerous emissions
	Ultrasonic irradiation	➢ Used as a supplementary process to accelerate dissolution process ➢ Simplified removal of EVA.	➢ Very costly process. ➢ Waste solution treatment.
Material Separation	Dry and wet mechanical process	➢ Non-chemical process. ➢ Simple process. ➢ Requires low energy. ➢ Equipment available.	➢ No removal of dissolved solids
	Etching	➢ Simple and effective process. ➢ Recovery of high purity materials	➢ High energy demand because of high temperatures. ➢ Use of chemical.

Table 8: Summary of Si solar recycling process. EVA - ethylene vinyl acetate [54].

Thin film solar module recycling methods.			
Technology	**Process**	**Advantages**	**Disadvantages**
Delamination	Physical disintegration	➢ Feasible to obtain various wastes by treatment (Split modules, submodules and laminated modules).	➢ Mixing of the various material fractions. ➢ Loss from each material fraction. ➢ Glass still partly combined with the EVA. ➢ Breakage of solar cells.
	Thinner dissolution (Organic Chemistry)	➢ Organic layer removed from glass. ➢ Reprocessing solutions. ➢ Simple removal of EVA.	➢ Time necessary for delamination depends on area. ➢ Cannot be dissolved fully and EVA still adheres to glass surface.
	Thermal treatment	➢ Complete elimination of EVA. ➢ Possible to recover whole cell by reusing wafers.	➢ High energy consumption. ➢ Hazardous emissions.
	Radiotherapy	➢ Easy to eliminate EVA	➢ Slow procedure ➢ Very expensive process.
Material Separation	Erosion	➢ No chemicals required ➢ Glass can be recovered	➢ Additional treatment of pre-purification is necessary
	Vacuum blasting	➢ Removal of semiconductor layer without chemical dissolution. ➢ Glass can be recovered	➢ Emission of metallic fractions ➢ Relatively long processing time.
	Dry and wet mechanical process.	➢ Non-chemical process. ➢ Simple procedure. ➢ Needs low energy. ➢ Apparatus usually available.	➢ No removal of dissolved solids
	Tenside chemistry	➢ Tensides are reusable. ➢ Metals fully removed from glass.	➢ Emulsions must be adapted to different cell technologies ➢ Delamination time depends on the area.
	Leaching	➢ Complete elimination of metal from glass. ➢ Further extraction of metal solutions possible.	➢ Very high use of chemicals. ➢ Complicated control of the chemical reactions.
	Flotation	➢ Comparatively easy method. ➢ Limited use of chemicals	➢ Material separated at various stages of flotation ➢ Inadequate purity of materials.
	Etching	➢ Recovery of high purity materials. ➢ Low cost and effective process	➢ High energy demand because of high temperatures. ➢ Chemical usage.
Material purification	Hydrometallurgical	➢ Commercially applicable. ➢ Low and controllable emissions ➢ Easy water management	➢ Many separation and absorption steps. ➢ Chemical process steps must be adapted to respective technology.
	Pyrometallurgical	➢ Established industrial process. ➢ Feedstock can contain different materials	➢ High throughput necessary. ➢ Some materials are lost in slag. ➢ Heavy metals or unwanted materials

Table 9: Summary of thin film solar module recycling methods [54].

As per the IEA, the current low volumes of EOL PVs, lack of efficient recycling technologies, logistics challenges, and undeveloped markets for recovered materials result in a high-cost, low-revenue scenario of PV module recycling. However, there are examples of market leaders in this space. *First Solar*, a U.S based thin film PV manufacturing company has a high value PV recycling process which recovers 90% of materials from end-of-life modules. Table 10 shows First Solar's material specific recovery rates published in their EPEAT disclosure report [55]. The company *We Recycle Solar* is the largest recycler of solar panels in the U.S. The process they follow is to remove the aluminum frame and wiring, shred the panels and then do secondary chemical processing and electrolysis to separate the metals, silicon and glass for shipments to downstream processors [56]. *Solar Cycle*, another key player, has established technology to recycle or repurpose 95% of panels currently in use and to recover metals such as silver, silicon, copper and aluminum [57].

First Solar PV Module Recycling Material Recovery Achievements	
Glass	= 90 mass-%
Metals (not including semiconductor materials)	≥ 90 mass-%
Semiconductor Materials	≥ 90 mass-%

Table 10: First Solar's published material recovery rates [55].

Rosi Solar in France and *Reiling* in Germany are examples of industrial initiatives for high-value PV recycling in Europe. *Rosi Solar* uses pyrolysis for delamination and chemical processing to recover high purity glass, silicon, silver and other metals next to aluminum from the frames. Reiling applies mechanical delamination and sorting processes followed by wet chemical etching for the recovery of high-purity silicon. This initiative produces new passivated emitter rear contact (PERC) solar cells from recycled silicon [58].

In Europe, several projects have been launched recently to promote circularity in the PV sector. The EU-funded Horizon 2020 CABRISS[1] project, a joint initiative of 16 European companies and research institutes, is one of them. The goal of the project is the implementation of a circular economy based on recycled, reused and recovered indium, silicon and silver materials for photovoltaic and other applications [59]. The project helps to transform the legal obligations of

[1] CABRISS: CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other applications

the WEEE directive into new business opportunities. The EU funded PHOTORAMA[2] project is another initiative implemented by a consortium of 12 organizations to improve PV panel recycling and recovery of raw materials [60]. The ReProSolar project, led by *Veolia Germany* and composed of tech startups, specialty chemical companies and research institutions, aims at developing an industrial process for recycling silicon-based PV modules to revalorize precious raw materials, copper, aluminum, silver, silicon, and glass [61]. Another project focused on resource efficiency is CIRCUSOL[3] which aims to explore a third-party ownership Product-Service System (PSS) business model for the PV sector [62].

The potential for environmental impact reduction through the use of recycled materials in manufacturing has been demonstrated by some PV manufacturers. For example, Origami Solar showed that by using a recycled steel frame instead of a standard aluminum frame in modules they can reduce environmental impact per frame by over 90% [80]. Figure 18 shows a comparison of carbon footprint of module frames made of aluminum with frames made from steel recycled in Europe and the USA. Frames using recycled steel is shown to have a significantly lower GHG footprint. Using recycled aluminum components can also reduce the carbon footprint of PV manufacturing since the aluminum recycling process requires only about 5% of the energy needed to produce primary aluminum from bauxite ore [79]. In another effort to build a circular economy for solar PVs, the U.S. based recycling company *SolarCycle* is building a facility to manufacture specialized crystalline-silicon (c-Si) solar glass using recycled materials from retired solar panels. The recycling technology is estimated to retrieve 95% of the value from retired solar panels and the solar glass is planned to be sold to the domestic solar

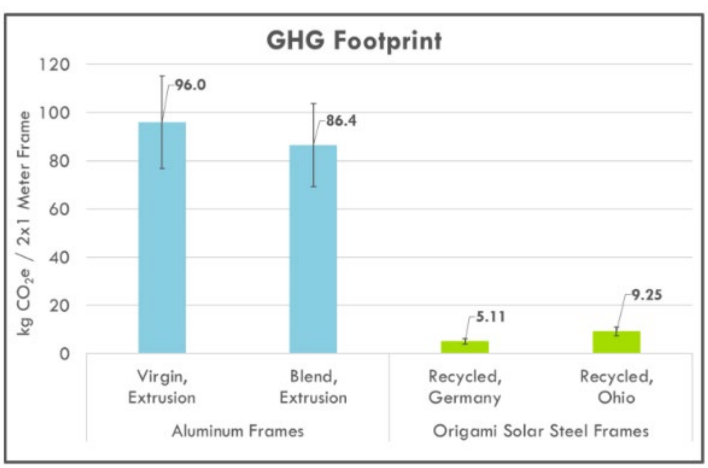

Figure 18: Comparison of module frame carbon footprint for virgin material and recycled material [80].

