Low Carbon Solar
State of Sustainability Research

Prepared for the Global Electronics Council in support of EPEAT criteria development

Report prepared by: Anthesis LLC

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Abbreviations

CdTe	Cadmium-telluride
CIS / CIGS	Copper-indium-selenide / Copper-indium-gallium-selenide
c-Si	Crystalline silicon
DU	Declared unit
EAC	Energy Attribute Certificate
EPD	Environmental product declaration
ESL	Estimated service life
FU	Functional unit
HJT	Heterojunction technology
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
micro-Si	Micromorphous silicon
mono-Si	Monocrystalline silicon
multi-Si	Multicrystalline silicon
PCR	Product category rules
PV	Photovoltaic
RSL	Reference service life
Si	Silicon
SoG-Si	Solar grade silicon
SOSR	State of Sustainability Research
VCP	Voluntary Consensus Process
Wp	Watt peak

Executive Summary

The purpose of this State of Sustainability Research (SOSR) is to provide information on the background, applicable previous work, likely requirements, and initial concepts for establishing an Ultra-Low Carbon Solar designation (ULCS) for solar photovoltaic (PV) modules. The SOSR is intended to form the foundation for the development of criteria on ULCS for the EPEAT Photovoltaic Modules and Inverters ecolabel[1], which is managed by the Global Electronics Council. The desired outcome of this process is to enable procurers of solar PV modules to specify low embodied carbon based on a life cycle assessment (LCA) framework and implemented in a manner that establishes confidence. The SOSR provides background information on the manufacturing processes associated with the dominant solar PV technologies, past work about solar PV module manufacturing carbon intensity, and a survey of voluntary standards and other references that are intended to be incorporated into the ULCS criteria development process.

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[1] EPEAT Photovoltaic Modules and Inverters Category criteria are based on NSF/ANSI 457 – 2019 Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters. The EPEAT ecolabel is the leading global Type-1 ecolabel for the technology products. The Global Electronics Council (GEC) manages the EPEAT ecolabel, including the Conformity Assurance Bodies that provide 3rd party verification of the products listed in this Registry: https://epeat.net/search-pvmi.

Introduction

The Global Electronics Council (GEC) proposes the development of criteria to identify low embodied carbon solar photovoltaic (PV) products that will be eligible for an Ultra-Low-Carbon Solar (ULCS) designation through the EPEAT ecolabel.

The purpose of this State of Sustainability Research (SOSR) is to provide background on embodied carbon in PV products and manufacturing processes, market drivers for low embodied carbon, and initial concepts for establishing the designation. The SOSR is intended to form the foundation for the drafting of ULCS criteria and a transparent designation for ULCS products. The desired outcome of this process is to distinguish solar modules with low embodied carbon based on a life cycle assessment (LCA) -informed framework and implemented in a manner that establishes confidence.

The Ultra Low Carbon-Solar Alliance shares GEC's goal of using market preferences to encourage supply chain decarbonization and looks forward to collaborating on this effort.

What is Ultra Low-Carbon Solar & Why is it Important?

Decarbonization of electricity generation is one of the most important efforts to prevent the worst consequences of global climate change. Fossil fuel-based electricity generation is a primary source of greenhouse gasses (GHGs), with solar PV being one of the most important replacements for fossil-based power. Decarbonization strategies to decrease the GHG emissions from PV manufacturing operations generates a significant increase in the climate benefit over the service life-time of a PV module[2]. The global solar PV market has been growing rapidly to address this issue and to meet the increasing demand for green power. Solar generating capacity has grown nearly 2500% globally since 2000, and it was estimated to reach 774 GW cumulatively by the end of 2020 (*Figure 1*)[3]. Since 2015, solar represents more than two-thirds of all electrical capacity additions by the private sector in the US[4].

Annual additions of solar PV are expected to triple by 2030 and continue to increase (*Figure 2*)[5]. In response to this expansion, buyers of solar modules are concerned with the upstream or embodied carbon related to the manufacture of PV modules. Differences in PV supply chain emissions can have a substantial impact on the greenhouse gas emissions avoided by solar projects. The use of materials with lower embodied carbon and energy efficient manufacturing process in PV modules can reduce the life cycle carbon footprint of solar systems by 40 percent or more[6]. The reduction is primarily dependent on the carbon intensity of the electricity grid powering the production process of where module components are produced. As an illustrative example, in comparison to manufacturing on a predominately coal-fired energy grid (i.e., 65% coal), polycrystalline Silicon solar PV manufactured on

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[2] Ravikumar, D., Wender, B., Seager, T.P., Fraser, M.P. and Tao, M., 2017. A climate rationale for research and development on photovoltaics manufacture. Applied Energy, 189, pp.245-256.

