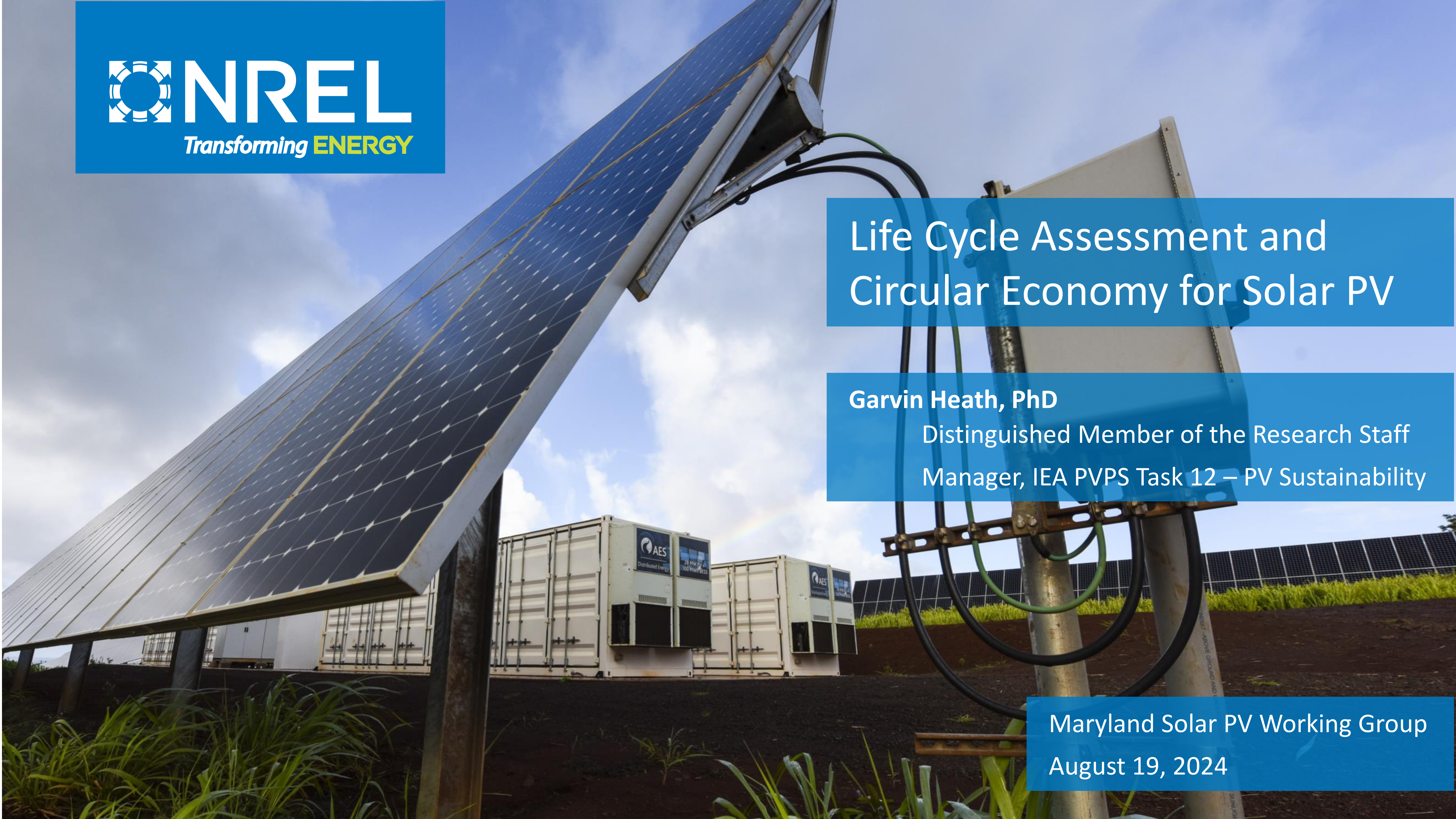


NREL
Transforming ENERGY

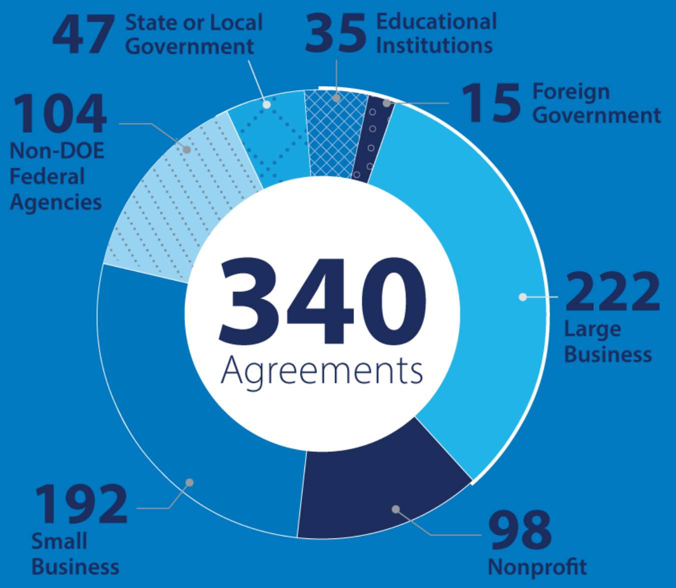
Life Cycle Assessment and Circular Economy for Solar PV

Garvin Heath, PhD
Distinguished Member of the Research Staff
Manager, IEA PVPS Task 12 – PV Sustainability

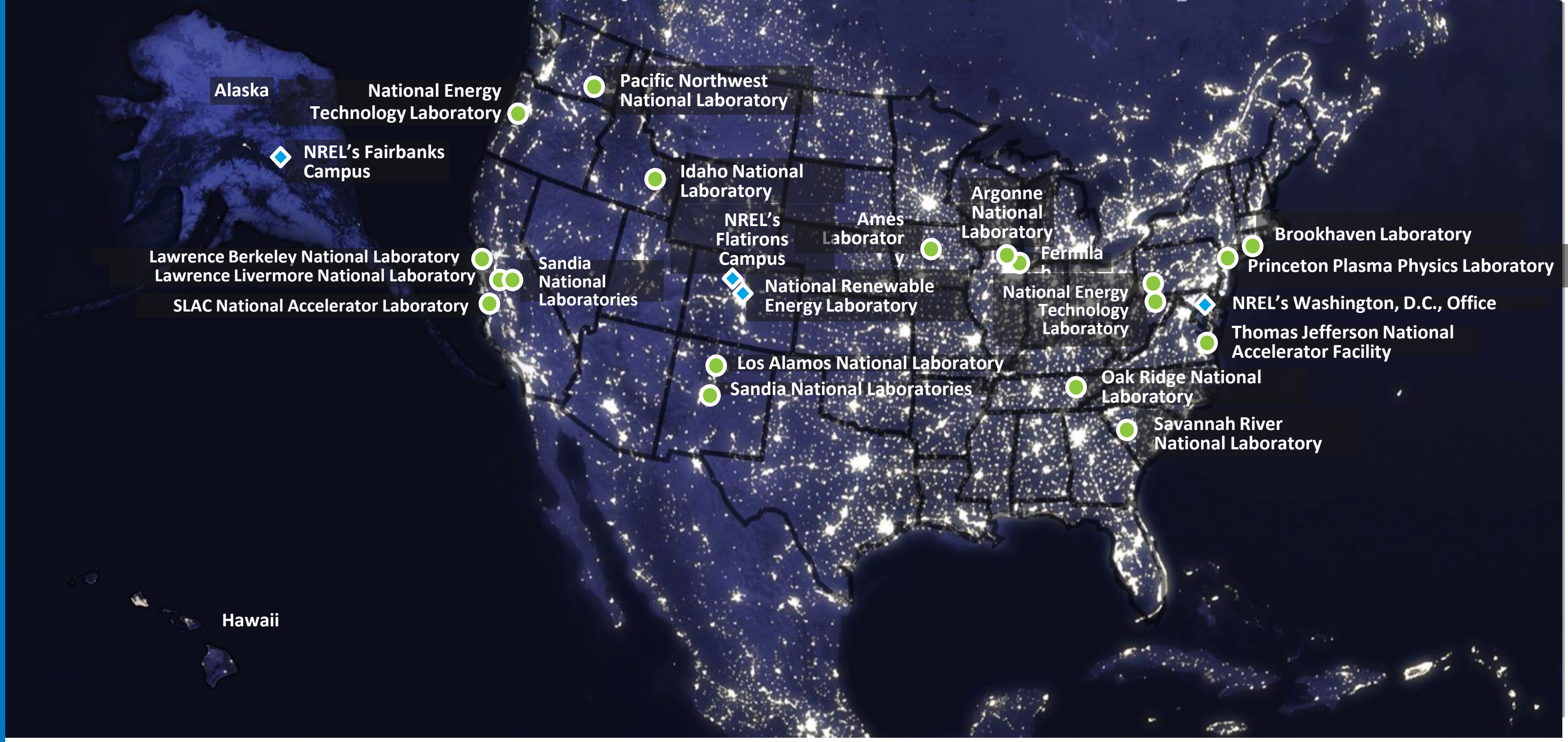
Maryland Solar PV Working Group
August 19, 2024