[2] PHOTORAMA: PHOtovoltaic waste management – advanced Technologies for recOvery & recycling of secondary RAw MAterials from end-of-life modules

[3] CIRCUSOL: Circular Business Models for the Solar Power Industry

manufacturers in the U.S. as part of building a U.S. solar panel recycling ecosystem [82]. The North American solar panel manufacturers, *Heliene* and *QCells* have already entered into partnership with *SolarCycle* to incorporate the companys' ultra-low carbon glass made of recycled materials into new panels [81].

Circularity measures have been proposed to reduce the impacts associated with PV inverters as well. These include (1) improving inverter design to allow easy access to and replacement of spare parts, (2) ensuring availability of inverter spare parts and software needed for product functioning for extended periods of time and (3) providing repair and maintenance information to repairers [35].

<u>PV Packaging</u>

Strategies for enabling circularity of PV packaging materials include avoiding mixed materials packaging and improving reusability and recyclability of packaging. Plastic straps with the same resin bands and wood with minimal metal are more recyclable. For example, using glue in wood pallets instead of metal brackets can reduce the complications in shredding and improve recyclability [92]. Reusable packaging is also becoming popular in solar industry as a measure to reduce PV packaging waste. 'PV Pallet' is a new packaging innovation launched in the PV sector which is advertised as the first recyclable, reusable, adjustable, and collapsible pallet. PV pallets are reusable pallet systems, made of post-consumer HDPE plastic. A recent study showed that the carbon footprint of a wood pallet system is almost ten times higher than for a PV pallet system when used for 20 cycles [93].

5.3. Responsible Supply Chains

Supply chain mapping and traceability are key in identifying solar modules and cell suppliers engaging in forced labor and avoiding such risks. Protocols have been developed by several organizations to improve traceability and avoid social risks throughout the solar supply chain.

The Solar Energy Industries Association (SEIA) launched the Solar Industry Commitment to Environmental & Social Responsibility ("Solar Commitment") in 2013, which is an industry code of conduct that defines common practices and expectations for environmental, ethical, labor, health & safety, and management systems in the solar industry. The SEIA later developed the Solar Supply Chain Traceability Protocol which is a set of recommended policies and procedures designed to identify the source of a product's material inputs and to trace the movement of these inputs throughout the supply chain. The protocol also incorporates third-party audits for measuring the traceability policy implementation of companies [63].

The Responsible Business Alliance's (RBA) Code of Conduct defines a set of social, environmental and ethical industry performance standards and the Validated Assessment Program (VAP) provides a comprehensive framework for independent third-party verification of on-site compliance. Together and in conjunction with other RBA on-line tools, these programs provide a framework for reducing operational risk by mapping supply chain trading relationships, establishing supplier and facility performance standards, assessing compliance and remediating non-conformance.

Solar Power Europe and Solar Energy UK came together to create the Solar Stewardship Initiative (SSI) which was designed to set out a clear set of expectations on ESG practices and supply chain transparency. The SSI Certification program evaluates companies against two Standards, the SSI ESG Standard and the SSI Supply Chain Traceability Standard, which was published in December 2024 after public consultation. The SSI Supply Chain Traceability Standard defines a 'segregated' chain of custody model for specific silicon supply chain tiers and requires a traceability system able to demonstrate a chain of entities to supply the material. The SSI requires manufacturer members to complete an assessment for at least two of their sites against the SSI Supply Chain Traceability Standard within 12 months of joining the SSI [64].

The OECD's *Five-Step Framework for Risk-Based Due Diligence in the Mineral Supply Chain* provides internationally recognized best practices for reducing risks of contributing to significant human rights abuses and conflict. Currently identified programs that align with the OECD's *Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas* include the Responsible Minerals Initiative (RMI),[4] and London Bullion Market Association (LBMA).[5,6]

Chain of Custody (CoC) standards also exist for additional raw materials used in PV manufacturing. IRMA (Initiative for Responsible Mining Assurance) Chain of Custody Standard for Responsibly Mined Materials (IRMA), the Aluminium Stewardship Initiative (ASI) and the

[4] https://www.responsiblemineralsinitiative.org/

[5] https://www.lbma.org.uk/prices-and-data/london-vault-holdings-data

[6] OECD assessed programs: http://mneguidelines.oecd.org/industry-initiatives-alignment-assessment-minerals.htm

Copper Mark chain of custody standards are some examples [51]. CoC is a documented sequence of physical and legal possession of material as it moves through a supply chain [64]. Since market share of such certified materials is low, the PV supply chain uses a mix of certified and non-certified materials. Therefore, it is difficult to track down the raw material origins, making the reach of these traceability schemes in PV supply chains very low [51].

6. Regulatory Developments and Standards

6.1 Responsible Reuse and Recovery Standards

As more solar panels started to enter the end-of-life stream, concerns regarding their management started to emerge. SERI, along with the photovoltaic industry, has taken a leadership role in developing standards for reuse and recycling of PV modules. The goal is to provide clear guidelines and requirements for e-waste companies looking to handle the material thereby avoiding potential mismanagement by certified facilities. In 2024, PV modules were added to the R2 Certification Standard through the addition of a PV module definition and updating of the "Focus Materials" definition to include solar cells. A new Appendix G was also added, and the R2 Equipment Categorization (REC) was updated to include a new table for PV Modules and two new categories of functioning PV Modules for reuse [65]. Solar panel recyclers can now achieve a specific SERI certification, under the newly added Appendix G for photovoltaic modules [66].

The EU introduced several standards with technical specifications for the handling of PV waste in the last decade; EN 50625-1 regulates WEEE treatment and emphasizes special care to avoid injury while handling PV broken glass, EN 50625-2-4 regulates specific treatment requirements for EOL modules and DIN CLC/TS 50625-3-5 includes technical specifications for PV module de-pollution [48].

The Basel Action Network's e-Stewards Standard for Ethical and Responsible Reuse, Recycling, and Disposition of Electronic Equipment and Information Technology includes requirements that ensure photovoltaic modules destined for reuse can produce power output that is at least 50% of original output [67].

