# Environmental Life Cycle Assessment of Electricity from PV systems – 2023 data update

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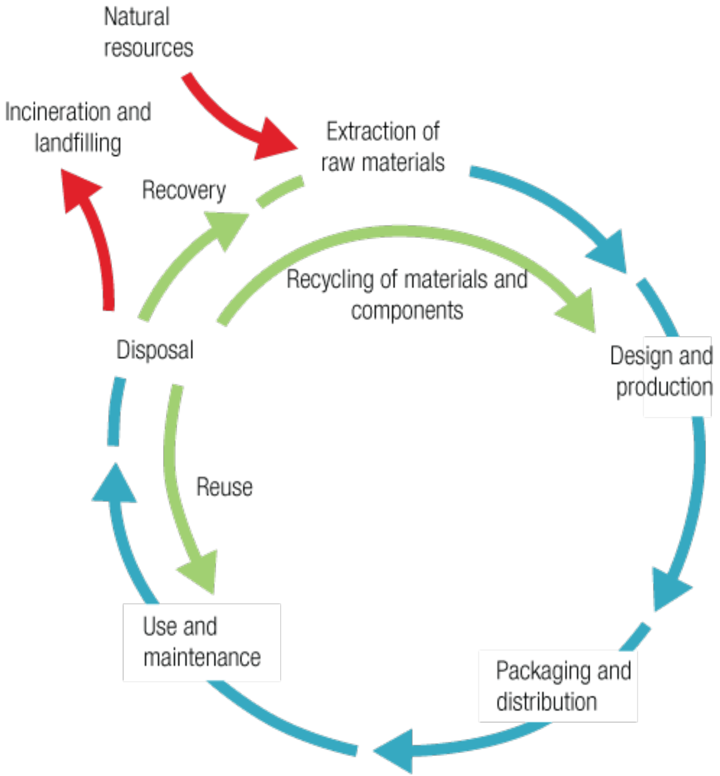
Technology Collaboration Programme
by iea

# Environmental Life Cycle Assessment

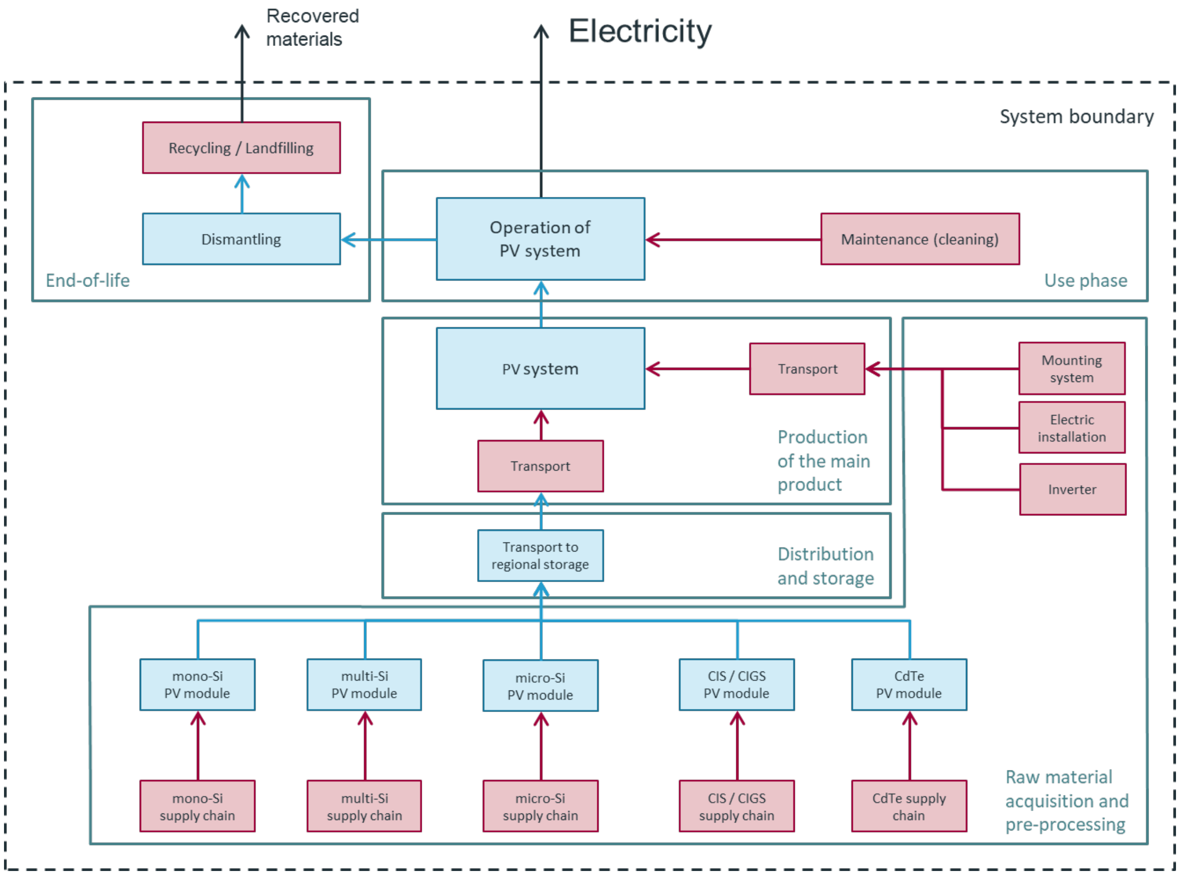
Life Cycle Assessment (LCA) is a structured, comprehensive method of quantifying material and energy flows, including the associated emissions caused in the life cycle of goods and services.