NREL at a Glance

More Than 1,100 Active Partnerships in FY 2023



Partnerships with:
Industry
Academia
Government



One of 17 DOE National Laboratories, only one with mission for renewable energy and energy efficiency

~4,000 person workforce

4 Campuses operate as living laboratories

World-class research expertise in:

- Renewable Energy
- Sustainable Transportation & Fuels
- Buildings and Industry
- Energy Systems Integration

NREL Science Drives Innovation

Renewable Energy

- Solar
- Wind
- Water
- Geothermal

Sustainable Transportation & Fuels

- Bioenergy
- Hydrogen and Fuel Cells
- Transportation and Mobility

Buildings and Industry

- Buildings
- Industrial Efficiency and Decarbonization
- Advanced Materials and Manufacturing
- State, Local, and Tribal Governments

Energy Systems Integration

- Energy Security and Resilience
- Grid Modernization
- Integrated Energy Solutions

Photo by Werner Slocum, NREL 66364

What is IEA PVPS Task 12 – PV Sustainability

Photovoltaic Power Systems Programme (PVPS) is a Technology Collaboration Programme established within the International Energy Agency in 1993

- 32 members - 27 countries, European Commission, 4 associations
- *“To enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems”*

The goal of Task 12 is to foster international collaboration and knowledge creation in PV environmental sustainability.

Task 12 Subtasks

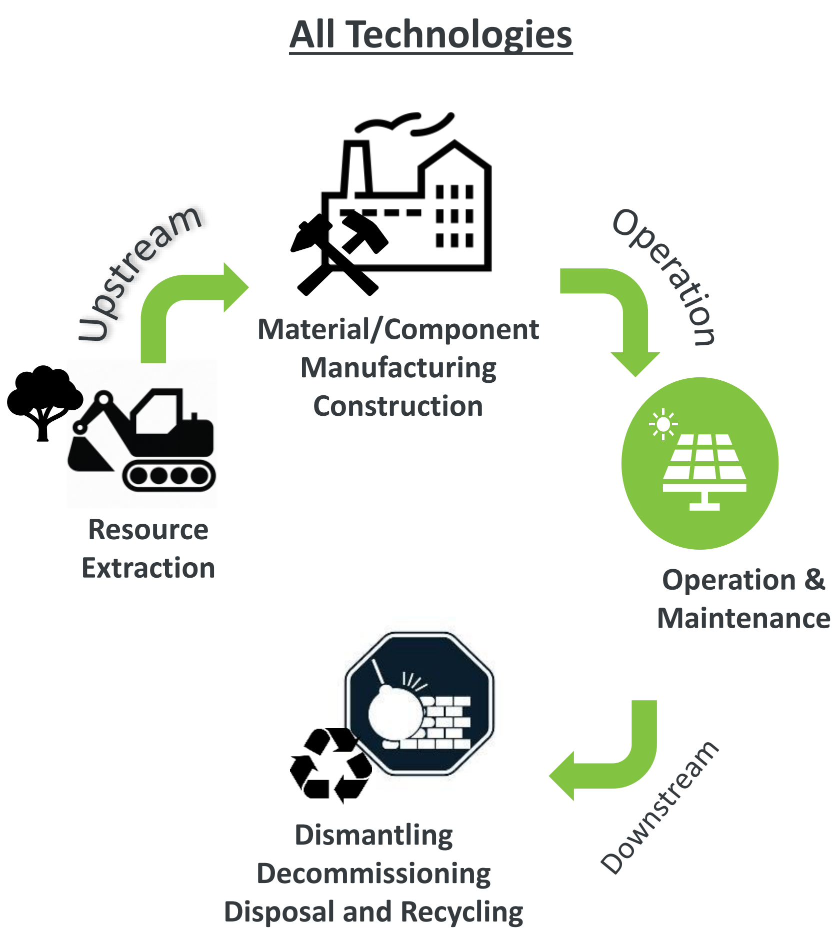
- PV Circular Economy
- Life Cycle Assessment (LCA)
- Ecosystem-integrated PV
- Other PV sustainability topics

Task 12 Managers

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

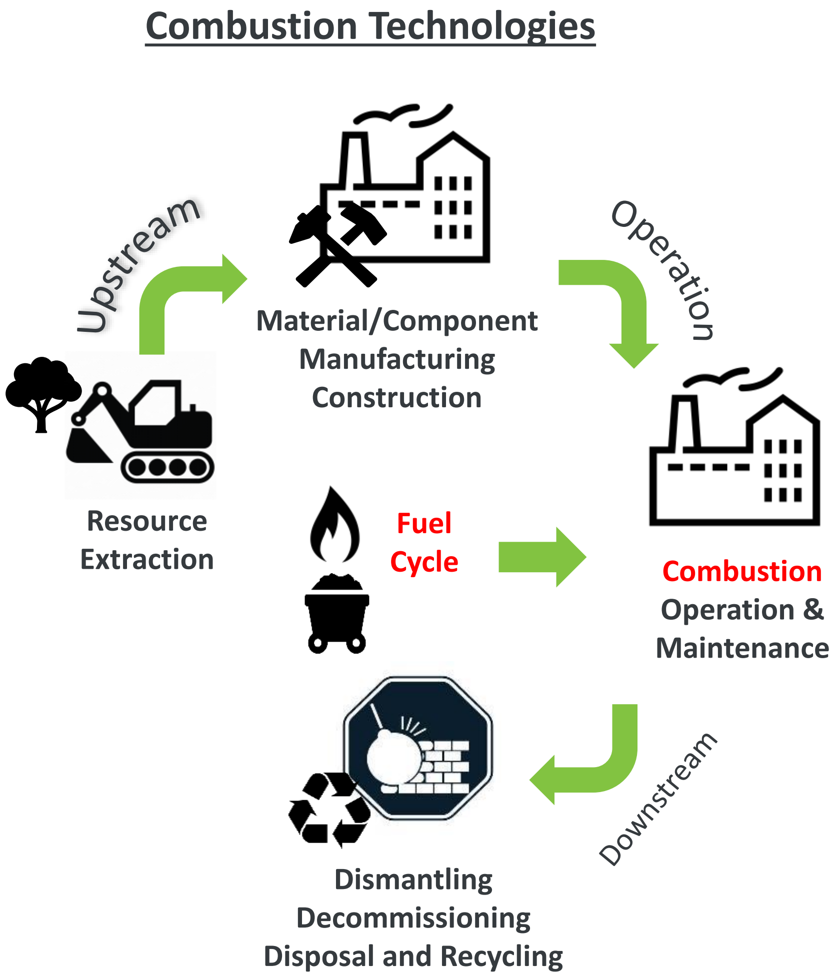
PVPS

The Life Cycle for Electricity Generation Technologies: Quantifying Attributable Impacts



Life Cycle Assessment (LCA) quantifies resource consumption, energy use, and emissions, from cradle to grave (or back to cradle)