6.2 PV Circularity Regulations

The EU has been a forerunner in implementing PV-specific waste regulations by including mandatory recycling of solar panels under the Waste Electrical and Electronic Equipment (WEEE) Directive. The WEEE Directive applies the EPR (extended producer responsibility) principle which requires the PV producers to finance the costs of collecting and recycling end-of-life PV modules put on the market in Europe. The EU has also formed the PV Cycle organization which provides collective waste management and legal compliance services for handling end-of-life PV panels. Every country in the EU has a national WEEE register which makes the reporting of installed PV modules and the collection and recycling plans for decommissioned PV modules an obligation.

The European Climate, Infrastructure and Environment Executive Agency (CINEA) is also working on the development of recyclability indexes for photovoltaic (PV) modules and inverters and has commissioned a study for the same. The project involves the identification of priority parts based on material relevance and recyclability, the determination of key parameters for recycling, the establishment of scoring criteria, and definition of recyclability score classes for PV products [68].

In the U.S, there is no federal level regulation to address PV system decommissioning or repair/reuse/recycling of PV system equipment. Washington, New Jersey, North Carolina, and California are the only U.S. states with laws and/or regulations that directly address PV system equipment. For example, the state of Washington has a Photovoltaic Module Stewardship and Takeback Program while New Jersey has established a Solar Panel Recycling Commission. Figure 19 presents state level PV management policies in the U.S. as of February 2021 [69].

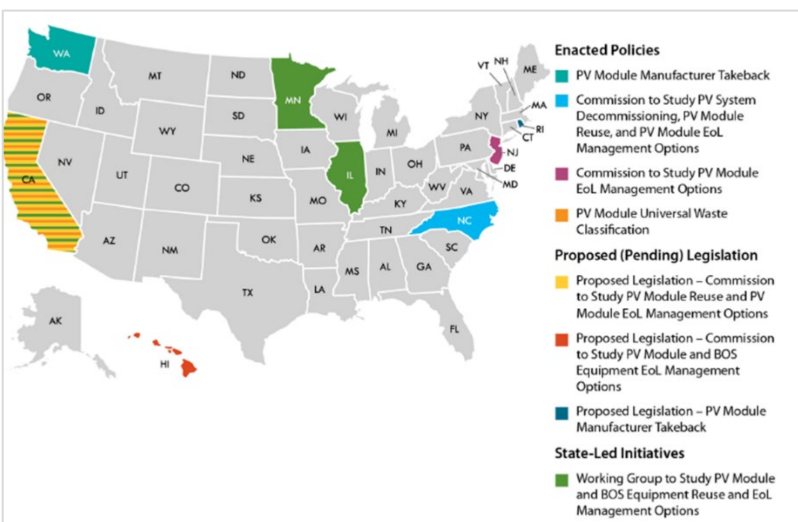

Figure 19: State PV system decommissioning, and PV equipment reuse and EoL management policies in the U.S [69].

There are no PV-specific waste regulations in China. However, the country has a sponsored program called the National High-tech Research & Development Programme for PV Recycling and Safety Disposal Research. In Japan, end-of-life PV panels are covered under the general regulatory framework for waste management (the Waste Management and Public Cleansing Act). The framework defines industrial waste generator and handler responsibilities and waste management requirements including landfill disposal in the country. In India, end-of-life solar PV is handled by the Ministry of Environment, Forest and Climate Change under the 2016 Solid Waste Management Rules and the Hazardous and Other Wastes [70].

6.3 Decarbonization through procurement

In recent years, there have been several efforts to address sustainability considerations in solar PV through procurement. The French government, a pioneer in carbon footprint regulations for the photovoltaic industry has issued ECS - Evaluation carbone simplifiée, a highly authoritative carbon footprint–related certification. The certification issued by French Energy Regulatory Commission (CRE) is required for photovoltaic products with a capacity of 100KW or above that enter the French market [71]. France and South Korea are the only two countries with carbon footprint criteria in their public tendering of PV modules. The CRE has set a maximum threshold of 550 kgCO2eq/kW for PV modules (without frame) in the ground and in buildings, and 500 kgCO2eq/kW for innovative PV technologies for the period 2021–2026 [72]. In South Korea, where the calculation of carbon footprint (CFP) is used to classify PV modules to 3 grades, the rating I corresponds to a CFP below or equal to 670 kgCO2eq/kW, which is considered to be less stringent than the French rating [31].

The European Commission's Ecodesign directive 2009/125/EC is also aiming to set a carbon footprint threshold as a minimum qualification for the European market thereby cutting out the least sustainable PV modules. However, the guidelines for carbon footprint calculation methodology are still under development [33]. GEC's Ultra Low Carbon Solar (ULCS) Criteria which is used within EPEAT provides a consensus-based definition of low-embodied carbon to aid in identifying and procuring low embodied carbon PV modules [36]. GEC awards 'Low Carbon Solar' designation to manufacturers demonstrating that the embodied carbon of their PV module, including the frame, is equal to or less than 630 kg CO2e / kWp and 'Ultra Low Carbon Solar' designation to PV modules with embodied carbon equal to or less than 400 kg CO2e / kWp [36]. To expand the number of EPEAT registered products in the solar market, the U.S federal government recently announced a $2.7 million prize for U.S.-based PV manufacturing organizations who meets sustainability regulations by registering with EPEAT [73].

6.4 Safety and Reliability Standards

Standards which include requirements for safe electrical and mechanical operation of PV modules have also been developed to ensure PV module reliability. The International Electrotechnical Commission (IEC) has established standards such as IEC 61730-1 and IEC 61730-2 which lists the tests a PV module is required to fulfil for safety qualification [74]. The Underwriters Laboratories (UL) 1703 Safety Standard for Flat-Plate Photovoltaic Modules and Panels confirms that solar modules with 'UL listed' certification mark have met safety and performance standards. The UL certification involves tests to check the solar panel's resilience to harsh climatic conditions and avoid mechanical, electrical, or fire hazards [75]. The UL 1703 standard was harmonized to the International Safety Standard for PV modules IEC 61730-1 and IEC 61730-2, resulting in the publication of more stringent UL 61730-1 and UL 61730-2 standards in 2017 [76]. PV modules installed must conform with the UL Standards in the U.S. Such standards ensure that manufacturers produce high-quality PV modules warranted for 20 years or more [75].

7. Summary of Recommended Criteria Updates

As identified in this *State of Sustainability Research*, leading mitigation strategies for addressing priority impacts are illustrated in Figure 20.