[3] Hannah Ritchie and Max Roser (2020) - "*Renewable Energy*". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/renewable-energy' [Online Resource]

[4] SEIA/Wood Mackenzie Power & Renewables U.S. Solar Market Insight 2020 Q4, https://www.seia.org/smi

[5] DNV-GL, Energy Transition Outlook 2020, https://eto.dnv.com/2020/index.html

[6] Dajun Yue, Fengqi You and Seth B.Darling (2014). "*Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis*." Argonne National Laboratory and Northwestern University. Solar Energy, Volume 107, September 2014, Pages 380.

an average North American grid can potentially help to avoid more than 1 billion metric tons of supply chain emissions cumulatively over the next 10 years (2021-2030) of projected solar PV deployment. [7]

Upstream Embodied Carbon

A solar PV module produces no direct greenhouse gases during its operation; however, solar PV does not have a zero-carbon footprint over its entire life cycle. When accounting for indirect emissions upstream and downstream of the module operation, life cycle greenhouse gas emissions are dominated by upstream raw materials and manufacturing emissions, and to a lesser extent end-of-life emission related to decommissioning and materials management. The upstream greenhouse gas emissions of a solar PV power plant, also known as "embodied carbon," represent nearly 60-70% of the total life cycle footprint of the solar modules *(Figure 3)*[8]. This carbon intensity is inherent in the module's raw materials and underlying manufacturing processes. For instance, solar grade polysilicon requires energy intensive processing and purification to reach the performance requirements demanded for solar PV applications. Life cycle assessments estimate that PV modules made with

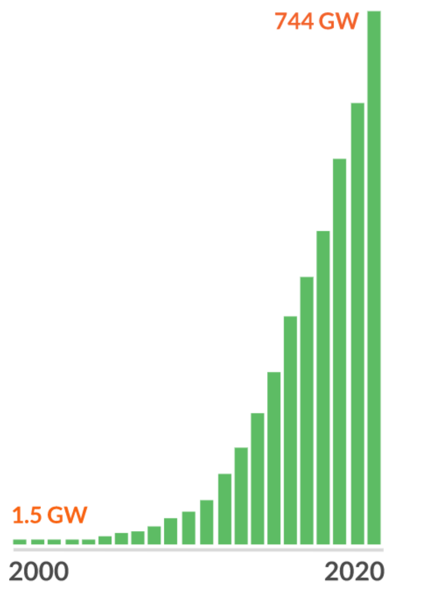

Figure 1. ***Global Solar PV Installed Capacity 2000-2020*** *(Source: Our World in Data, Global Change Data)*

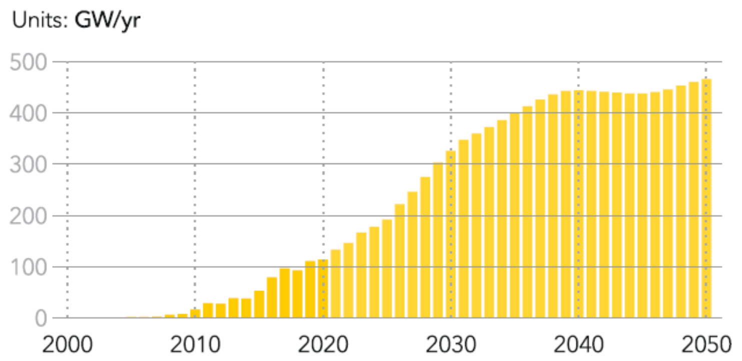

Figure 2 *World Solar PV Gross Additions* *(Source: DNV-GL, 2020)*

[7] Dr. Annick Anctil, Michigan State, unpublished research, updating Yue, You and Darling 2014 study resulting in reduction of life cycle savings from ~ 50% to ~41%.

[8] National Renewable Energy Laboratory (2012). "*Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics"*. NREL/FS-6A20-56487. November 2012.

energy from high carbon resources can have nearly twice the embodied carbon as modules produced with lower carbon resources[9] [10] [11].