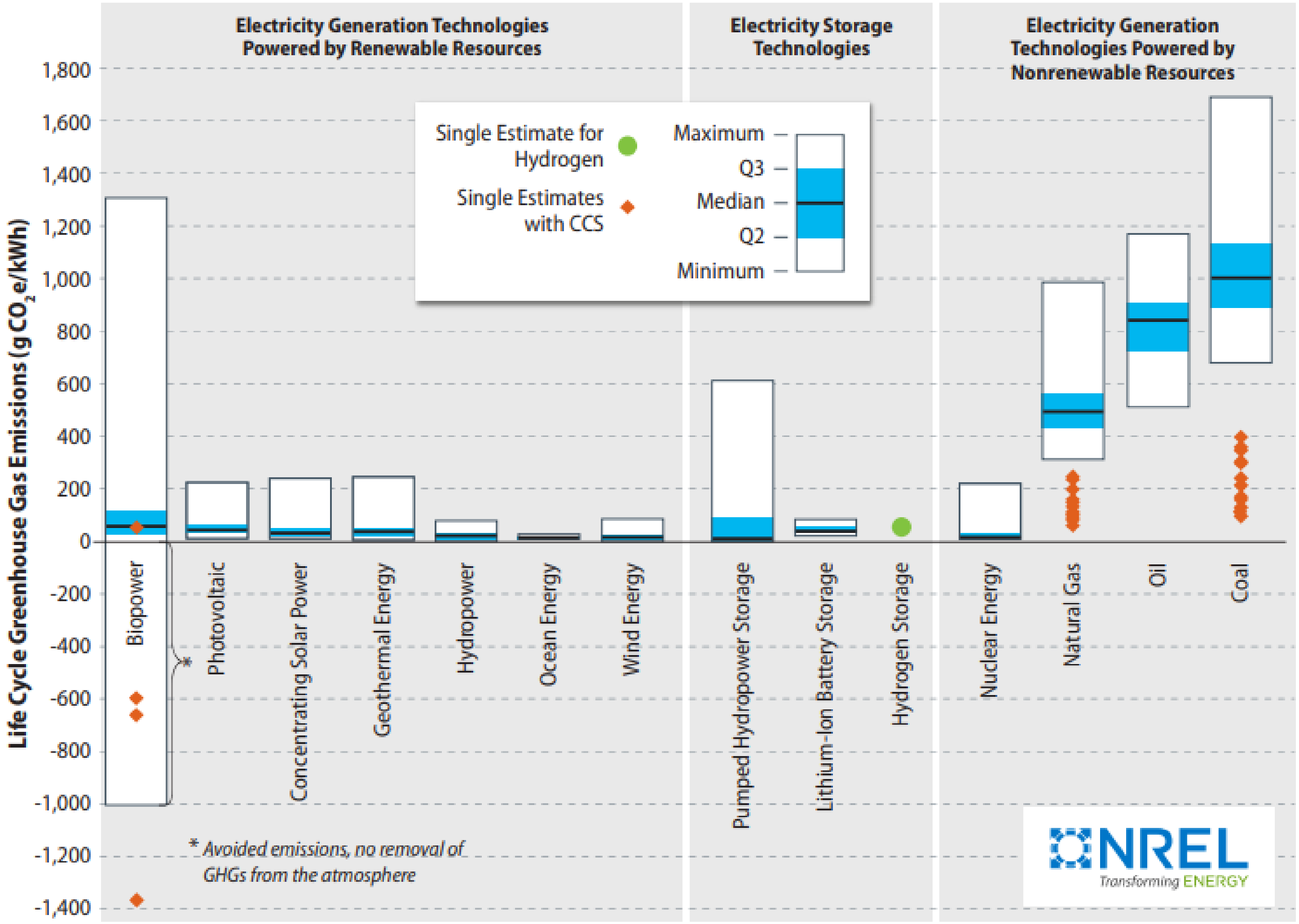
- Practiced for 40 years
- Methods codified in standards and guidelines



Systematic Review of Published Electricity Generation LCAs:

First published in the IPCC Special Report on Renewables (2012), updated through DOE Vision studies, and most recently in LA100

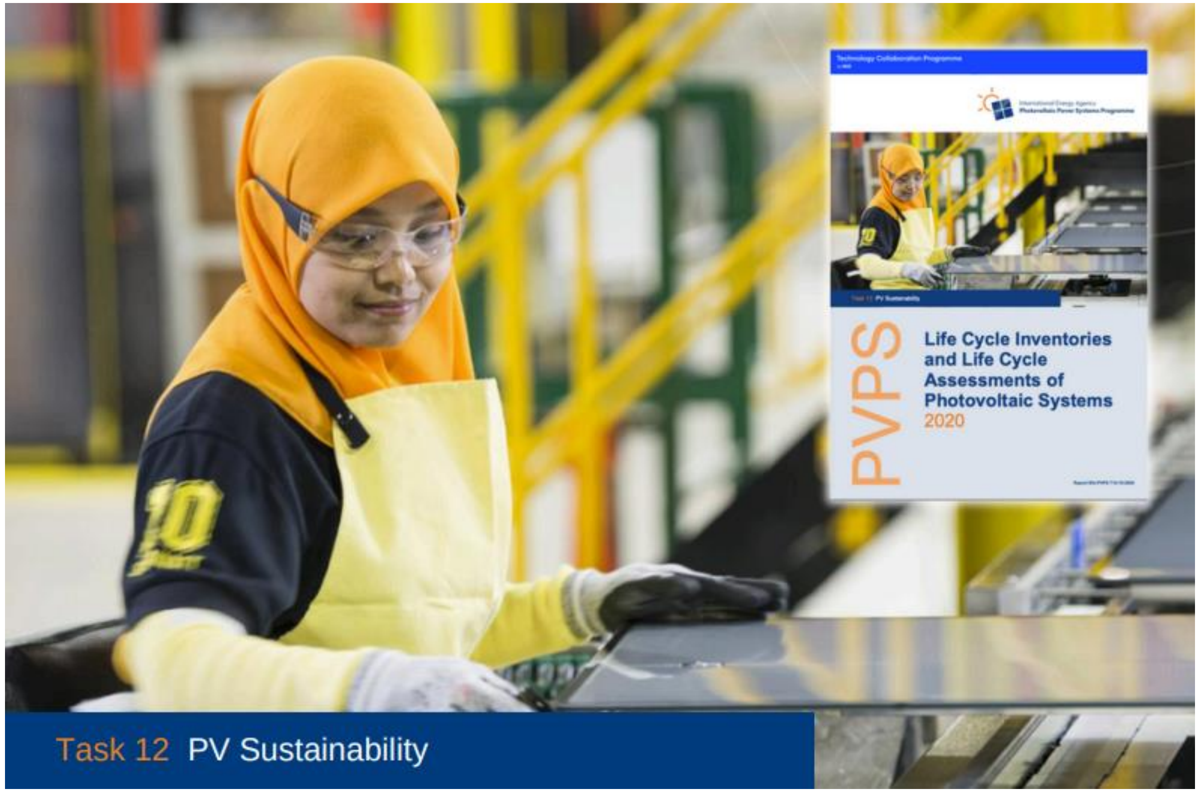
Figure 2. Life cycle greenhouse gas emission estimates for selected electricity generation and storage technologies, and some technologies integrated with carbon capture and storage (CCS).