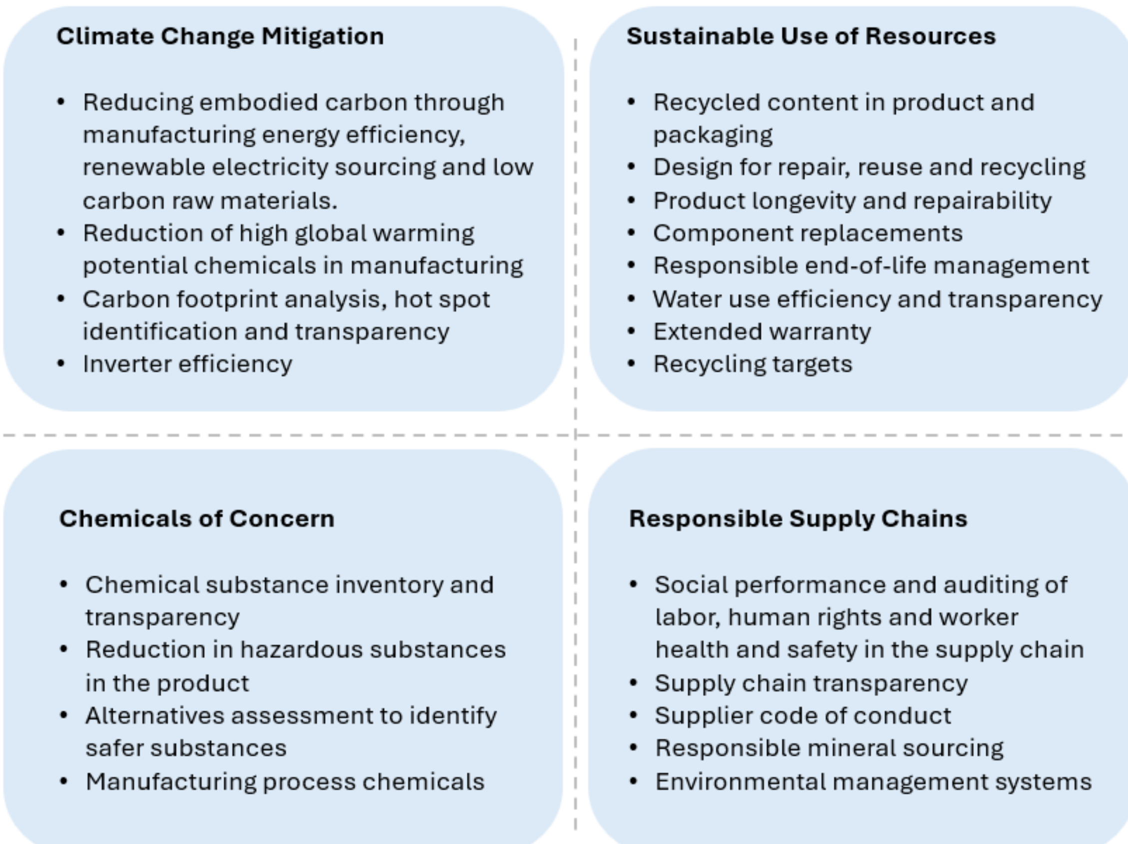

Figure 20: Impact mitigation strategies for PV systems.

Appendix A, Tables A1 and A2, identifies the current EPEAT Criteria for the PVMI product category that are published in NSF/ANSI 457-2019 (r2024*), Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters* and EPEAT-ULCS-2023, Criteria for the Assessment of Ultra-Low Carbon Solar *Modules*.

These criteria are designed to address priority sustainability impacts throughout the life cycle of PVMI products, inclusive of the supply chain. An analysis of the current EPEAT Criteria finds that many of the criteria remain relevant and reflective of industry leadership. Identified opportunities for continuous improvement, however, include consideration of new internationally recognized best practices for responsible end-of-life management and social supply chain due diligence. In addition, there are references to standard methods and programs that should be updated.

Based on an analysis of current EPEAT PVMI Criteria, the aforementioned impact mitigation strategies and advancements in and current uptake of best practices, GEC proposes to focus the revision of the EPEAT PVMI Criteria in 3 areas:

1) Low carbon emissions - Since the publication of the initial NSF-457, EPEAT added the Ultra Low Carbon Solar criteria to help purchasers identify solar panels with lower embodied carbon. As part of this revision, GEC intends to work with stakeholders to evaluate if there is redundancy and opportunity for consolidation and simplification of criteria in NSF 457. GEC will also propose consideration of the inclusion of a separate criterion for use of credible and verifiable renewable electricity in manufacturing operations, as a recognized best practice for reducing upstream GHG emissions.
2) Responsible end-of-life – GEC proposes to update the existing criteria to reflect the latest internationally recognized best practices. These include references for responsible EOL standards and safer alternatives methodologies. For example, since publication of NSF-457, SERI R2 and EN standards for responsible end-of-life management of PV modules have been published. Additionally, OHSAS 18001 is now an outdated reference, having been superseded by ISO 45001.
3) Chemicals of concern – GEC proposes to retain the existing criteria in NSF-457.
4) Responsible supply chains – GEC proposes to adopt newer versions of criteria for social supply chain due diligence, recognizing increased expectations for supply chain mapping and traceability as some stakeholders perceive these to be potentially the only effective manner for addressing deep embedded risks. Potential opportunities for continuous improvement include more robust requirements for confirming prohibition of forced labor, documented assessment of supply chain risks, social audits, inclusion of evolutions in best practices for responsible mineral sourcing due diligence and avoiding or disengaging from regions where due diligence in accordance with the *United Nations Guiding Principles on Business and Human Rights* is not possible.

Appendix A. Criteria

Table A1. Summary of existing PVMI Criteria (NSF 457) organized based on impact modules.

Existing Criteria and section		Required or optional	PV modules points	PV inverters points
Climate Change Mitigation				
7	Life cycle assessment (LCA)			
7.1	**PV module LCA**			
7.1.1	Required – Conducting LCA	Required	R	R
7.1.2	Optional – Public disclosure of LCA results	Optional	1	1
7.1.3	Optional – Public disclosure of LCI inventory data	Optional	2	2
7.2	**Reduction in LCA impacts**			
7.2.1	Optional – Environmental hot spot identification	Optional	1	1
7.2.2	Optional – Environmental leadership compared to industry average (applicable to PV modules	Optional PV modules only	2	—
8	**Energy efficiency and water use**			
8.1	Energy efficiency and management system			
8.1.1	Optional – Energy management system for manufacturing facilities	Optional	2	2
8.1.2	Optional – Certified energy management system	Optional	2	2
8.1.3	Optional – Certified energy management performance improvement	Optional	2	2
8.1.4	Required – Weighted efficiency reporting (applicable onlyto PV inverters)	Required (PV inverters only)	R	R
8.1.5	Required – Tare loss reporting (applicable only to PVinverters)	Required (PV inverters only)	R	R
	ULCS			
4.1	Required – Low Carbon Solar		R	
4.2	Optional – Ultra Low Carbon Solar		4	
4.3	Optional – Publicly Available LCI Data in IEA PVPS Task 12 Format		1	