The life cycle of goods and services covers raw material and primary energy extraction, material and energy supply, manufacture, use and end of life, including transport and waste management services where needed.




www.lifecycleinitiative.org

# Product System and System Boundary PV Electricity Generation




**Primary data from industry:**
e.g. inventory data for module production from manufacturing companies

**Data from industry and secondary sources:**
e.g. data derived from scientific publications, reports and statistics or industry average data.

Note: this diagram represents Task 12's LCI as a whole, not specific to the 2023 update.

IEA PVPS Report T12-19:2020

# Environmental Footprint PV: Scope

- **Reference flow:**
  1 kWh AC electricity (at grid connection point), produced with a 3 kWp PV system, rooftop mounted.
- **Reference year:**
  The data used for the update describe production and market conditions in the reference year 2022.
- **Annual production (Europe):**
  976 kWh/kWp, including degradation (linear, 0.7 %/a *)
- **Service life:**
  30 years (panel), 15 years (inverter)
- **PV technologies and efficiencies**
  - **Cadmium-Telluride (CdTe): 18.4 % (updated)**
  - Copper-Indium-Gallium-Selenide (CIS/CIGS): 17.0 % (no technology-specific update)
  - Multi-crystalline Silicon (multi-Si): 18.0 % (no technology-specific update)
  - **Mono-crystalline Silicon (mono-si): 20.9 % (updated)**



* As per current Task 12 LCA methodology (IEA-PVPS T12-18:2020), though research on recent systems suggests degradation rates in the order of 0.5-0.6 %/a (Jordan et al. 2016). Results presented here can be adjusted by assuming a linear relationship with the degradation rate dependent yield. For a degradation rate of 0.5 %/a simply multiply results by a factor of 0.968; while for a degradation rate of 0.9 %/a multiply results by a factor of 1.053.

# Main Updates for 2023 Edition / Data Sources

- **Crystalline silicon PV modules**
  - module efficiency (mono-Si: Fraunhofer ISE, 2023; VDMA, 2023; multi-Si: no update *)
  - market shares polysilicon, ingot, wafer, cell and panel manufacturing (S&P global, 2023)
  - mono-Si: electricity and thermal energy consumption in polysilicon, ingot, wafer, cell and panel manufacturing (de Wild-Scholten, 2023; VDMA, 2023; IEA PVPS Trends Report, 2023; various 2022 Annual Reports from manufacturers (REC, Wacker, Hemlock))
  - mono-Si: wafer thickness and silicon losses in wafer production (VDMA, 2023)
  - mono-Si: metallization paste demand (VDMA, 2023)
- **CIS PV modules**
  - not updated **
- **CdTe**
  - module type, module efficiency and production site capacities (Sinha 2023)



* Multi-Si market and production capacity shares declined to below 3 % in 2022 and around 1 % in 2023 (S&P global, 2023; VDMA, 2023). As a result, no technology-specific data was available to update the multi-Si key parameters.