	Biopower	Photovoltaic	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Pumped Hydropower Storage	Lithium-Ion Battery Storage	Hydrogen Storage	Nuclear Energy	Natural Gas	Oil	Coal
Estimates	276 (+4)	46	36	35	149	10	186	16	29	1	99	80 (+13)	24	164 (+11)
References	57 (+2)	17	10	15	22	5	69	4	3	1	27	47 (+11)	10	53 (+9)

Source: https://www.nrel.gov/docs/fy21osti/80580.pdf

And data file: https://data.nrel.gov/submissions/171



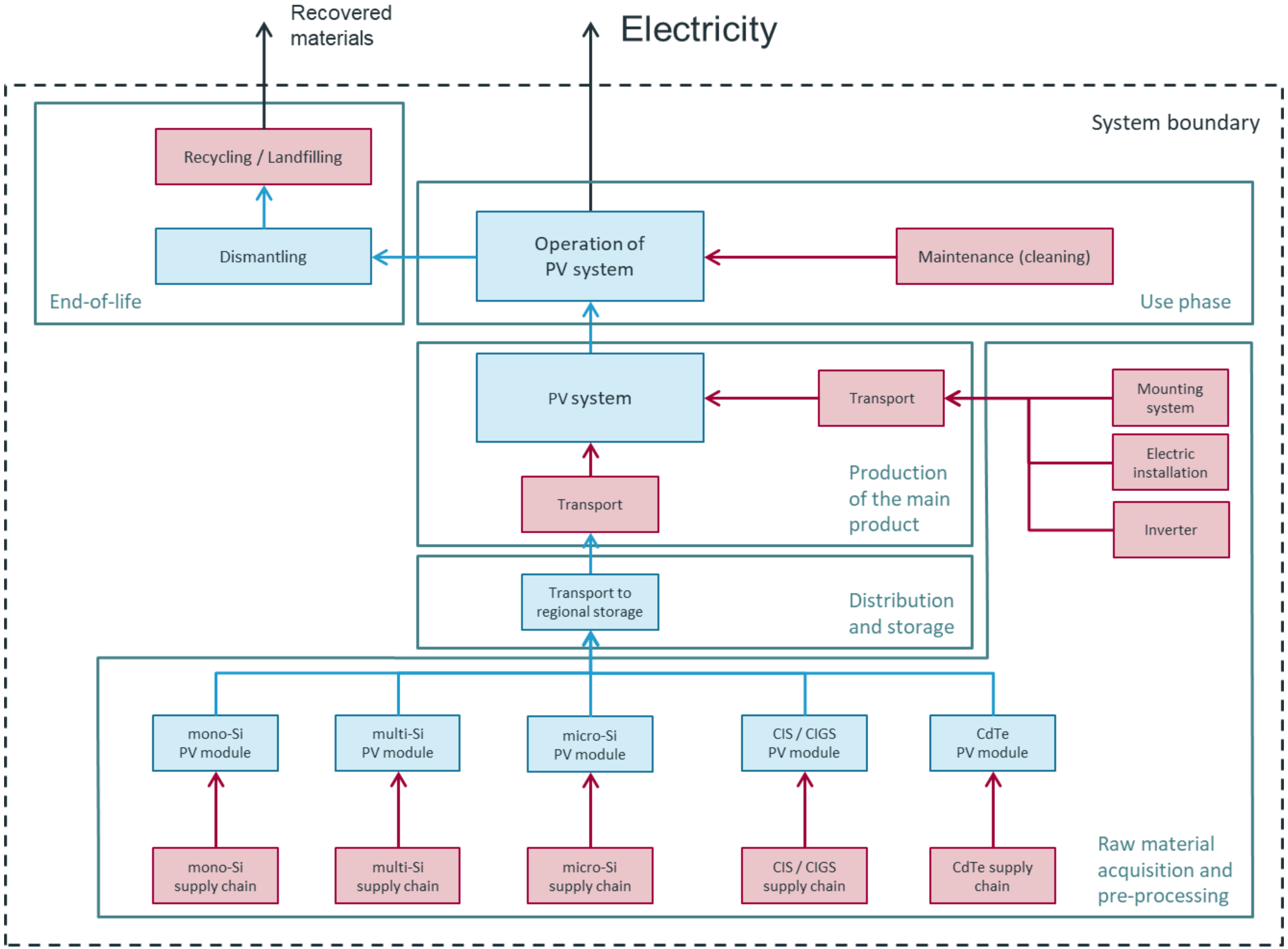
Environmental Life Cycle Assessment of Electricity from PV systems – 2023 data update

Authors: Stucki, M., Götz, M., de Wild-Scholten, M. , Frischknecht, R.

April 2024

https://iea-pvps.org/wp-content/uploads/2024/05/Task-12-Fact-Sheet-v2-1.pdf

Product System and System Boundary PV Electricity Generation



IEA PVPS Report T12-19:2020

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.

Key Parameters and 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) 2.8 (back)
electricity consumption					
- metallurgical grade silicon	kWh/kg	12			
- polysilicon production	kWh/kg	52.3 (electricity) + 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)

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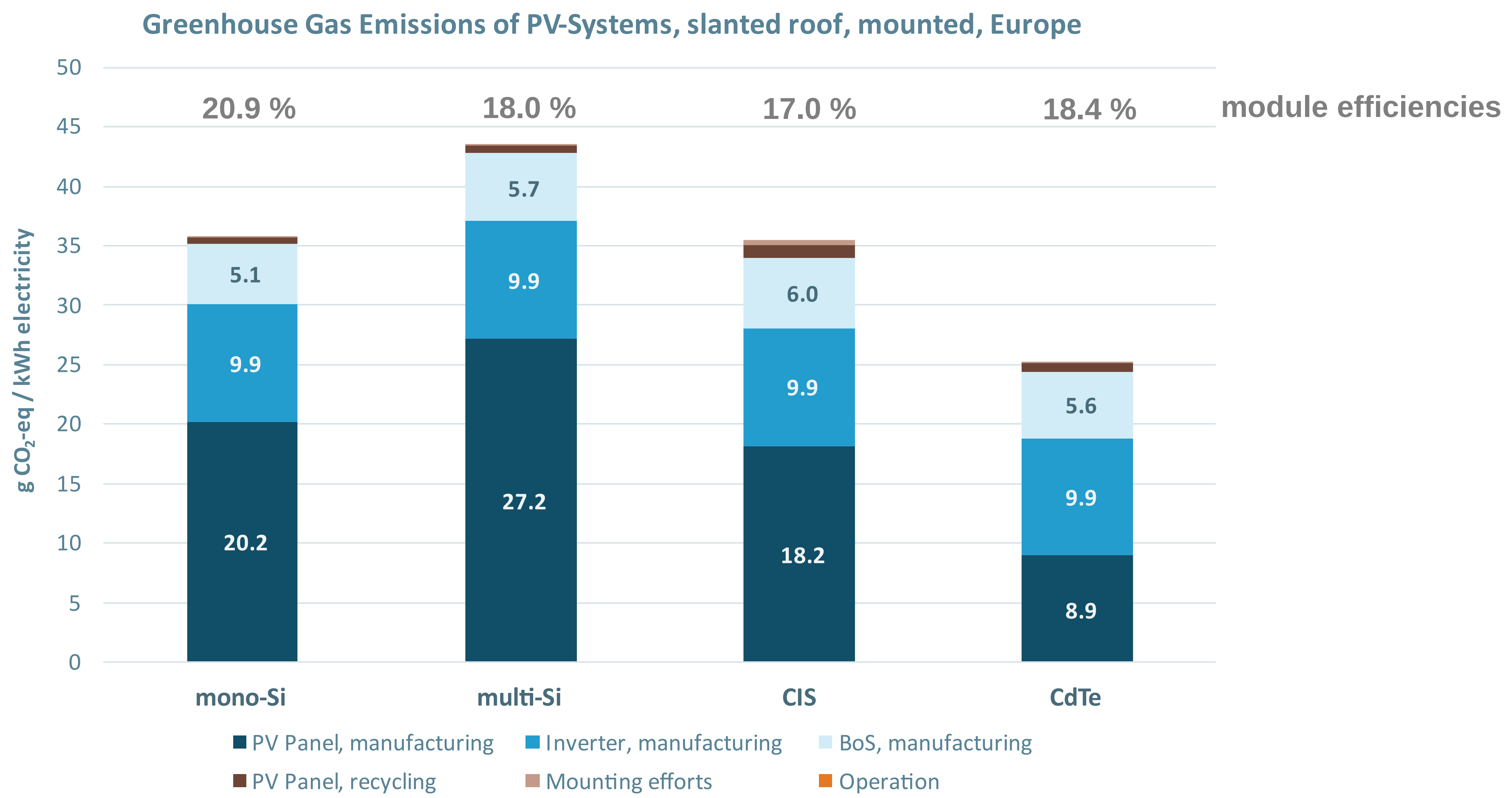
Greenhouse Gas Emissions 1 kWh PV-System 3kWp



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)

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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.