Sustainable Use of Resources				
6	Preferable materials use			
6.1	**Recycled content**			
6.1.1	Required – Declaration of recycled content in product	Required	R	R
6.1.2	Optional – Recycled content in product	Optional	4	4
8.2	**Water use metrics**			
8.2.1	Required – Water inventory	Required	R	R
8.2.2	Optional – Quality of wastewater discharges	Optional	1	1
8.2.3	Optional – Improved water use efficiency	Optional	2	2
9	**End of life management and design for recycling**			
9.1	End-of-life (EOL) management			
9.1.1	Required – Product take-back service and processingrequirements (corporate)	Required	R	R
9.1.2	Optional – Publicly available record of annual recycling andrecovery achievement (corporate)	Optional	1	1
9.1.3	Optional – Material recovery targets (corporate)	Optional	2	2
9.2	Design for recycling			
9.2.1	Optional – Identification of materials for EOL management (only applicable to PV modules)	Optional (PV modules only)	1	—
9.2.2	Optional – Replacement components availability (applicable only to PV inverters)	Optional (PV inverters only)	—	2
10	**Product packaging**			
10.2	Recyclability of packaging			
10.2.1	Required – Enhancing recyclability of packaging materials	Required	R	R
10.3	Recycled content in packaging			
10.3.1	Optional – Recycled content paper-based packaging	Optional	1	1
10.3.2	Optional – Postconsumer recycled content plastic in packaging	Optional	1	1

Chemicals of Concern				
5.1	**List and assessment of substances**			
5.1.1	Required – List of declarable substances in product	Required	R	R
5.1.2	Required – List of declarable substances used in manufacturing	Required	R	R
5.1.3	Optional – Disclosure of declarable substances	Optional	1	1
5.1.4	Optional – Database of substances in product	Optional	2	2
5.1.5	Optional – Alternatives assessment	Optional	2	2
5.1.6	Optional – Making alternatives assessment publicly available	Optional	1	1
5.2	**Reduction of substances of concern (SVHC)**			
5.2.1	Required – Disclosure of substances on the European Union REACH Regulation Candidate List of Substances of Very High Concern (SVHC)	Required	R	R
5.2.2	Optional – Presence of substances on the European Union REACH Regulation Candidate List of Substances of Very High Concern (SVHC)	Optional	1	1
5.2.3	Optional – Bromine, chlorine, and fluorine content inelectric cables	Optional	1	1
5.2.4	Optional –- Bromine, chlorine, and fluorine content inplastic parts other than electric cables	Optional	1	1
5.2.5	Required – Avoidance or reduction of high global warmingpotential (GWP) gas emissions	Required	R	R
5.2.6	Required – Conformance with provisions of European Union RoHS Directive (applicable only to PV inverters)	Required (PV inverters only)	R	R
10.1	**Eliminate substances of concern**			
10.1.1	Required – Elimination of substances of concern in product packaging	Required	R	R
10.1.2	Required – Elimination of chlorine in processing packaging materials	Required	R	R

Responsible Supply Chains				
11.1	**Environmental, health, and safety management systems**			
11.1.1	Required – Environmental management system (EMS) certification	Required	R	R
11.1.2	Required – Manufacturer conformance with occupational health and safety performance (corporate)	Required	R	R
11.2	**Corporate reporting**			
11.2.1	Required – Reporting on key performance indicators (corporate)	Required	R	R
11.2.2	Optional – Reporting additional key performance indicators (corporate)	Optional	2	2
11.2.3	Optional – Reporting on screening of Tier 1 suppliers (corporate)	Optional	2	2
11.3	**Corporate social performance**			
11.3.1	Required – Commitment to environmental and socialresponsibility (corporate)	Required	R	R
11.3.2	Optional – Auditing or certification to social responsibilityperformance standard (corporate)	Optional	2	2
11.4	**Conflict mineral sourcing**			
11.4.1	Required – Public disclosure of use of conflict minerals in products (corporate)	Required	R	R
11.4.2	Optional – Conflict mineral sourced only from validated conflict free smelters (corporate)	Optional	1	1
11.4.3	Optional – Participation in in-region conflict-free sourcing program (corporate)	Optional	1	1

Table A2. Summary of Ultra Low Carbon Solar (ULCS) Criteria [75]

4.0	**ULCS Criteria**	**PV modules points**
4.1	Required – Low Carbon Solar; The embodied carbon of the PV module, including the frame18, shall be equal to or less than 630 kg CO2e / kWp	R
4.2	Optional – Ultra Low Carbon Solar; The embodied carbon of the PV module, including the frame, shall be equal to or less than 400 kg CO2e / kWp.	4
4.3	Optional – Primary life cycle inventory data underlying alternative GWPij coefficients shall be publicly available in the IEA PVPS Task 12 Life Cycle Inventory format.	1

References

[1] "Solar PV," iea.org. Accessed: Feb. 27, 2025. [Online]. Available: https://www.iea.org/energy-system/renewables/solar-pv

[2] D. Feldman *et al.*, "Spring 2024 Solar Industry Update," National Renewable Energy Laboratory, NREL/PR--7A40-90042, 2376145, MainId:91820, May 2024. doi: 10.2172/2376145.

[3] "Renewables 2024. Analysis and forecast to 2030," International Energy Agency, 2024. Accessed: Feb. 28, 2025. [Online]. Available: https://www.smartenergydecisions.com/upload/research_+_reports/renewables2024_iea.pdf

[4] E. Gervais, S. Herceg, S. Nold, and K.-A. Weiß, "Sustainability strategies for PV: framework, status and needs," *EPJ Photovolt.*, vol. 12, p. 5, 2021, doi: 10.1051/epjpv/2021005.

[5] "Solar PV Panels Market Size, Share & Trends Report, 2030," Grand View Research. Accessed: Feb. 27, 2025. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/solar-panels-market

[6] International Energy Agency, "Special Report on Solar PV Global Supply Chains," International Energy Agency, 2022. doi: 10.1787/9e8b0121-en.

[7] N. Dodd and N. Espinosa, "Solar photovoltaic modules, inverters and systems: options and feasibility of EU Ecolabel and Green Public Procurement criteria," European Commission, Joint Research Centre, 2018. [Online]. Available: https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/contentype/product_group_documents/1581689975/190410_PV_Prep_study_Ecolabel_and_GPP_Preliminary_Consultation_Draft.pdf

[8] "Solar Photovoltaic Technology Basics," NREL. Accessed: Feb. 27, 2025. [Online]. Available: https://www2.nrel.gov/research/re-photovoltaics

[9] "Exploring Third-Generation Photovoltaic Cells," Solar Panels Network USA. Accessed: Mar. 02, 2025. [Online]. Available: https://us.solarpanelsnetwork.com/blog/third-generation-photovoltaic-cells/

[10] "Organic Photovoltaics Research," U.S. Department of Energy. Accessed: Feb. 27, 2025. [Online]. Available: https://www.energy.gov/eere/solar/organic-photovoltaics-research

[11] A. S. Mahdi, L. M. Shaker, and A. Alamiery, "Recent advances in organic solar cells: materials, design, and performance," *J Opt*, vol. 53, no. 2, pp. 1403–1419, Apr. 2024, doi: 10.1007/s12596-023-01262-2.