** The key parameters of CIS / CIGS modules have not been updated. As the only remaining large-scale manufacturer ceased CIS / CIGS thin-film production in late 2021, no recent technology-specific data are available to be used for the current update.

# Key Parameters and Key Data (2023 updates shown in orange color)

| Update 2023 | Unit | mono-Si [1] | multi-Si | CIS | CdTe |
|---|---|---|---|---|---|
| module efficiency | % | 20.9 | 18.0 | 17.0 | 18.4 |
| wafer thickness | µm | 160 | 172.5 | n.a. | n.a. |
| kerf loss | µm | 57 | 65 | n.a. | n.a. |
| further losses | µm | 3.4 | 21.4 | n.a. | n.a. |
| glass thickness | mm | 3.2 | 3.2 | 3.2 | 2.1 (front)<br>2.8 (back) |
| electricity consumption | | | | | |
| - metallurgical grade silicon | kWh/kg | 12 | | | |
| - polysilicon production | kWh/kg | 52.3 (electricity)<br>+ 11.6 (thermal) | | n.a. | n.a. |
| - Czochralski monocrystal production / casting | kWh/kg | 13.5 | 7.0 | n.a. | n.a. |
| - wafer manufacture | $kWh/m^2$ | 2.7 | 5.6 | n.a. | n.a. |
| - cell manufacture | $kWh/m^2$ | 9.7 | 17.7 | n.a. | n.a. |
| - panel manufacture | $kWh/m^2$ | 3.6 | 7.6 [2] | 45 | 19-23 |
| year of key production and market data | | 2019 - 2023 | 2019 - 2021 | 2010 / 2020 [3] | 2020 - 2022 |

[1] mono-Si technologies: PERC / TOPCon

[2] Change due to harmonisation of calculation.

[3] 2010: production data; 2020: module efficiency

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# Environmental Impacts of 1 kWh AC Electricity

| | unit | mono-Si | multi-Si | CIS | CdTe |
|---|---|---|---|---|---|
| greenhouse gas emissions * | g $CO_2$ eq | 35.8 | 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 |

* IPCC 2021, GWP, 100 a
** Environmental Footprint Method EF3.1 (adapted)

1 kWh AC electricity. Annual in-plane irradiation: 1'331 kWh/m$^2$. Annual yield: 976 kWh/kW$_p$, including degradation (linear, 0.7 %/a). To adjust results for a degradation rate of 0.5 %/a multiply results by 0.968; while for a degradation rate of 0.9 %/a, multiply results by a factor of 1.053. Service life: 30 years (panel), 15 years (inverter)