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.

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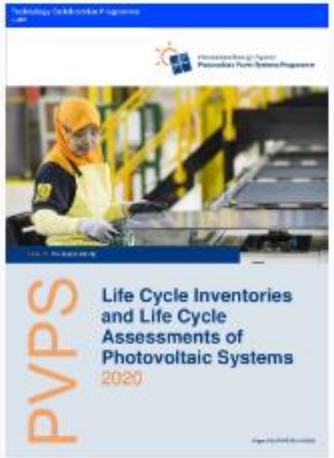
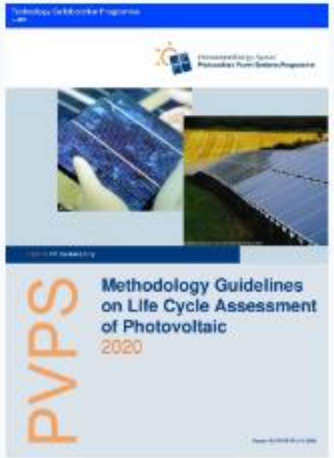
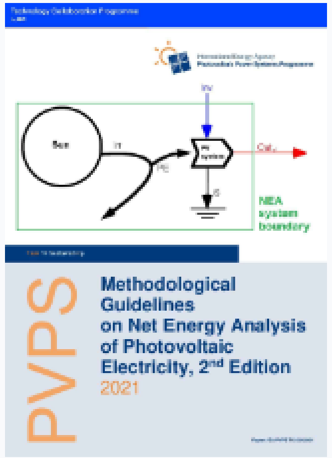
Other Relevant Task 12 LCA Publications



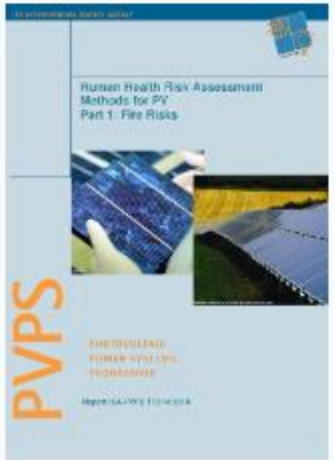
Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems



Methodology Guidelines on Life Cycle Assessment of Photovoltaic 2020



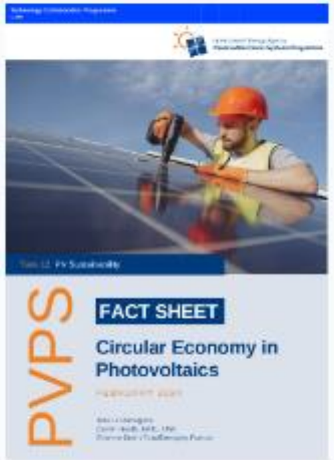
Methodological Guidelines on Net Energy Analysis of Photovoltaic Electricity, 2nd Edition



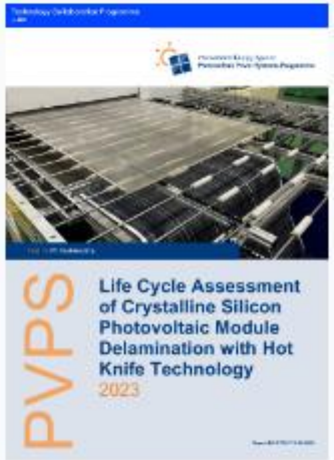
Human Health Risk Assessment Methods for PV part 1 – Fire risks

Human Health Risk Assessment Methods for PV part 2 – Breakage risks

Human Health Risk Assessment Methods for PV Part 3: Module Disposal Risks



Fact sheet: Circular Economy in Photovoltaics

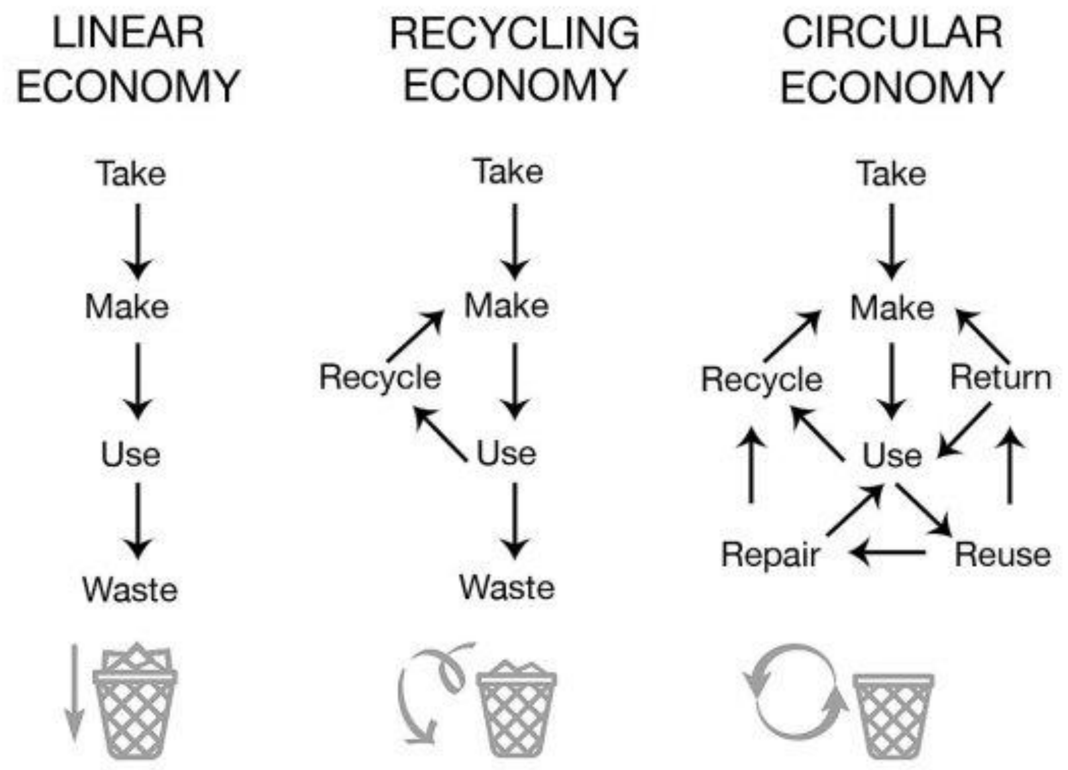


Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology

All found here: https://iea-pvps.org/research-tasks/pv-sustainability/

What is a **Circular Economy?**

A *circular economy* shifts from a take-make-waste linear economic model to one that retains the value of materials and products as long as possible, recovering materials at end of life to recirculate back into the economy.



- Defined as opposed to our current linear economy
- Goes farther than recycling only
  - The recycling economy is the current focus of research, investment, and policy
  - Fits easiest into our current linear system.

Image source: https://rfittingroom.com/circular-vs-linear-economy/

Expanding on the Elementary School Mantra: The 10 Rs

- Prioritized from top to bottom
  - Logic: the more you change what's already manufactured, the more value you lose and greater effort/cost/carbon.
  - If you do not use materials in the first place, all the better.
- Some variability in R strategy definitions
  - A manufacturer or consumer perspective can be used for the lower-numbered R strategies.
  - Literature largely focuses on the manufacturer perspective and thus is the focus of our review.
- Application of the terms can vary
  - For example, refurbish, repair and remanufacture are often used synonymously.
  - For consistency, we enforce our definitions to sometimes change the author-identified R strategy.