[12] J. Vickerman, "Organic solar cells: Benefits, limitations & opportunities," RatedPower. Accessed: Mar. 02, 2025. [Online]. Available: https://ratedpower.com/blog/organic-solar-cells/

[13] O. López-Rojas and J. G. Guzmán, "A review on quantum dot solar cells: properties, materials, synthesis and devices," in *2019 IEEE International Conference on Engineering Veracruz (ICEV)*, Oct. 2019, pp. 1–5. doi: 10.1109/ICEV.2019.8920641.

[14] "Perovskite Solar Cells: What You Need To Know," EnergySage. Accessed: Feb. 28, 2025. [Online]. Available: https://www.energysage.com/solar/solar-photovoltaic-cells/perovskite-solar-cells/

[15] R. He *et al.*, "Wide-bandgap organic–inorganic hybrid and all-inorganic perovskite solar cells and their application in all-perovskite tandem solar cells," *Energy Environ. Sci.*, vol. 14, no. 11, pp. 5723–5759, 2021, doi: 10.1039/D1EE01562A.

[16] "Oxford PV ships first commercial perovskite tandem modules," PVTech. Accessed: Feb. 28, 2025. [Online]. Available: https://www.pv-tech.org/oxford-pv-ships-first-commercial-perovskite-tandem-modules/

[17] "IEA-PVPS-T12-29-2024-REPORT-Floating-PV-Carbon-Footprint2.pdf," International Energy Agency, 2024. Accessed: Feb. 28, 2025. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2024/07/IEA-PVPS-T12-29-2024-REPORT-Floating-PV-Carbon-Footprint2.pdf

[18] R. I. Woolway, G. Zhao, S. M. G. Rocha, S. J. Thackeray, and A. Armstrong, "Decarbonization potential of floating solar photovoltaics on lakes worldwide," *Nat Water*, vol. 2, no. 6, pp. 566–576, Jun. 2024, doi: 10.1038/s44221-024-00251-4.

[19] G. Kakoulaki *et al.*, "Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe," *Renewable and Sustainable Energy Reviews*, vol. 171, p. 112989, Jan. 2023, doi: 10.1016/j.rser.2022.112989.

[20] "BIPV - PV with Architectural Significance," Architectural Solar Association. Accessed: Feb. 28, 2025. [Online]. Available: https://www.archsolar.org/what-is-bipv

[21] "Summary: Challenges and Opportunities for Building-Integrated Photovoltaics RFI," Department of Energy. Accessed: Feb. 28, 2025. [Online]. Available: https://www.energy.gov/eere/solar/summary-challenges-and-opportunities-building-integrated-photovoltaics-rfi

[22] "What Is BIPV?," Just Solar. Accessed: Mar. 02, 2025. [Online]. Available: https://www.justsolar.com/blog/photovoltaic-bipv-architecture

[23] "A Guide to Solar Inverters: How They Work & How to Choose Them," Solar Magazine. Accessed: Feb. 28, 2025. [Online]. Available: https://solarmagazine.com/solar-inverters/

[24] A. Lafitte *et al.*, "Existing evidence on the effects of photovoltaic panels on biodiversity: a systematic map with critical appraisal of study validity," *Environmental Evidence*, vol. 12, no. 1, p. 25, Nov. 2023, doi: 10.1186/s13750-023-00318-x.

[25] "IEA-PVPS releases fact sheet on environmental life cycle assessment of PV Systems," PV Magazine International. Accessed: Feb. 28, 2025. [Online]. Available: https://www.pv-magazine.com/2024/06/27/iea-pvps-releases-fact-sheet-on-environmental-life-cycle-assessment-of-pv-systems/

[26] M. Stucki, M. Götz, M. de Wild-Scholten, and R. Frischknecht, "PVPS Task 12 Fact Sheet Environmental Life Cycle Assessment of Electricity from PV Systems," International Energy Agency, 2023. Accessed: Feb. 28, 2025. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2024/05/Task-12-Fact-Sheet-v2-1.pdf

[27] "What is the energy payback time for solar systems?," SinoVoltaics. Accessed: Feb. 28, 2025. [Online]. Available: https://sinovoltaics.com/learning-center/solar-panels/energy-payback-time-for-solar-systems/

[28] "PV FAQs : What is the energy payback for PV?," U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Jan. 2004. Accessed: Feb. 28, 2025. [Online]. Available: https://www.nrel.gov/docs/fy04osti/35489.pdf

[29] "Low Carbon Solar State of Sustainability Research," Global Electronics Council (GEC), Jul. 2021. [Online]. Available: https://globalelectronicscouncil.org/resources/state-of-sustainability-research/state-of-sustainability-research-for-low-carbon-solar/

[30] N. Dodd and N. Espinosa, "Solar photovoltaic modules inverters and systems: options and feasibility of EU Ecolabel and Green Public Procurement criteria," European Commission. Joint Research Centre., LU, 2021. Accessed: Mar. 02, 2025. [Online]. Available: https://data.europa.eu/doi/10.2760/29743

[31] D. Polverini, N. Espinosa, U. Eynard, E. Leccisi, F. Ardente, and F. Mathieux, "Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive," *Solar Energy*, vol. 257, pp. 1–9, 2023, doi: 10.1016/j.solener.2023.04.001.

[32] "Product Category Rules EN 15804 NPCR 029 version 1.1," The Norwegian EPD Foundation. Accessed: Feb. 28, 2025. [Online]. Available: https://www.epd-norge.no/getfile.php/1315101-1601554095/PCRer/NPCR%20029%202020%20Part%20B%20for%20photovoltaic%20modules%201.1%20011020.pdf

[33] A. A. Khan *et al.*, "The European Union's Ecodesign Directive – Analysis of Carbon Footprint Assessment Methodology and Implications for Photovoltaic Module Manufacturers," *Solar RRL*, vol. 8, no. 10, p. 2301011, 2024, doi: 10.1002/solr.202301011.

[34] "Differences Between The kW & kWhr of Your Home Solar System," Green Power Energy. Accessed: Feb. 28, 2025. [Online]. Available: https://greenpowerenergy.com/the-kw-and-kwhr-of-your-home-solar-system-explained/

[35] "Expert Input Paper - Ecodesign & Energy Labelling for Photovoltaic Modules, Inverters and Systems in the EU," European Technology & Innovation Platform, 2021. [Online]. Available: https://www.pvthin.org/wp-content/uploads/2021-02-ETIP-PV-Report-expert-input-paper.pdf

[36] "Criteria for the Assessment of Ultra-Low Carbon Solar Modules," Global Electronics Council (GEC), Mar. 2023. Accessed: Feb. 28, 2025. [Online]. Available: https://globalelectronicscouncil.org/wp-content/uploads/EPEAT_ULCS_2023.pdf

[37] "Mineral requirements for clean energy transitions – The Role of Critical Minerals in Clean Energy Transitions," IEA. Accessed: Feb. 28, 2025. [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions

[38] "Human Rights in the Mineral Supply Chains of Solar Panels - Business & Human Rights Resource Centre," Business & Human Rights Resource Centre. Accessed: Feb. 28, 2025. [Online]. Available: https://www.business-humanrights.org/en/from-us/briefings/transition-minerals-sector-case-studies/human-rights-in-the-mineral-supply-chains-of-solar-panels/

[39] B. Al Zaabi and A. Ghosh, "Managing photovoltaic Waste: Sustainable solutions and global challenges," *Solar Energy*, vol. 283, p. 112985, Nov. 2024, doi: 10.1016/j.solener.2024.112985.