# Environmental Impacts of 2023 Update Relative to 2021 Systems

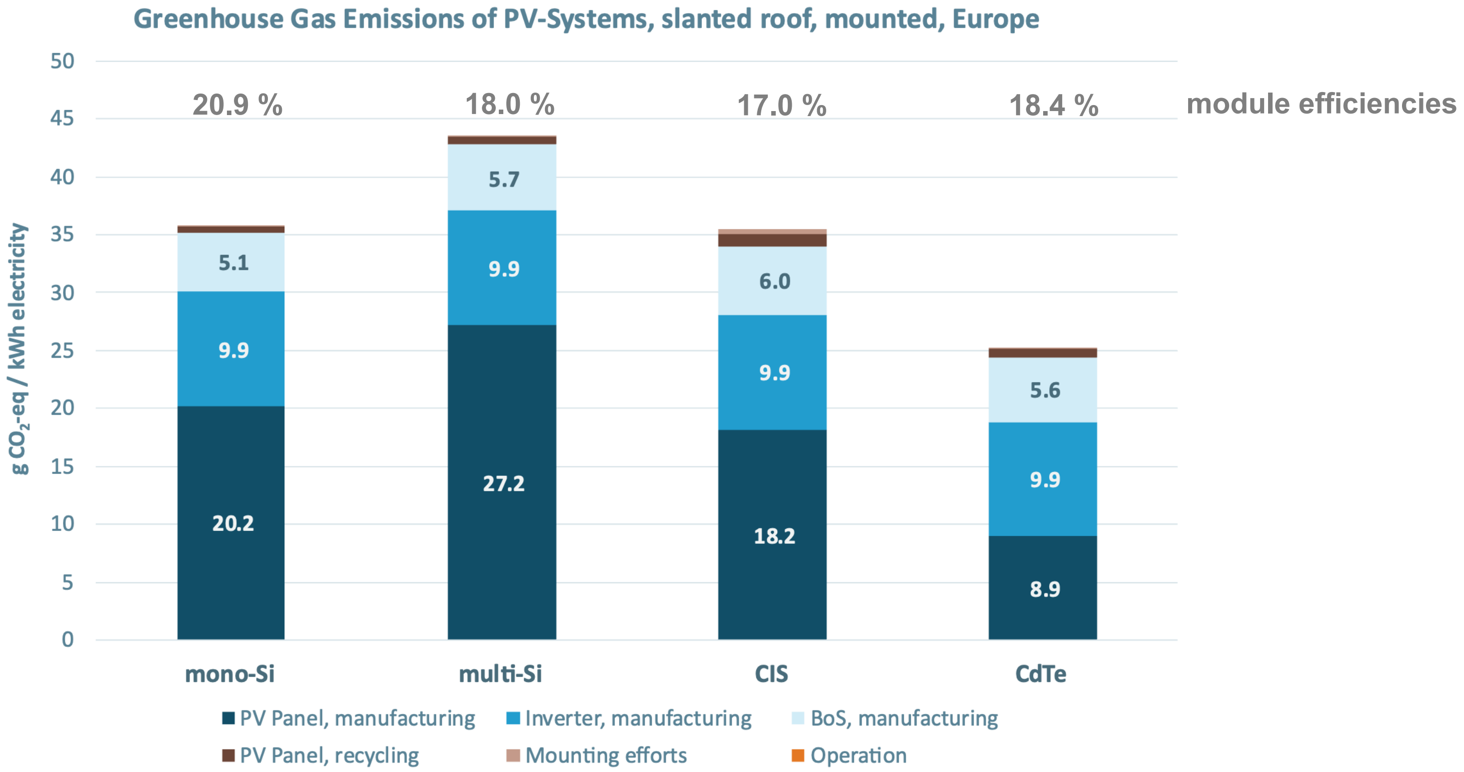
| | mono-Si | multi-Si | CIS | CdTe |
|---|---|---|---|---|
| greenhouse gas emissions | 83 % | 99 % | 100 % | 99 % |
| resource use, fossil fuels | 87 % | 99 % | 100 % | 99 % |
| resource use, minerals and metals | 97 % | 100 % | 100 % | 100 % |
| particulate matter | 74 % | 102 % | 109 % | 108 % |
| acidification | 80 % | 99 % | 100 % | 99 % |
| module efficiency | 20.9 % (20.0 %)* | 18.0 % (18.0 %)* | 17.0 % (17.0 %)* | 18.4 % (18.2 %)* |

Values >100 % indicate an increase in environmental impact relative to 2021 PV systems. Information on 2021 systems provided by Frischknecht (2022).
See slide 12 for discussion of reasons for these changes

* In brackets: Module efficiencies of 2021 PV systems

1 kWh AC electricity. Annual in-plane irradiation: 1’331 kWh/m$^2$. Annual yield: 976 kWh/kW$_p$, including degradation (linear, 0.7%/a). Service life: 30 years (panel), 15 years (inverter).
Impacts of 2021 systems equal 100 %.