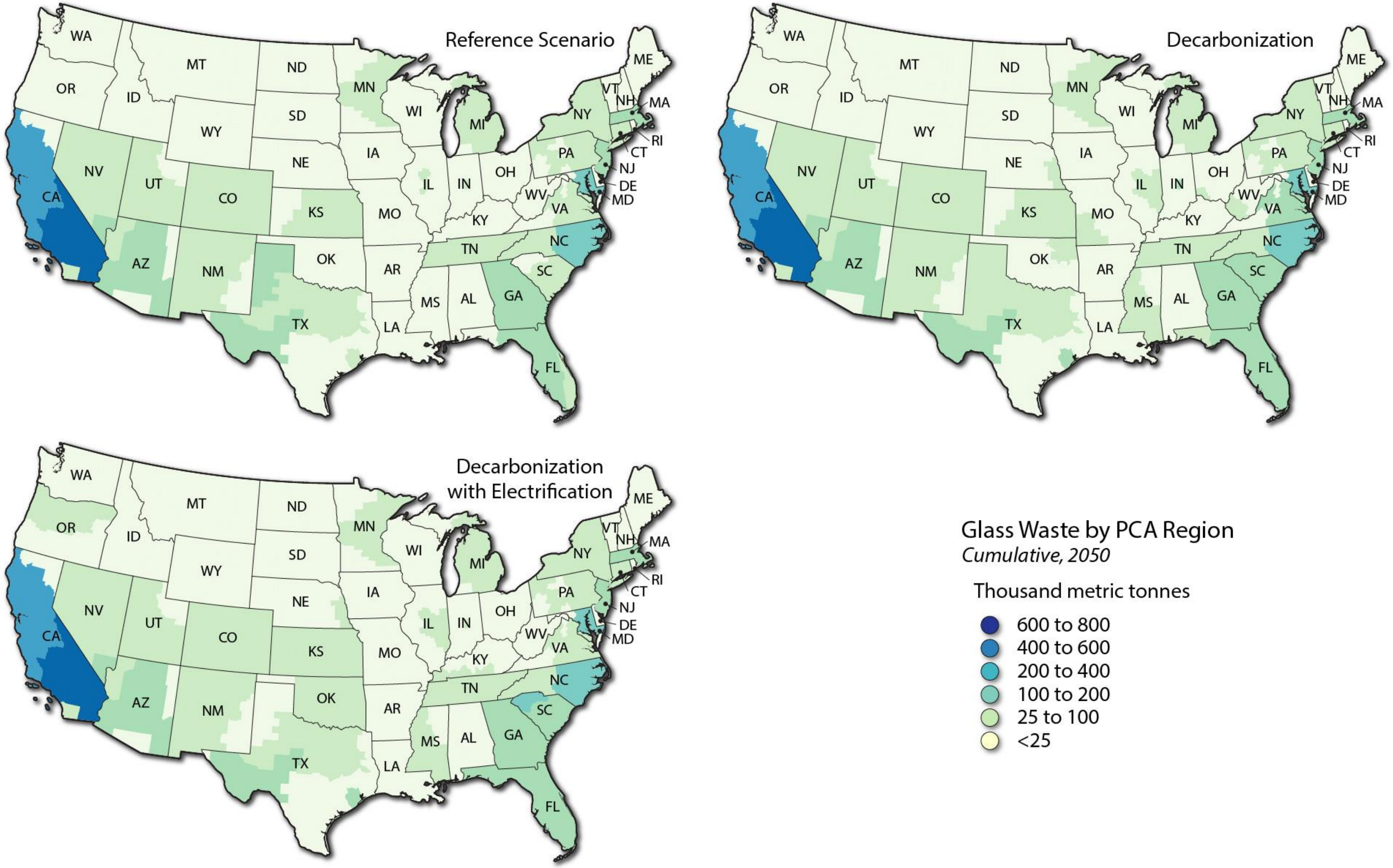
Circular Economy

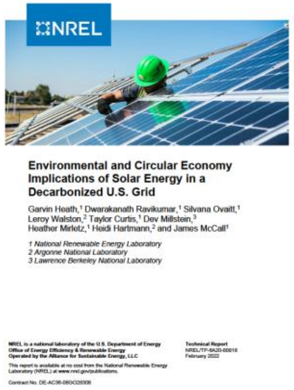
Linear Economy

CE Strategy	
Smarter product use and manufacture. Parts of these strategies contribute to Design for Circularity	R0 – **Refuse**
	R1 – **Rethink**
	R2 – **Reduce**
Extend lifespan of product and its parts	R3 – **Reuse**
	R4 – **Repair**
	R5 – **Refurbish**
	R6 – **Remanufacture**
	R7 – **Repurpose**
Useful application of materials	R8 – **Recycle**
	R9 – **Recover**

Source: Adapted from Potting et al. 2017, Reike, Vermeulen, and Witjes 2018; Morseletto 2020

Low Volumes Now, End-of-Life (EOL) PV Will be Significant Challenge in Future – USA