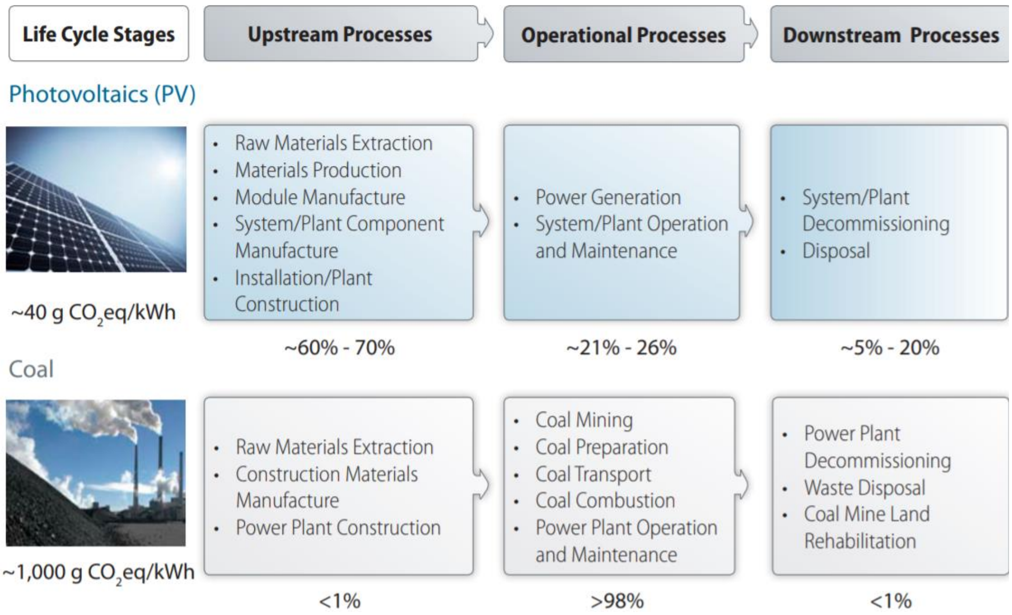

Figure 3. Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics (Source: NREL)

Market Signals

The growing solar PV market is already indicating the importance of reducing embodied carbon, as illustrated by the following examples of relevant market activity.

- France has pioneered the method for understanding embodied carbon of solar modules, incorporating two pathways of LCA estimates in the French procurement tenders beginning in 2016. The French tenders provide a simplified methodology as well as a validated methodology for solar module makers to specify the embodied carbon of their modules.
- Korea is piloting a procurement tender system, similar to the French system, to prioritize projects utilizing solar PV modules with a low carbon footprint [12].

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[9] Fthenakis, V., und M. Raugei (2017). "*Environmental life-cycle assessment of photovoltaic systems*", 2017, 209–32. https://doi.org/10.1016/B978-1-78242-336-2.00007-0.

[10] Leccisi, Enrica, Marco Raugei, und Vasilis Fthenakis (2016). "*The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update*". Energies 9, Nr. 8 (8. August 2016): 622. https://doi.org/10.3390/en9080622.

[11] Louwen, Atse, Ruud E.I. Schropp, Wilfried G.J.H.M. van Sark, und André P.C. Faaij. "*Geospatial Analysis of the Energy Yield and Environmental Footprint of Different Photovoltaic Module Technologies*". Solar Energy 155 (Oktober 2017): 1339–53. https://doi.org/10.1016/j.solener.2017.07.056.

[12] Bellini, Emilliano (2021). "*South Korea may tender 4 GW of solar PV this year*". PV Magazine. 12 January 2021. Retrieved from: https://www.pv-magazine.com/2021/01/12/south-korea-may-tender-4-gw-of-solar-pv-this-year/

- Companies are making substantial commitments requiring more ambitious reduction in GHG emissions along their value chains. Toyota has pledged half their sales from EVs by 2025 and GM has said most of their models will be EV by 2030. PepsiCo plans to reduce absolute GHG emissions across its indirect value chain (Scope 3) by 40% by 2030.
- Investors are stepping up their expectations. For example, Blackrock Inc. has clearly communicated its expectation of Science Based Targets and Net Zero commitments[13] for its portfolio companies. Top asset managers including BlackRock and Vanguard Group Inc have joined an investor push to limit greenhouse gas emissions to Net Zero by 2050. Signatories to the Net Zero Asset Managers Initiative[14] commit to press companies in their portfolios to achieve net zero emissions by 2050 or sooner.
- Large corporate buyers of solar PV are looking to make the most positive impact from their procurement efforts. As an example, one of the key insights from a recent analysis published by Salesforce[15] indicates that the emissions reduction of a potential renewable energy project can change dramatically based on its grid location and production profile. For example, it was estimated that a West Virginia-based solar project – one that would displace primarily coal-fired power generation - would avoid almost 3x the emissions than that of a California-based solar project. To maximize the emissions potential of a new renewable investment, buyers should compare different projects' avoided emissions rates and leverage this information to select projects in grid regions that cause the greatest avoided emissions.
- International product category rules (PCR) have been developed in Norway[16] and Italy[17], providing guidelines for the development of environmental product declarations (EPD) for a photovoltaic module, cell, wafer, ingot block or solar grade silicon, either cradle to gate with options or cradle to grave for a photovoltaic module. In doing so it further specifies underlying requirements of the life cycle assessment (LCA). There is also a generic PCR under the French PEP Ecopassport system[18], which can also be applied to PV modules.
- The European Union is evaluating the viability of a new policy option to mandate disclosure requirement for the carbon footprint of PV modules and inverters in the EU