# Greenhouse Gas Emissions 1 kWh PV-System 3kWp

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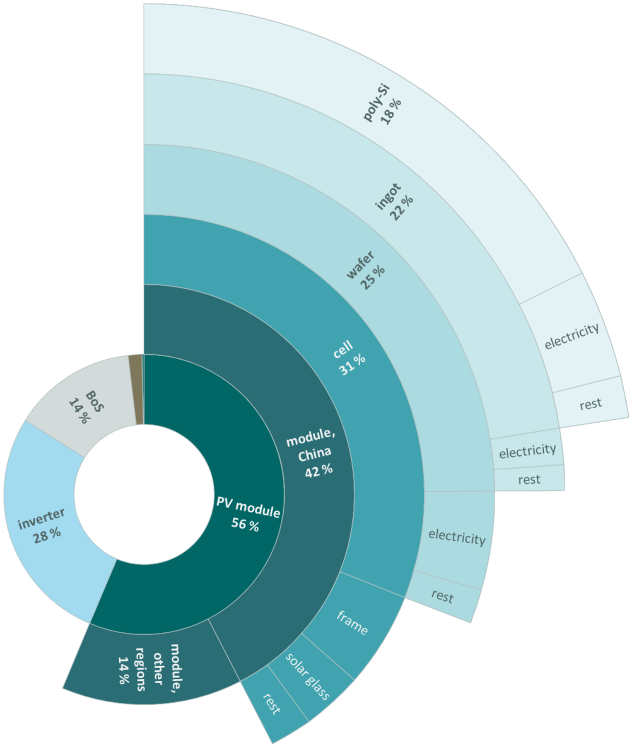
1 kWh AC electricity. Annual in-plane irradiation: 1'331 kWh/m$^2$. Annual yield: 976 kWh/kW$_p$, including degradation (linear, 0.7%/a). To adjust results for a degradation rate of 0.5 %/a multiply results by 0.968; while for a degradation rate of 0.9 %/a, multiply results by a factor of 1.053. Service life: 30 years (panel), 15 years (inverter)

# Supply Chain Contributions to mono-Si Module GHG Emissions




**total mono-Si system GHG emissions:**
35.8 g $CO_2$-eq / kWh

**mono-Si module GHG emissions:**
20.2 g $CO_2$-eq / kWh

PVPS

1 kWh AC electricity. Annual in-plane irradiation: 1’331 kWh/m$^2$. Annual yield: 976 kWh/kW$_p$, including degradation (linear, 0.7%/a). To adjust results for a degradation rate of 0.5 %/a multiply results by 0.968; while for a degradation rate of 0.9 %/a, multiply results by a factor of 1.053. Service life: 30 years (panel), 15 years (inverter)

# Time Series Greenhouse Gas Emissions for mono-Si PV System

## Residential, rooftop mounted, mono-Si crystalline silicon photovoltaic system

Installed in Switzerland

| | unit | 1996 | 2003 | 2007 | 2014 | 2016 | 2020 | 2021 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| greenhouse gas emissions | g $CO_2$ eq / kWh | 121 | 72 | 76 | 80 | 107 | 43 | 43 | 36 |
| module efficiency | % | 13.6 | 14.8 | 14.0 | 14.0 | 15.1 | 19.5 | 20.0 | 20.9 |
| annual yield | kWh / kWp | 862 | 882 | 922 | 922 | 882 | 976 | 976 | 976 |

**Assumptions and Data Sources**

Service life: 30 years (panel), 15 years (inverter)

Background data:

1996: Ökoinventare von Energiesystemen

2003: ecoinvent v1.01

2007: ecoinvent v2.0

2014: ecoinvent v2.2

2016: KBOB LCA data DQRv2:2016

2020: UVEK LCA data DQRv2:2020

2021: UVEK LCA data DQRv2:2022

2023: UVEK LCA data DQRv2:2022

**References**

**1996**: Ciseri L., Doka G., Vollmer M. (1996). Photovoltaik, in Frischknecht et al. (1996) Ökoinventare von Energiesystemen, Bern

**2003/2007**: Jungbluth N. (2003). Photovoltaik. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH

**2014**: Jungbluth N., Stucki M., Flury K., Frischknecht R. and Buesser S. (2012). Life Cycle Inventories of Photovoltaics. ESU-services Ltd., Uster, CH

**2016**: Frischknecht, R., Itten R., Sinha P., de Wild-Scholten, M., Zhang, J., Fthenakis, V., Kim, H. C., Raugei, M., Stucki, M. (2015). Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015

**2020**: IEA-PVPS Report T12-19:2020

**2021**: Frischknecht, R. (Ed.) (2022). Environmental Life Cycle Assessment of Electricity from PV systems, 2021 data update. IEA-PVPS.