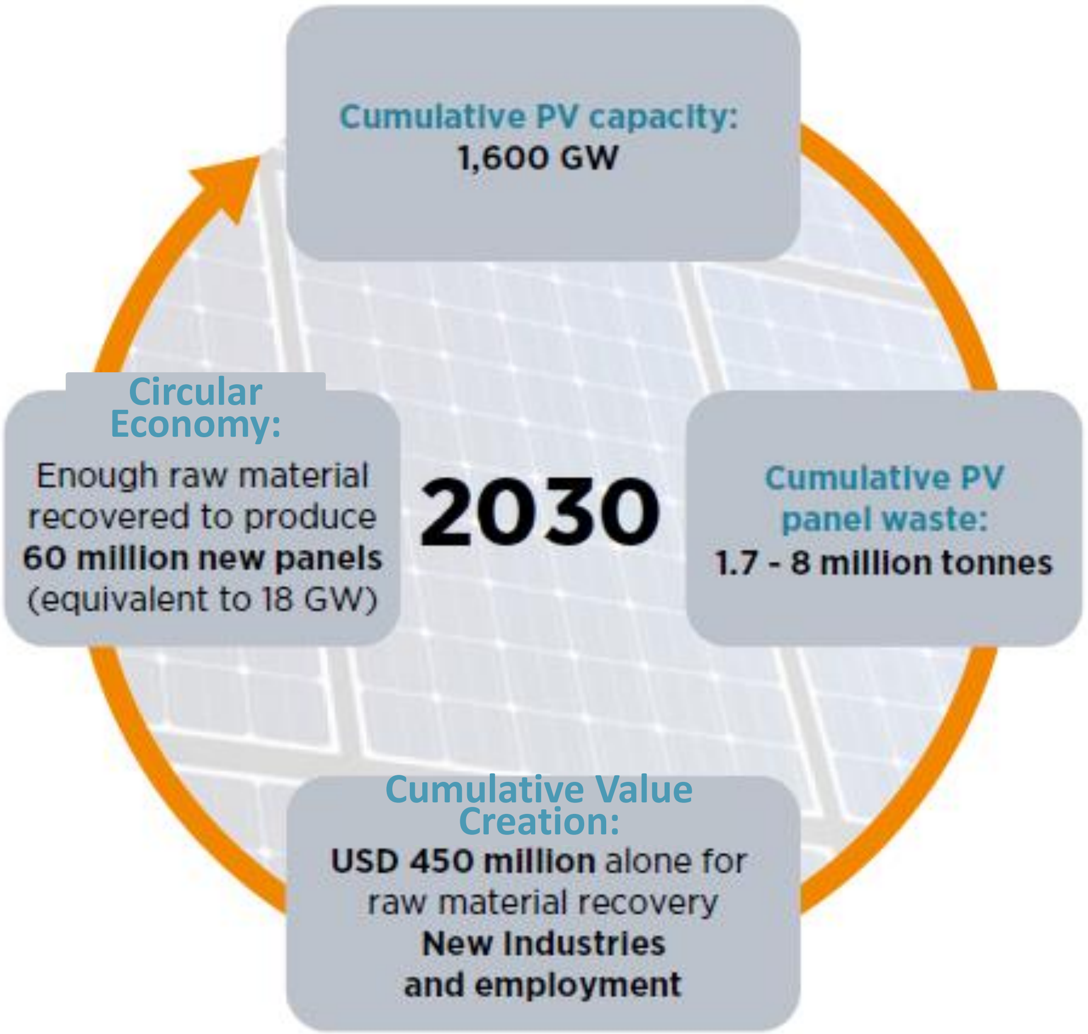


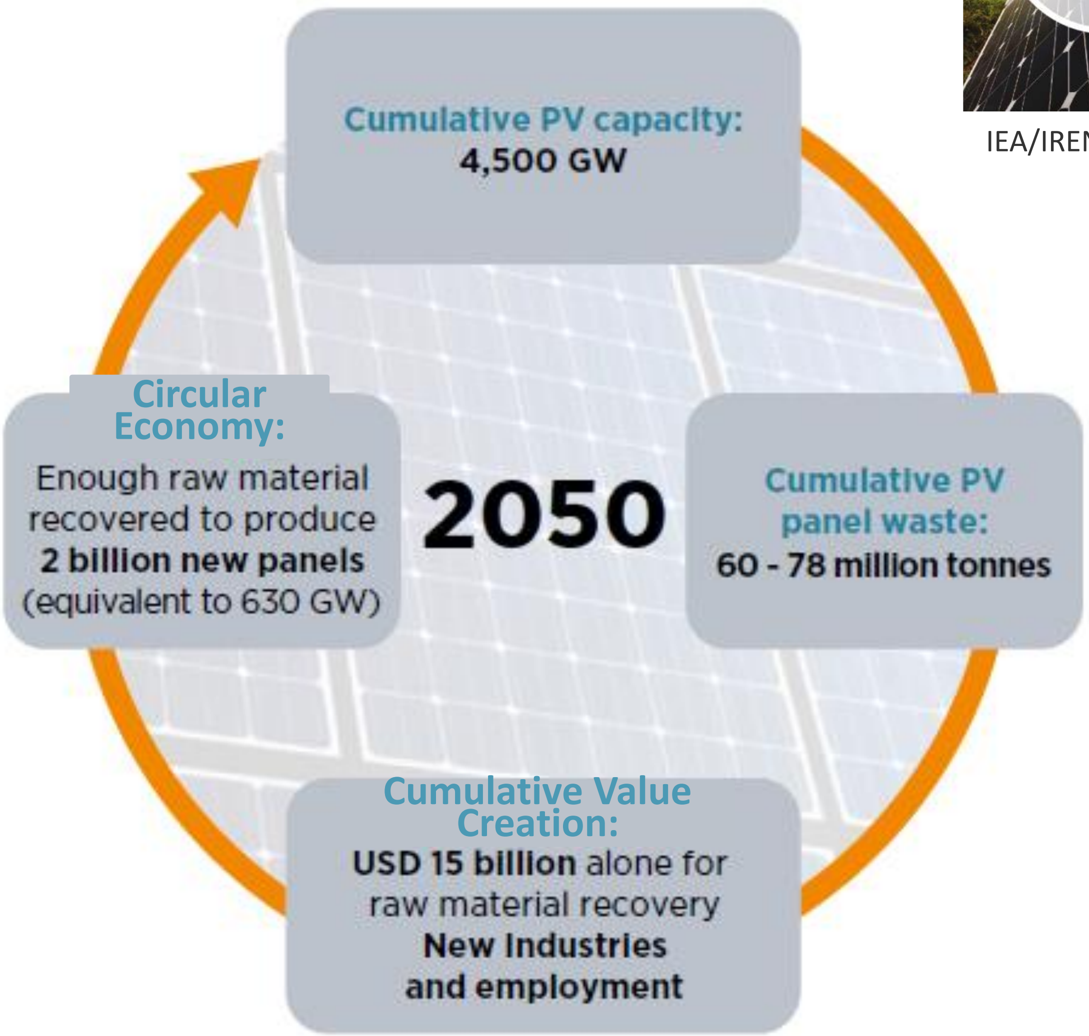


Heath et al. 2022

Output from NREL PViCE model

Potential Value Creation: EOL Recovered Materials





IEA/IRENA, 2016

Source: IEA/IRENA, 2016

Jobs

- "Recycling also creates more than 10 jobs for every 1 job created by landfilling waste (per ton)." (Lara Rezzarday, Waste Management Inc.)
- Opportunity to participate in the clean energy economy
- Circular economy strategies other than recycling require higher skill (e.g., repair)

Advances in Photovoltaic Module Recycling

K. Wambach, C. Libby, S. Shaw

Task 12 Report, May 2024

https://iea-pvps.org/wp-content/uploads/2024/06/IEA-PVPS-T12-28-2024-Report-PV-Recycling-LCI_EPRI.pdf

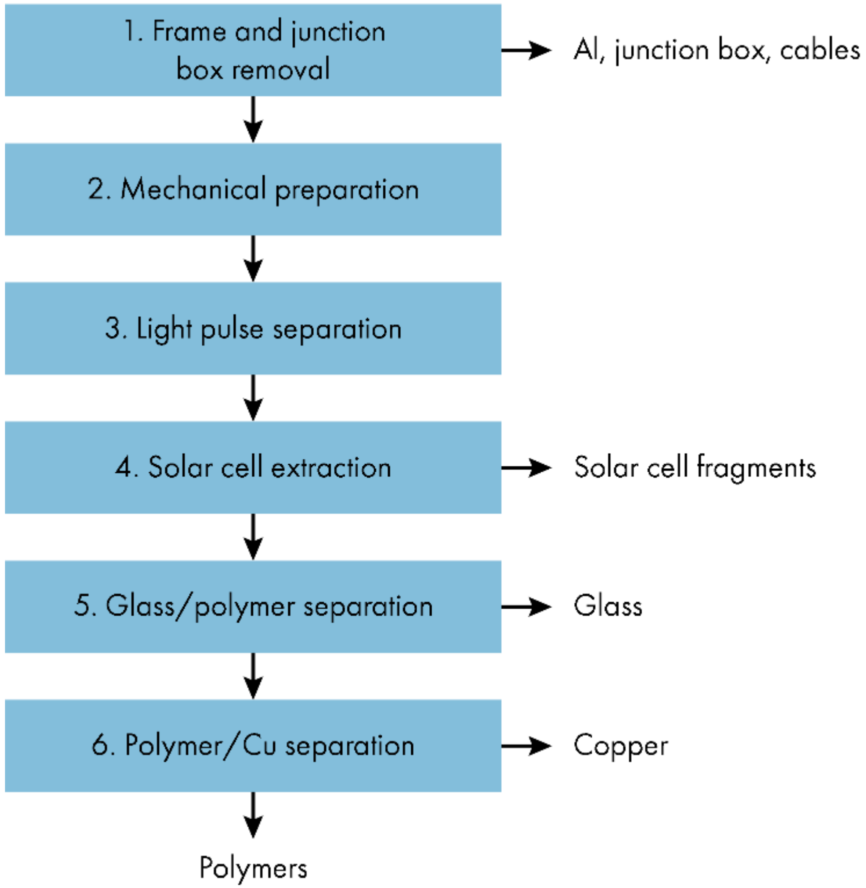
Literature Review and Update to Empirical Life Cycle Inventories and Patent Review

Study Objective

Identify advances in PV recycling technology that have the potential to be affordable, technically feasible, and environmentally responsible

Scope & Approach

- Survey global PV module recyclers identified through press releases, existing connections, past studies, and commercial activities
- Interview recyclers and conduct a life cycle inventory assessment, e.g., material recovery rates, energy consumption, water usage
- Analyze trends in patents and literature
- Identify knowledge gaps, technology development and demonstration needs, and collaboration opportunities



Example novel recycling approach:
Mobile mechanical and thermal recycling treatments developed by Flaxres GmbH