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[13] BlackRock (2021). "*Larry Fink's 2021 letter to CEOs*". Retrieved from: https://www.blackrock.com/corporate/investor-relations/larry-fink-ceo-letter [Online Resource]

[14] https://www.netzeroassetmanagers.org/

[15] Lorenzen, Megan, Max Scher, Erica Brand, Patty Dillon, Lily Donge, Pasha Feinberg, Sarah Freiermuth, u. a. "*More Than a Megawatt: Embedding Social & Environmental Impact in the Renewable Energy Procurement Process*". Salesforce White Paper. San Francisco, CA, USA: 2020. https://c1.sfdcstatic.com/content/dam/web/en_us/www/assets/pdf/sustainability/sustainability-more-than-megawatt.pdf.

[16] The Norwegian EPD Foundation (2020). "*PCR – Part B for photovoltaic modules used in the building and construction industry, including production of cell, wafer, ingot block and solar grade silicon*". Product Category Rules. EN 15804: NPCR 029 Version 1.0. 11 June 2020.

[17] EPD Italy. "*PCR for PV Module*". EPDItaly 014 – rel. 1. 03 February 2020. Retrieved from: https://www.epditaly.it/en/pcr_/pcr-for-pv-module-epditaly-014/

[18] PEP EcoPassport (2015). "*Product Category Rules for Electrical, Electronic and HVAC-R Products*". PEP-PCR-ed3-EN-2015 04 02. P.E.P. Association. 02 April 2015.

Eco-Design, Energy & Eco-Labelling – potentially followed by Green Public Procurement (GPP) recommendations for other public tenders in the EU[19].

- In the United States, the Federal Acquisition Regulation (FAR) subpart 23.704 requires that 95% of all electronic product acquisitions be EPEAT-registered products[20]. Recognizing the current U.S. administration's position[21] on climate change and renewable energy goals, the ULCS criteria will further enable the US government procurement of low-embodied carbon solar PV.
- Additionally, U.S. state government agencies are also shifting towards low embodied carbon materials in general. For example, the California Department of General Services (DGS) requires that construction materials purchased with state funding comply with The Buy Clean California Act (BCCA) to reduce the carbon emissions associated with the production of structural steel, concrete reinforcing steel, flat glass, and mineral wool board insulation. These materials must have a Global Warming Potential that does not exceed the limit set by DGS.

Background on Solar Module Technologies

Photovoltaic systems are made up of several components including the solar modules, the frames and other mounting equipment, electrical connectors, and solar inverters. The majority of CO2e emissions are from module manufacturing, thus the production of modules will be the focus of this initial ULCS criteria development effort (*Figure 4*). Additional components of the PV system supply chain may be considered in future expansions of this low carbon solar effort.

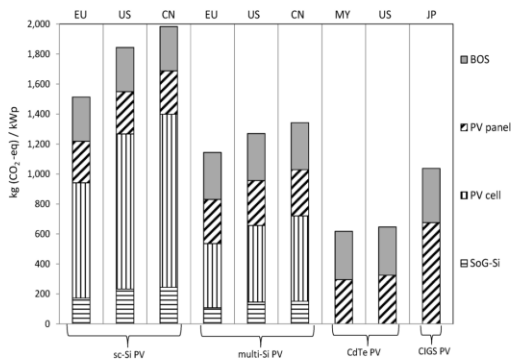

Figure 4 Carbon footprint of different PV systems indicating the solar module carbon emission dominance. *Balance of system (BOS) includes typically includes inverters, mounting structures, cable and connectors[10]*

Solar modules are the focus of substantial basic and applied research, resulting in an abundance of established and novel technologies. For this effort, two primary module technologies will be the focus:

- Crystalline silicon-based PV, including mono- and multi-crystalline silicon
- Thin-film PV based on Cadmium telluride (CdTe)