# Main Reasons for Changes in 2023 Results Compared to 2021 PV Systems

- **mono-Si**
  - increased panel efficiency (leading to a decrease in life cycle (LC) environmental impacts)
  - decreased kerf loss / reduced poly-Si consumption (leading to a decrease in LC impacts)
  - lower electricity and thermal energy demand for Cz-Si, wafer, cell and panel manufacture (leading to a decrease in LC impacts)
  - increased market share of Chinese and APAC production of cells and wafers (increase in impacts)
- **CdTe**
  - increased panel efficiency (decrease in impacts)
- **All technologies**
  - minor changes in calculation setups and LCI modelling (leading to both minor increases and decreases in life cycle impacts)
  - new versions of life cycle assessment methods (IPCC 2013 → IPCC 2021; EF3.0 → EF3.1; minor deviations in impacts, increased results for particulate emissions for CdTe and CIS)

# Non Renewable Energy Payback Time

**NREPBT**

Non renewable energy payback time is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of non renewable primary energy equivalent) that was used to produce the system itself.

| | unit | mono-Si | multi-Si | CIS | CdTe |
|---|---|---|---|---|---|
| NREPBT | year | 1.0 | 1.2 | 1.2 | 0.8 |
| module efficiency | % | 20.9 | 18.0 | 17.0 | 18.4 |

1 kWh AC electricity. Annual in-plane irradiation: 1'331 kWh/m$^2$. Annual yield: 976 kWh/kW$_p$, including degradation (linear, 0.7 %/a).
Service life: 30 years (panel), 15 years (inverter).
Reference electricity mix: mix of power plants using non renewable energy sources (coal, oil, natural gas, uranium) in Europe.

# Bill of Materials

| Material | | | Photovoltaic module (laminate/unframed and panel/framed) | | | |
|---|---|---|---|---|---|---|
| | | | mono-Si | multi-Si | CI(G)S | CdTe |
| Source | | | PVPS Task 12 2020 | PVPS Task 12 2020 | Jungbluth et al. 2012 | FirstSolar 2021-2023 |
| Laminate/unframed | **Subtotal wafer / semiconductor** | | **4.54%** | **5.32%** | **0.06%** | **0.18%** |
| | Wafer / semiconductor | silicon for photovoltaics | 4.54% | 5.32% | 0.00% | 0.00% |
| | | silane, at plant | 0.00% | 0.00% | 0.00% | 0.00% |
| | | indium | 0.00% | 0.00% | 0.02% | 0.00% |
| | | cadmium telluride | 0.00% | 0.00% | 0.00% | 0.18% |
| | | cadmium sulphide | 0.00% | 0.00% | 0.00% | 0.00% |
| | | gallium | 0.00% | 0.00% | 0.01% | 0.00% |
| | | selenium | 0.00% | 0.00% | 0.04% | 0.00% |
| | **Subtotal metals** | | **1.32%** | **1.33%** | **0.55%** | **0.11%** |
| | Metals | aluminium | 0.23% | 0.24% | 0.00% | 0.00% |
| | | aluminium, production mix | 0.00% | 0.00% | 0.30% | 0.00% |
| | | aluminium alloy | 0.00% | 0.00% | 0.00% | 0.00% |
| | | copper | 0.94% | 0.93% | 0.07% | 0.03% |
| | | lead | 0.01% | 0.01% | 0.00% | 0.00% |
| | | molybdenum | 0.00% | 0.00% | 0.04% | 0.00% |
| | | silver | 0.02% | 0.03% | 0.00% | 0.00% |
| | | steel | 0.00% | 0.00% | 0.00% | 0.00% |
| | | chromium steel | 0.00% | 0.00% | 0.00% | 0.09% |
| | | tin | 0.12% | 0.12% | 0.08% | 0.00% |
| | | zinc oxide | 0.00% | 0.00% | 0.06% | 0.00% |
| | | brazing solder | 0.00% | 0.00% | 0.00% | 0.00% |
| | | soft solder | 0.00% | 0.00% | 0.00% | 0.00% |
| | **Subtotal plastics** | | **13.52%** | **13.41%** | **12.20%** | **4.70%** |
| | Plastics | ethylvinylacetate | 8.00% | 7.94% | 5.05% | 2.95% |
| | | polyvinylfluoride film | 1.02% | 1.01% | 0.00% | 0.00% |
| | | polyvinylbutyral foil | 0.00% | 0.00% | 1.27% | 0.00% |
| | | polyphenylene sulfide | 0.00% | 0.00% | 0.58% | 0.00% |
| | | polyethylene terephthalate, PET | 3.16% | 3.14% | 2.26% | 0.00% |
| | | polyethylene, HDPE | 0.22% | 0.22% | 0.33% | 0.00% |
| | | packaging film, LDPE | 0.00% | 0.00% | 0.00% | 0.00% |
| | | glass fibre reinforced plastic, polyamide | 0.00% | 0.00% | 0.00% | 0.84% |
| | | silicone product | 1.11% | 1.11% | 2.72% | 0.91% |
| | | synthetic rubber | 0.00% | 0.00% | 0.00% | 0.00% |
| | **Subtotal solar glass** | | **80.62%** | **79.94%** | **87.19%** | **94.72%** |
| | Solar glass | flat glass | 0.00% | 0.00% | 35.43% | 42.01% |
| | | solar glass | 80.62% | 79.94% | 51.76% | 52.70% |
| | **Subtotal chemicals** | | **0.00%** | **0.00%** | **0.00%** | **0.30%** |
| | Chemicals | chemicals, unspecified | 0.00% | 0.00% | 0.00% | 0.30% |
| Panel/ frame | **Subtotal metals panel** | | **19.44%** | **19.28%** | **14.79%** | **12.45%** |
| | Metals | aluminium alloy | 19.44% | 19.28% | 14.79% | 12.45% |
| **Total laminate/unframed** | | | **100.00%** | **100.00%** | **100.00%** | **100.00%** |
| **Total panel/framed** | | | **119.44%** | **119.28%** | **114.79%** | **112.45%** |
| **Total weight in kg per square meter of unframed module** | | | **10.9** | **11.0** | **14.9** | **12.9** |
| **Rated power in Wp per square meter of module** | | | **209** | **180** | **170** | **184** |
| **Module efficiency in percent** | | | **20.9%** | **18.0%** | **17.0%** | **18.4%** |
| **Module area for 3kWp PV systems in square meter** | | | **14.4** | **16.7** | **17.6** | **16.3** |
| **Module area for 570kWp PV systems in square meter** | | | **2727** | **3167** | **3353** | **3098** |