[40] C. P. Baldé *et al.*, "THE GLOBAL E-WASTE MONITOR 2024," International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR)., 2024.

[41] K. Komoto *et al.*, "Task 12 PV Sustainability - Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries," International Energy Agency, NREL/TP--6A20-83074, 2308819, MainId:83847, 2022. doi: 10.2172/2308819.

[42] J. Paben, Jared, "Solar panels are 'the new CRT' but sector is preparing," EScrap News. Accessed: Feb. 28, 2025. [Online]. Available: https://resource-recycling.com/e-scrap/2021/05/13/solar-panels-are-the-new-crt-but-sector-is-preparing/

[43] T. Curtis, H. Buchanan, G. Heath, L. Smith, and S. Shaw, "Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives," NREL/TP-6A20-74124, 1774839, MainId:6273, 2021. doi: 10.2172/1774839.

[44] "Recycling materials from green energy technologies (Signal)." Accessed: Feb. 28, 2025. [Online]. Available: https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/recycling-from-green-technology

[45] "End of Life Management of Photovoltaic Systems," SCDHEC South Carolina Department of Health and Environmental Control. Accessed: Feb. 28, 2025. [Online]. Available: https://scdhec.gov/sites/default/files/Library/OR-1695.pdf

[46] "Busting myths around solar PV toxicity," PV Tech. Accessed: Feb. 28, 2025. [Online]. Available: https://www.pv-tech.org/busting-myths-around-solar-pv-toxicity/

[47] "Per- And Polyfluoroalkyl Substances (PFAS)," NYS Department of Environmental Conservation. Accessed: Feb. 28, 2025. [Online]. Available: https://dec.ny.gov/environmental-protection/site-cleanup/pfas

[48] P. Nain and A. Anctil, "End-of-life solar photovoltaic waste management: A comparison as per European Union and United States regulatory approaches," *Resources, Conservation & Recycling Advances*, vol. 21, p. 200212, May 2024, doi: 10.1016/j.rcradv.2024.200212.

[49] "PFAS waste from solar panels: 'This is something that people in the sector don't like to talk about,'" Chemsec. Accessed: Feb. 28, 2025. [Online]. Available: https://chemsec.org/pfas-waste-from-solar-panels-this-is-something-that-people-in-the-sector-dont-like-to-talk-about/

[50] "Boviet Solar's PV Modules Earn PFAS Certification from TÜV SUD | USA Solar Cell," SolarCell. Accessed: Feb. 28, 2025. [Online]. Available: https://usasolarcell.com/news/2024/09/28/boviet-solars-pv-modules-earn-pfas-certification-from-tuv-sud/

[51] "Sector supply-chain guidance-solar energy," European Bank for Reconstruction and Development, 2024. [Online]. Available: https://www.ebrd.com/find?keywords=Sector%20supply-chain%20guidance%20%E2%80%93%20%20solar%20energy&content-all=true&dates-all=true&search-type=search-all&page=1&order-by-date=false

[52] "State of Sustainability Research Climate Change Mitigation," Global Electronics Council, Apr. 2021. [Online]. Available: https://globalelectronicscouncil.org/wp-content/uploads/GEC_Climate_Change_SOSR_DRAFT_For_Public_Comment_1APR2021.pdf

[53] "Solar Equipment Lists Program," California Energy Commission. Accessed: Feb. 28, 2025. [Online]. Available: https://www.energy.ca.gov/programs-and-topics/programs/solar-equipment-lists

[54] Md. S. Chowdhury *et al.*, "An overview of solar photovoltaic panels' end-of-life material recycling," *Energy Strategy Reviews*, vol. 27, p. 100431, Jan. 2020, doi: 10.1016/j.esr.2019.100431.

[55] "EPEAT Disclosure Report 2022," FirstSolar, 2022. [Online]. Available: https://www.firstsolar.com/-/media/First-Solar/Sustainability-Documents/EPEAT-Disclosure-Report-2022.ashx

[56] "How the recycling industry is preparing to tackle solar panels," Resource Recycling. Accessed: Feb. 28, 2025. [Online]. Available: https://resource-recycling.com/recycling/2021/06/15/how-the-recycling-industry-is-preparing-to-tackle-solar-panels/

[57] "SOLARCYCLE® Raises $6.6 Million Seed Round to Rapidly Accelerate Buildout of Advanced Recycling Platform for the Solar Industry," SolarCycle. Accessed: Feb. 28, 2025. [Online]. Available: https://www.solarcycle.us/press-releases/solarcycle-raises-6-6-million-seed-round

[58] F. Lenzmann, "PV Recycling – Status and Perspectives," in *Photovoltaic Solar Energy: From Fundamentals to Applications, Volume 2*, IEEE, 2024, pp. 555–566. doi: 10.1002/9781119578826.ch34.

[59] "Implementation of a CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other applications," ASPIRE. Accessed: Feb. 28, 2025. [Online]. Available: https://www.aspire2050.eu/cabriss

[60] "Photorama," PHOTORAMA. Accessed: Feb. 28, 2025. [Online]. Available: https://www.photorama-project.eu/

[61] "ReProSolar: Demonstrator of High Grade PV Recovery Value Chain in Europe," EIT RawMaterials. Accessed: Feb. 28, 2025. [Online]. Available: https://old.eitrawmaterials.eu/project/reprosolar/

[62] "Horizon 2020 Circular business models for the solar power industry," European Commission. Accessed: Feb. 28, 2025. [Online]. Available: https://cordis.europa.eu/project/id/776680

[63] "Solar Supply Chain Traceability Protocol," SEIA Solar Energy Industries Association. Accessed: Feb. 28, 2025. [Online]. Available: https://seia.org/research-resources/solar-supply-chain-traceability-protocol/

[64] "Supply Chain Traceability Standard," Solar Stewardship Initiative. Accessed: Feb. 28, 2025. [Online]. Available: https://www.solarstewardshipinitiative.org/ssi-standards/supply-chain-traceability-standard/

[65] "Public Comment for the Addition of PV Modules," SERI. Accessed: Feb. 28, 2025. [Online]. Available: https://sustainableelectronics.org/r2-pv-public-comments/

[66] "SERI starts solar panel recycling certification," EScrap News. Accessed: Feb. 28, 2025. [Online]. Available: https://resource-recycling.com/e-scrap/2024/09/12/seri-starts-solar-panel-recycling-certification/

[67] "The e-Stewards® Standard for Ethical and Responsible Reuse, Recycling, and Disposition of Electronic Equipment and Information Technology Version 4.0©," e-Stewards. Accessed: Feb. 28, 2025. [Online]. Available: https://e-stewards.org/wp-content/uploads/2020/09/e-Stewards-Standard-V4-2020-09-17.pdf

[68] "Development of a recyclability index for photovoltaic products." Accessed: Feb. 28, 2025. [Online]. Available: https://www.pv-recyclability-index.eu/

[69] T. Curtis, H. Buchanan, L. Smith, and G. Heath, "A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations," National Renewable Energy Laboratory, NREL/TP-6A20-74550, 1774574, MainId:6505, 2021. doi: 10.2172/1774574.