[19] Dodd, N. and Espinosa Martinez, M.D.L.N., Solar photovoltaic modules, inverters and systems: options and feasibility of EU Ecolabel and Green Public Procurement criteria, Preliminary report, EUR 30474 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-26819-2 (online), doi:10.2760/29743 (online), JRC122430. Retrieved from: https://ec.europa.eu/jrc/en/publication/solar-photovoltaic-modules-inverters-and-systems-options-and-feasibility-eu-ecolabel-and-green

[20] Federal Acquisition Regulation (2021). "*Part 23 - Environment, Energy and Water Efficiency, Renewable Energy Technologies, Occupational Safety, and Drug-Free Workplace*". FAC Number/Effective Date: 2021-03/2-16-2021- Download Entire FAR. Retrieved from: https://www.acquisition.gov/far/part-23

[21] The White House. "Executive Order on Tackling the Climate Crisis at Home and Abroad". Retrieved March 31, 2020 from https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

Other PV technologies, including heterojunction technology (HJT), copper indium gallium disselenide (CIGS) solar cells[22] and tandem solar cells[23], may be considered in future efforts. However, they are not the focus of the current ULCS criteria development.

Photovoltaic Module Production Processes

Crystalline Silicon Modules

Crystalline silicon is the predominant technology in global PV deployment, with the Fraunhofer Institute reporting that 95% of the PV modules produced in 2017 were crystalline silicon, such that the assessment reflects most global PV installations[24]. As per the Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems[25], published by the International Energy Agency (IEA) Photovoltaic Power Systems Program Task 12[26], the following production processes are the most important elements in the production of crystalline-Si modules:

1. Metallurgical-grade Silicon production
2. Solar-grade Silicon production
3. Mono- or multi-crystalline Ingot/block production
4. Silicon wafer production
5. Photovoltaic cell production
6. Module production, including glass, laminate, and frame

Thin Film Modules

Thin film modules using CdTe technology are the second most common form of photovoltaic module available on the market currently.[27] They have a simpler and more resource efficient manufacturing process in comparison to Silicon-based modules. As per ULCSA[28], the primary production process components for CdTe thin-film include the following:

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[22] Mansfield, Lorelle (2021). "*Copper Indium Gallium Diselenide Solar Cells*." National Renewable Energy Laboratory. Photovoltaic Research: Materials Science. Retrieved February 28, 2021 from https://www.nrel.gov/pv/copper-indium-gallium-diselenide-solar-cells.html.

[23] Helmholtz-Zentrum Berlin für Materialien und Energie. (2020, April 14). Tandem solar cell world record. ScienceDaily. Retrieved February 28, 2021 from www.sciencedaily.com/releases/2020/04/200414122758.htm.

[24] Fraunhofer ISE (2020). "*Photovoltaics Report".* Freiburg, Germany. 16 September 2020.

[25] R. Frischknecht, P. Stolz, L. Krebs, M. de Wild-Scholten, P. Sinha, V. Fthenakis, H. C. Kim, M. Raugei, M. Stucki, 2020, "*Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems"*, International Energy Agency (IEA) PVPS Task 12, Report T12-19:2020.

[26] 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.

[27] Department of Energy (2021). *Cadmium Telluride*. Office of Energy Efficiency & Renewable Energy. Retrieved from: https://www.energy.gov/eere/solar/cadmium-telluride. February 28, 2021. [Online Resource]

[28] Ultra Low-Carbon Solar Alliance (2021). "Thin Film PV Supply Chain". Retrieved from: https://ultralowcarbonsolar.org/ultra-low-carbon-solar/. February 28, 2021. [Online Resource]

1. Glass manufacturing
2. Semiconductor deposition
3. Cell definition
4. Module production, including glass, laminate, and frame

Because of the integrated nature of thin-film module production, these four processes can be considered together as a single unit-process.

Photovoltaic Module Life Cycle Data Availability

The life cycle global warming potential of crystalline silicon module is largely determined by the solar-grade silicon & ingot production, due to the energy intensity of the process and the respective supply chain of electricity[10]. The most recent LCA data available for solar PV module production has recently been compiled by IEA PVPS Task 12, providing an opportunity to use the report as one of the foundations of the ULCS criteria[25]. Key components of this report include:

- Unit process LCI data for crystalline Silicon and Thin Film PV modules
- Electricity consumption on all process levels with specific electricity mixes by region
- Supply chains of the regions modelled based on the market shares by region
- Other inputs and outputs related to material, energy, and environmental efficiencies of the production in the different world regions

Enabling Procurement of Ultra Low Carbon Solar

The desired outcome of this process is an ULCS designation that distinguish solar modules with low embodied carbon based upon life cycle assessment (LCA) framework, which can be used within procurement processes to specify buying of ULCS modules. The ULCS designation will be based upon criteria and approaches from existing life cycle studies, standards, and regulatory approaches. See the Appendix 1 for a listing of all applicable standards, labels and voluntary agreements expected to be considered as part of ULCS designation development.