Originally based on IEA PVPS report T12-19:2020, partially updated for mono-Si as part of the 2023 update.

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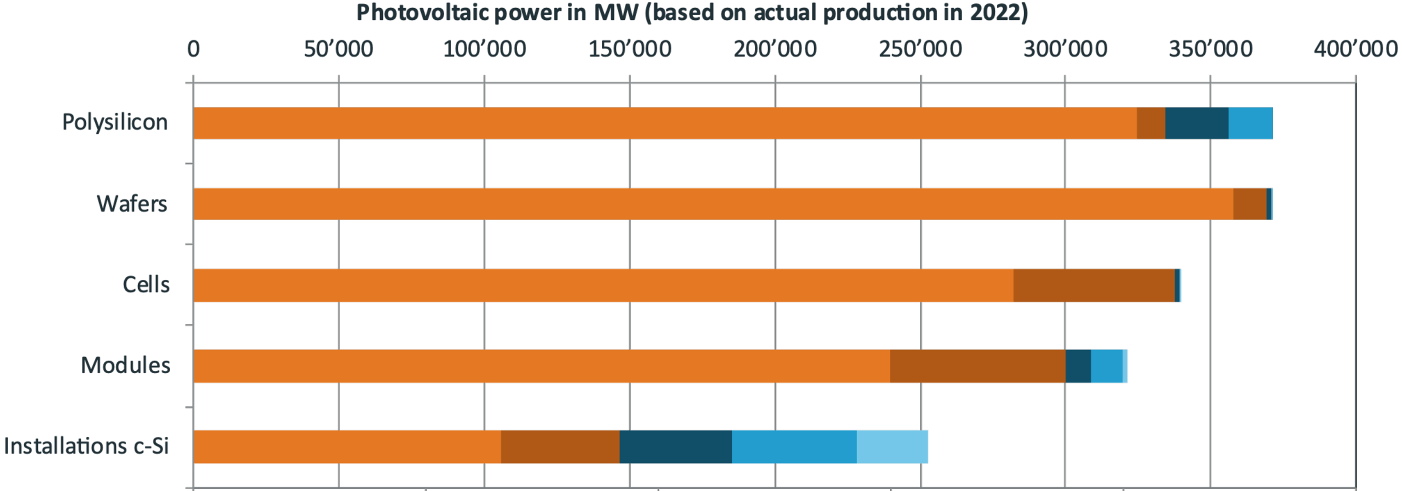
# Market Situation Crystalline Silicon 2022 in MW PV Power Capacity