[70] P. Sinha, S. Raju, K. Drozdiak, and A. Wade, "Life cycle management and recycling of PV systems," *Photovoltaics International*, 2018.

[71] "DAS Solar N-type modules awarded French carbon footprint," PV Magazine International. Accessed: Feb. 28, 2025. [Online]. Available: https://www.pv-magazine.com/press-releases/das-solar-n-type-modules-awarded-french-carbon-footprint/

[72] “What verification of carbon footprints that LONGi’s products have obtained?,” Longi. Accessed: Feb. 28, 2025. [Online]. Available: https://www.longi.com/en/comments/carbon-footprints//

[73] “PRIME Prize,” American Made | U.S Department of Energy. Accessed: Feb. 28, 2025. [Online]. Available: https://americanmadechallenges.org/challenges/prime

[74] “IEC 61730-2,” International Electrotechnical Commission. Accessed: Feb. 28, 2025. [Online]. Available: https://webstore.iec.ch/en/publication/63895

[75] “Understanding PV System Standards, Ratings, and Test Conditions,” EE Power. Accessed: Feb. 28, 2025. [Online]. Available: https://eepower.com/technical-articles/understanding-pv-system-standards-ratings-and-test-conditions/#

[76] “UL1703 / UL 61730 – PV Module Safety Standards Updates: Making the Transition,” UL Solutions. Accessed: Feb. 28, 2025. [Online]. Available: https://www.ul.com/news/ul1703-ul-61730-pv-module-safety-standards-updates-making-transition

[77] H. J. T. Nkuissi *et al.*, “Toxic Materials Used in Thin Film Photovoltaics and Their Impacts on Environment,” in *Reliability and Ecological Aspects of Photovoltaic Modules*, IntechOpen, 2020. doi: 10.5772/intechopen.88326.

[78] “Responsible mineral supply chains,” OECD. Accessed: Feb. 28, 2025. [Online]. Available: https://www.oecd.org/en/topics/sub-issues/due-diligence-guidance-for-responsible-business-conduct/responsible-mineral-supply-chains.html

[79] “Aluminum in Solar Energy Systems.” Accessed: Feb. 28, 2025. [Online]. Available: https://elkamehr.com/en/aluminum-in-solar-energy-systems/

[80] “Origami Solar Steel Solar Module Frames,” Origami Solar, Inc., Environmental Impact Report, Mar. 2024. Accessed: Feb. 28, 2025. [Online]. Available: https://origamisolar.com/wp-content/uploads/2024/03/Origami-Steel-Module-Frames-Reduce-GHG-Impact.pdf

[81] “Solarcycle invests $344 million in solar factory,” PV Magazine International. Accessed: Feb. 28, 2025. [Online]. Available: https://www.pv-magazine.com/2024/02/16/solarcycle-invests-344-million-in-solar-factory/

[82] “SOLARCYCLE to manufacture solar glass in U.S. using recycled solar panels,” Solar Builder. Accessed: Feb. 28, 2025. [Online]. Available: https://solarbuildermag.com/news/solarcycle-to-manufacture-solar-glass-in-u-s-using-recycling-solar-panels/

[83] G. A. Heath *et al.*, “Research and development priorities for silicon photovoltaic module recycling to support a circular economy,” *Nat Energy*, vol. 5, no. 7, pp. 502–510, Jul. 2020, doi: 10.1038/s41560-020-0645-2.

[84] “Global PV Module Market Analysis and 2025 Outlook,” EnergyBin. Accessed: Feb. 28, 2025. [Online]. Available: https://resources.energybin.com/solar-resources/global-pv-module-market-analysis-and-2025-outlook

[85] “Best Research-Cell Efficiency Chart | Photovoltaic Research,” NREL. Accessed: Feb. 28, 2025. [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html/

[86] E. Leccisi, M. Raugei, and V. Fthenakis, “The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update,” *Energies*, vol. 9, no. 8, p. 622, Aug. 2016, doi: 10.3390/en9080622

[87] “Sustainability Report 2024,” First Solar. [Online]. Available: https://www.firstsolar.com/-/media/First-Solar/Sustainability-Documents/FirstSolar_Sustainability-Report_2024.pdf

[88] V. Fthenakis, E. Leccisi, and P. Sinha, “Updated sustainability status of cadmium telluride thin-film photovoltaic systems and projections,” *Progress in Photovoltaics*, vol. 32, no. 12, Dec. 2024, doi: https://doi.org/10.1002/pip.3837.

[89] P. Sinha, S. Sajja, T. W. Ooi, S. Jayaraman and S. Raju, "Net Zero Water Withdrawal Strategies and Multicriteria Impacts for PV Manufacturing," in IEEE Journal of Photovoltaics, vol. 14, no. 1, pp. 201-207, Jan. 2024, doi: 10.1109/JPHOTOV.2023.3323777.

[90] “Solar jobs on the rise,” PV Magazine. Accessed: May 13, 2025. [Online]. Available: https://pv-magazine-usa.com/2024/09/17/solar-jobs-on-the-rise/

[91] S. Benjamins *et al.*, “Potential environmental impacts of floating solar photovoltaic systems,” *Renewable and Sustainable Energy Reviews*, vol. 199, p. 114463, Jul. 2024, doi: 10.1016/j.rser.2024.114463.

[92] E. O'Leary, "Recyclable Packaging: How Solar Manufacturers Can Improve Hard-to-Recycle Materials," Green CLEAN SOLAR. Accessed: May 14, 2025. [Online]. Available: https://www.greenclean-solar.com/post/recyclable-packaging-how-solar-manufacturers-can-improve-hard-to-recycle-materials

[93] "Wood or Plastic Pallets? A Life Cycle Assessment for Solar Panel Packaging," PV PALLET. Accessed: May 14, 2025. [Online]. Available: https://www.pvpallet.com/news/wood-or-plastic-pallets-a-life-cycle-assessment-for-solar-panel-packaging

[94] "Packaging Materials for Solar Modules," MJK Power. Accessed: May 14, 2025. [Online]. Available: https://mjkpower.com/packaging-materials-for-solar-modules/

[95] "The Benefits of Reusable Packaging on Utility-Scale Solar Installations," PV PALLET. Accessed: May 14, 2025. [Online]. Available: https://www.pvpallet.com/news/benefits-of-reusable-packaging-on-utility-scale-solar-installations

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