Several factors will be considered throughout the criteria development process, including but not limited to the following:

- The suitability of the unit processes within the IEA PVPS Task 12 LCI to form the basis of an ULCS designation
- The importance of specific process flows, e.g. recycling rates, for reusing internal manufacturing waste.
- The appropriate level of geographic or process resolution for energy grid mix emission factors
- Usability on a global scale, including geographies and technologies not currently covered in the IEA PVPS Task 12 LCI.
- Comparability of environmental footprint information provided by multiple bidders as part of a procurement processes.8

- Application of Energy Attribute Certificates (EAC)[29] as renewable energy credits
- Companies ranging in size from small to large, and ones with different levels of understanding and experience with broader environmental issues.
- Verification that procured PV modules are conforming with modelled CO2e data
    - Specifically, the method to verify accuracy of energy input carbon intensity and other critical life cycle flow assumptions such as recycled content
- Relationship between the ULCS criteria and EPEAT NSF/ANSI 457 – 2019 Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters

[29] An Energy Attribute Certificate, or EAC, is a certificate that provides information about the environmental attributes of one megawatt hour (MWh) of electricity. EACs verify that one megawatt-hour of electricity was generated and fed into the grid from an eligible renewable source.

Certification Pathways

The intent of this criteria development is to establish two pathways for manufacturers and suppliers to certify their PV modules using LCA modelling results made in alignment with ISO 14040/4 and supporting standards (*Figure 5*). The two pathways will be developed in partnership with stakeholders following a voluntary consensus process to determine what the system boundaries and processes of the pathways. The pathways will be modelled after the French government procurement regulations to offer the following:

- Path A – Fast track that leverages standardized life cycle carbon footprint values (i.e., secondary data) pre-determined by countries and by unit processes and likely verified by accredited processes to confirm origin of components
- Path B – Validated track that calculates life cycle carbon footprint based primarily on primary data as per ISO 14040, 14044 and 14067, and reported by the manufacturer or supplier of the PV module, including associated appropriate verification processes.

While Path B provides more flexibility to use manufacturer or supplier-specific data than Path A, it also requires third-party validated adherence to LCA standards to ensure accuracy and credibility. Several standards already exist for LCA and EPDs for building products and specific to PV modules (see Appendix 2 for summary and comparative information for useful and applicable standards). These will be reviewed and evaluated with consideration of parameters that significantly affect the PV module carbon footprint and its interpretation, such as functional unit and system boundary, production electricity mix, recycled content, and benchmark.

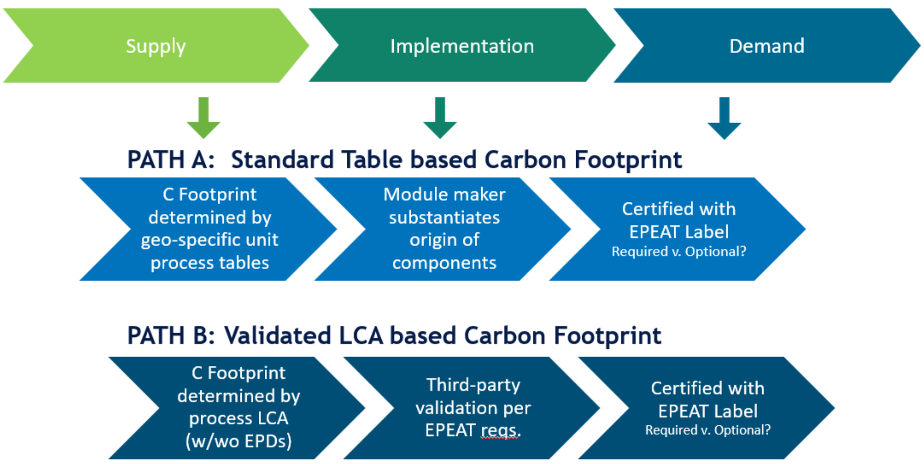

Figure 5 Preliminary ULCS Certification Pathways

Path Forward

Criteria Development Process

It is expected that the ULCS criteria development and implementation process will comprise of several key milestone represented in *Figure 6*. The criteria drafting and finalization process is expected to take place from April 2021 through Fall 2021. An Expert Ad Hoc Group will be formed to support the criteria drafting process, consisting of manufacturers, suppliers, academia, government entities, and non-profit organizations. Once the full draft criteria are complete and ready for review, it will be submitted to a broader multi-stakeholder Technical Committee for review and agreement via a Voluntary Consensus Process adopted by GEC. At this point, the criteria will be made available for a 30-day public consultation period anticipated to occur in Fall 2021.