| | Installations c-Si | Modules | Cells | Wafers | Polysilicon |
|---|---|---|---|---|---|
| China | 106’000 | 239’670 | 282’001 | 357’870 | 324’627 |
| Asia & Pacific | 40’291 | 60’247 | 55’498 | 11’347 | 9’556 |
| Europe | 38’700 | 8’655 | 1’841 | 1’622 | 22’004 |
| Americas | 43’400 | 11’329 | 0 | 0 | 15’330 |
| Middle East and Africa | 24’417 | 1’579 | 415 | 110 | 0 |

PV supply chain market share from S&P Global Commodity Insights (S&P Global, 2023).
Conversion factor for polysilicon demand per MW of PV power: 2.54 tons / MW (S&P Global, 2023).

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# Methodology and Database

- **Methodology protocol**
  IEA PVPS Task 12 Methodology guidelines, 4th edition (IEA PVPS Report T12-18:2020)
- **System model**
  Attributional LCI
- **Allocation**
  - Multifunctional processes: economic relationships
  - Recycling: recycled content approach
- **Background data**
  UVEK LCI data DQRv2:2022
- **LCA software**
  SimaPro v9.5.0.2

# Environmental Footprint PV: Environmental Indicators

## Selection of indicators from Life Cycle Impact Assessment Method "Environmental Footprint v3.1":

- **Climate change:**
  Greenhouse gas emissions, kg $CO_2$-eq;
  IPCC (2021)

- **Resource depletion, minerals and metals:**
  ADP for mineral and metal resources, based on van Oers et al. (2002) as implemented in CML, v. 4.8 (2016).
  van Oers, L, Koning, A, Guinée, JB, Huppes, G. (2002). Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam

- **Resource depletion, fossils:**
  ADP for energy carriers, based on van Oers et al. (2002) as implemented in CML, v. 4.8 (2016).
  van Oers, L, Koning, A, Guinée, JB, Huppes, G. (2002). Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam

- **Acidification:**
  Accumulated Exceedance (AE), mol $H^+$-eq;
  (Posch et al., 2008; Seppälä et al., 2006)

- **Particulate matter:**
  Impact on human health, disease incidence;
  (Fantke et al., 2016)

# Main References


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- VDMA (2023). International Technology Roadmap for Photovoltaic (ITRPV) - 2022 Results, 14th edition, VDMA Photovoltaic Equipment.

# What is PVPS Task 12 – PV Sustainability

The goal of Task 12 is to foster international collaboration and knowledge creation in PV environmental sustainability and safety, as crucial elements for the sustainable growth of PV as a major contributor to global energy supply and emission reductions of the member countries and the world. In doing so, Task 12 aims to facilitate a common understanding of PV Sustainability, with a focus on Environment Health and Safety (EH&S), among the various country-members and disseminate the Task's outcomes and knowledge to stakeholders, energy and environmental policy decision makers, and the general public.

Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and TotalEnergies. Support from the United States' Department of Energy (DOE) and others are gratefully acknowledged.

**Task 12 Subtasks**

- Subtask 1: Circular Economy (CE)
- Subtask 2: Life Cycle Assessment (LCA)
- Subtask 3: Ecosystem Integrated PV (ecoPV)
- Subtask 4: Broader Sustainability Aspects (BSA)

**Task 12 Operating agents**

- Garvin Heath, NREL, USA
- Etienne Drahi, TotalEnergies, France

# Other PVPS Task 12 Reports


- T12-25:2023: Frischknecht, R., Komoto, K., Doi, T. (2023). Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology. IEA-PVPS Task 12, Report T12-25:2023. International Energy Agency, IEA, Paris.
- T12-24:2022: Komoto K. et al. (2022). Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries, IEA-PVPS Task 12, Report T12-24:2022. International Energy Agency, IEA, Paris.
- T12-23:2020: Bilbao, J., Heath, G., Norgren, A., Lunardi, M., Carpenter, A., Corkish, R. (2021). PV Module Design for Recycling Guidelines 2021. International Energy Agency, IEA, Paris.
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- see https://iea-pvps.org/research-tasks/pv-sustainability/ for further publications of IEA PVPS Task 12

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