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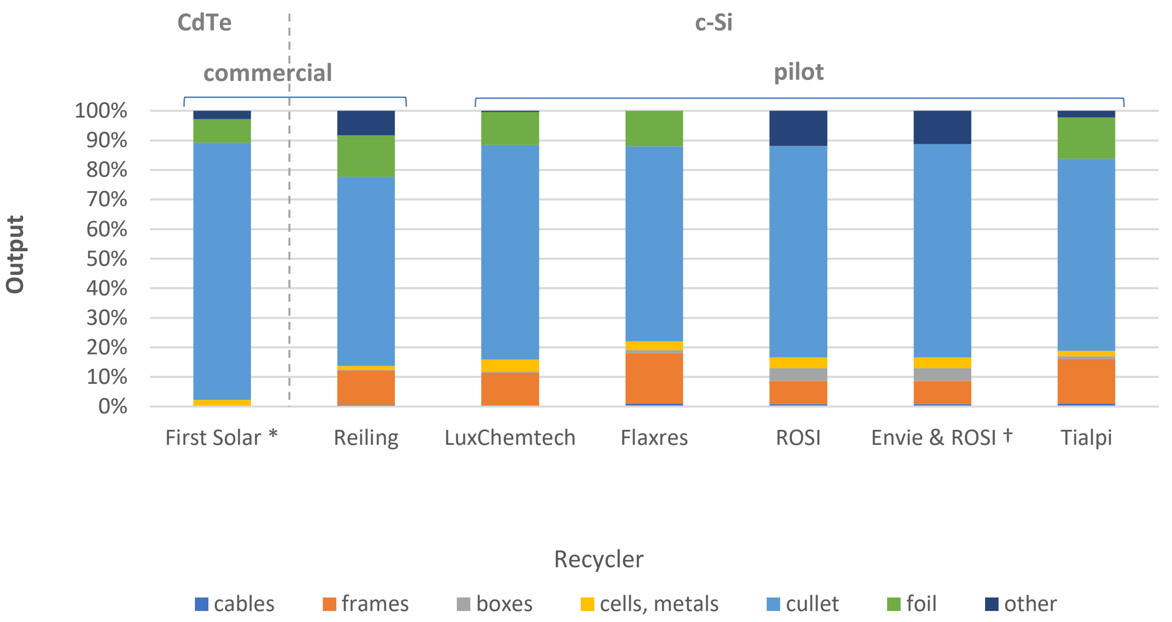
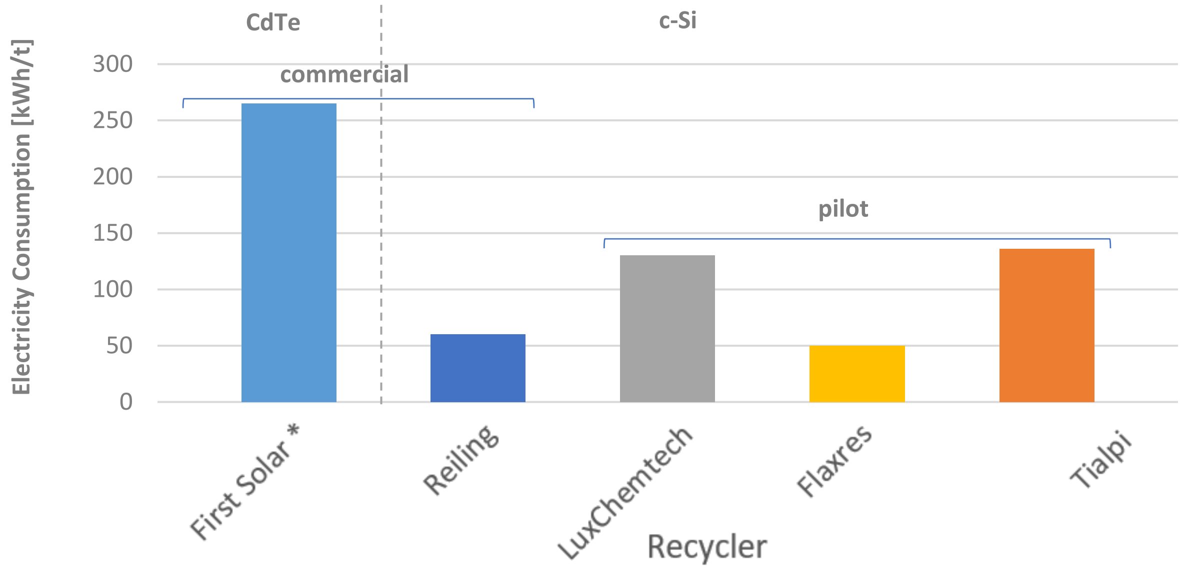
Summary of Recycling LCI Data

Relative Output Composition



Electricity Consumption



* First Solar LCI data includes recovery of cadmium and tellurium, whereas the system boundary for the other recyclers is at the point where a cell fraction (including metals) is separated from the glass and polymers. † Envie uses NPC's commercial process, but the combined Envie & ROSI process is considered a pilot.

Direct comparisons of LCI data are challenging due to differences in scale, module composition, projected vs. actual values, and full vs. partial treatments.

First Solar is an experienced CdTe recycler.

Reiling's improved mechanical process represents a fully commercial best available technology and sets a benchmark for maturity, cost, and low energy consumption.

Other recyclers have pilot-scale facilities using advanced thermal, mechanical, and/or chemical treatments to impr recovery.

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Thank You

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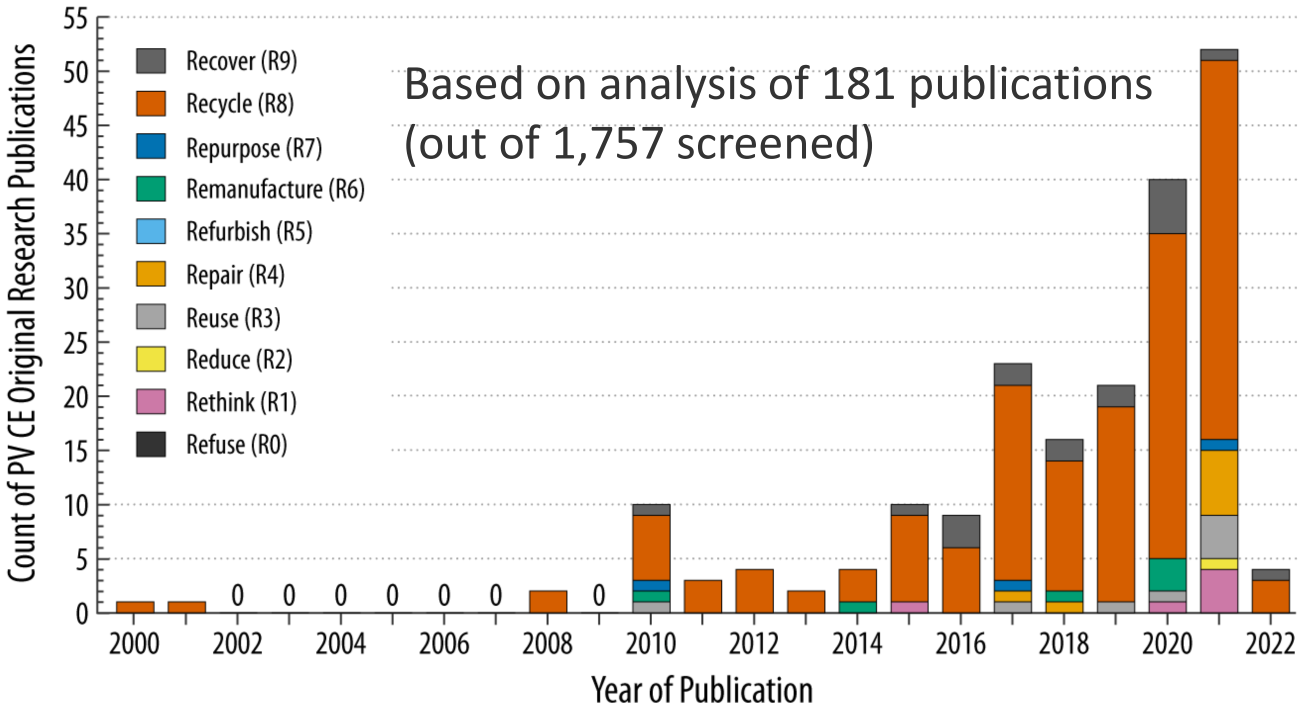
NREL's Conclusions on PV Circular Economy Research Needs



1. Expand research beyond recycling
2. Support technology deployment with economic, environmental and policy analysis
3. Leverage digital information systems
4. Improve recycling technologies
5. Study CE-related aspects of PV markets

Source: [Heath et al. "A critical review of the circular economy for lithium-ion batteries and photovoltaic modules – status, challenges, and opportunities." 2022]