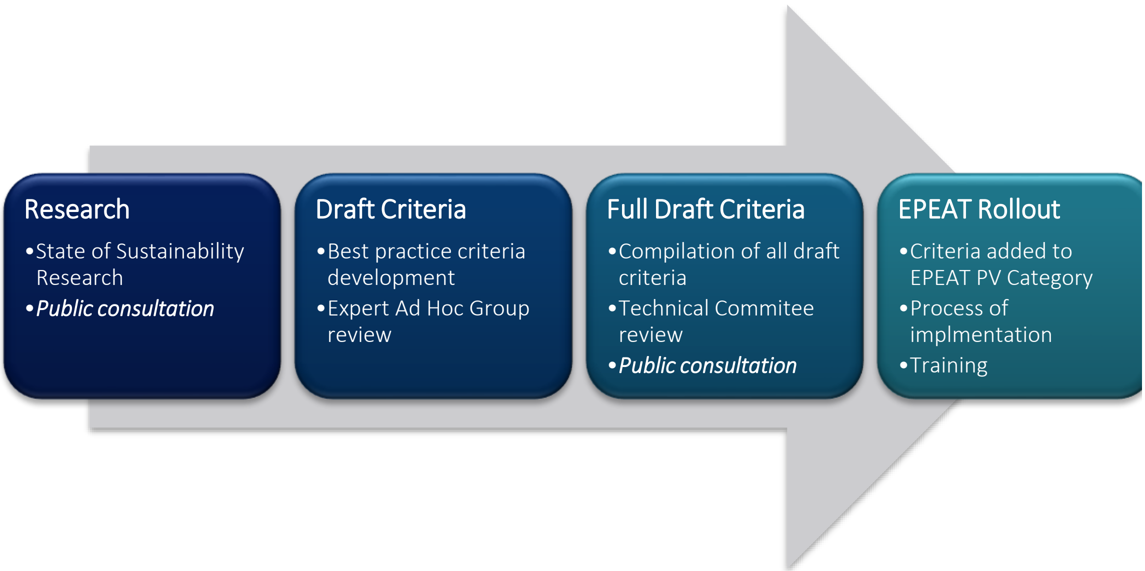

Figure 6 Expected Process for ULCS Designation Creation

Appendix 1: Applicable Standards, Labels and Voluntary Agreements

Life Cycle Assessments (LCA) guidance has also been developed – both broadly, and more focused on PV systems:

- ISO 14067 Greenhouse gases — Carbon footprint of products
- ISO 14040/44 Environmental management — Life cycle assessment
- IEA PVPS Task 12 — Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems
- IEA PVPS Methodology — Guidelines on Life Cycle Assessment of Photovoltaic Electricity

There are a number of labels and voluntary agreements that have been developed globally. A few of the more recognized are:

- NSF 457 — Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters
- EPEAT Ecolabel — Based on NSF 457

On a broader perspective, there are a number of systems that provide guidance for development of Product Category Rules.

- PEFCR — Products Environmental Footprint Category Rules
- PCR EPD Norway – The Norwegian EPD Foundation search database
- EPD Italy — PCR for PV Panel: EPDItaly 014 – rel. 1
- UL PCR — Verify Environmental Product Declarations by using existing PCRs created by other program operators
- European PCR — The International EPD System search database
- PEP Ecopassport PCR — PEP is an environmental identity card
- Carbon Leadership Forum – E3 Database of EPDs

Other related guidance and/or standards.

- GHG Protocol Product Standard – Product Life Cycle Accounting and Reporting Standard to evaluate full lifecycle GHG emissions of a product
- IEC TR 62726:2014 Ed. 1.0 – Guidance on quantifying greenhouse gas emission reductions
-

Appendix 2. Comparison of existing LCA and EPD standards and guidelines applicable to solar photovoltaics.

	PEFCR[a]	French tender[b]	EN 15804[c]	Norway PCR[d]	IEA PVPS Task 12[e]	EPEAT/NSF 457[f]	UL PCR[g]	ISO 14067[h]	Italy PCR[i]	Korea tender[j]
Functional unit	kWh DC	kWp	-	Wp	kWh	kWh	-	-	kWh	kWp
Reference flow	kWp	-	-	-	kWp	kWp	-	-	-	-
System boundary	Roof-mounted PV system excluding inverter and AC cabling	PV module excluding frame	-	PV module	PV system (roof residential, roof commercial and ground mount utility scale)	PV system	-	-	PV system	PV module including frame
Life cycle stages	Cradle to grave	Cradle to gate	Cradle to grave	Cradle to grave	Cradle to grave	Cradle to grave	Cradle to gate or Cradle to grave	Cradle to grave	Cradle to grave	Cradle to gate
Background data	EF-compliant	Ecoinvent	-	Ecoinvent	Ecoinvent	Refers to PEFCR or IEA PVPS Task 12	Ecoinvent, Gabi, others	-	Ecoinvent	Ecoinvent LCI DB ver 3.5
Production electricity mix	Can be supplier-specific and requires guarantee of origin or onsite generation	National mix	-	National mix	The electricity consumption on all process levels is modelled with specific electricity mixes corresponding to these world regions (Europe, China, Americas, APAC)		Regional or national mix. Supplier-specific mix with guarantee of origin can be reported separately.	Can be supplier-specific and requires guarantee of origin or onsite generation or direct connection to generator	National mix, national residual mix, or supplier-specific with guarantee of origin or residual mix	IEA Electricity information 2018: World gross electricity, by source
Transport data	All Transport	Transport to production facility	Rules provided	All Transport	All transport		All transport	All transport	All transport	-
Data quality	Rules provided	-	Rules provided	Rules provided	unit process data provided in LCI report		Rules provided	Rules provided	Rules provided	-

	PEFCR[a]	French tender[b]	EN 15804[c]	Norway PCR[d]	IEA PVPS Task 12[e]	EPEAT/NSF 457[f]	UL PCR[g]	ISO 14067[h]	Italy PCR[i]	Korea tender[j]
Allocation	Rules provided	-	Rules provided	Rules provided	unit process data provided in LCI report		Rules provided	Rules provided	Rules provided	-
Recycled content	Rules provided	Max 25-34%	Follows allocation rules	Follows allocation rules	unit process data provided in LCI report		Rules provided	Follows allocation rules	Follows allocation rules	-
Reporting	Rules provided	By component	Rules provided	By component	Rules provided		Rules provided	Rules provided	Rules provided	By component
Impact Categories	ILCD	GWP100	ILCD	ILCD	ILCD	ILCD, Traci, CML, or LIME	Traci, CML, others	IPCC GWP-100	IPCC (2013) GWP-100	GWP100 (IPCC 2007)
Verification	Yes	Yes for Method 2	Yes	Yes	-	Yes or peer-reviewed journal publication	Yes	Optional	Yes	Yes for Method 2
Benchmark	Representative product	50-1150 kg CO2-eq/kWp	-	-	-	Representative product	Rules provided	Rules provided	Rules provided	<670 to >830 kg CO2-eq/kWp
Chemical content	-	-	SVHC	IEC 62474	-	SVHC and IEC 62474	SVHC and other country-specific (Table 4)	-	SVHC	-

Notes:

a - https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm "Product Environmental Footprint Category Rules (PEFCR) PHOTOVOLTAIC MODULES USED IN PHOTOVOLTAIC POWER SYSTEMS FOR ELECTRICITY GENERATION Version 1.1"

b - https://www.cre.fr/ "Cahier des charges de l'appel d'offres portant sur la réalisation et l'exploitation d'Installations de production d'électricité à partir de l'énergie solaire « Centrales au sol »", Annexe 2

c - https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:70014,481830&cs=1538D502078F136C61227E09322AB3FD9

d - https://www.epd-norge.no/getfile.php/1313823-1591956540/PCRer/NPCR%20029%202020%20Part%20B%20for%20photovoltaic%20modules%20final%20version%20approved%20110620.pdf

e - https://iea-pvps.org/key-topics/task-12-methodology-guidelines-on-life-cycle-assessment-of-photovoltaic-electricity-3rd-edition/

f - https://www.techstreet.com/standards/nsf-ansi-457-2019?product_id=2091842

g - https://www.ul.com/offerings/product-category-rules-pcrs

h - https://www.iso.org/standard/71206.html

i - https://www.epditaly.it/en/pcr_/pcr-for-pv-module-epditaly-014/

j - https://www.knrec.or.kr