Solar Energy Technologies Office:

Photovoltaics End-of-Life Action Plan Update

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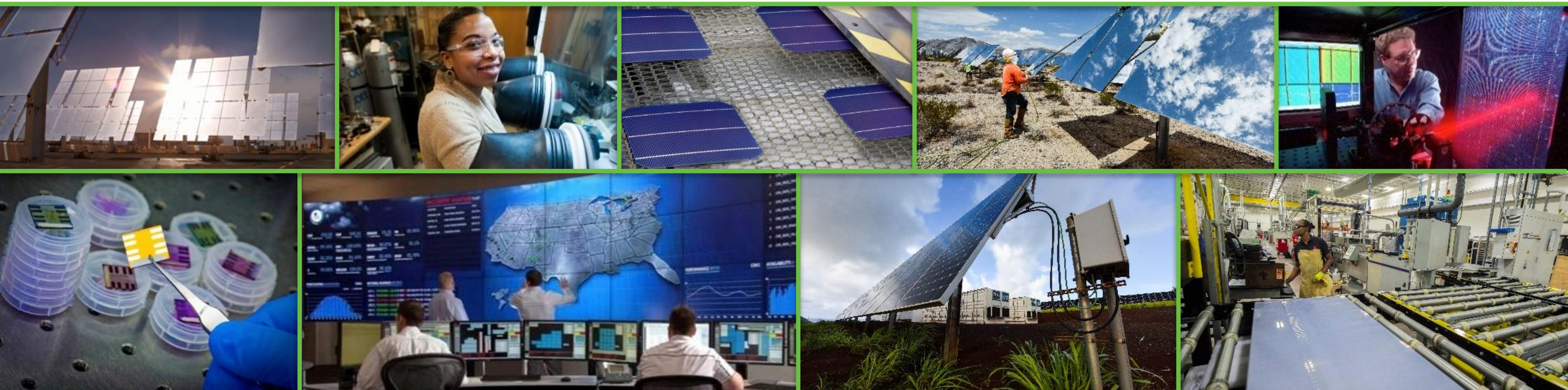
Susan Huang, PhD, Solar Energy Technologies Office (SETO)

Noreen Gentry, PhD, Boston Government Services Contractor Supporting SETO

October 21, 2024



DOE Solar Energy Technologies Office (SETO) Overview

MISSION

We accelerate the **advancement** and **deployment of solar technology** in support of an **equitable** transition to a **decarbonized economy no later than 2050**, starting with a decarbonized power sector by 2035.

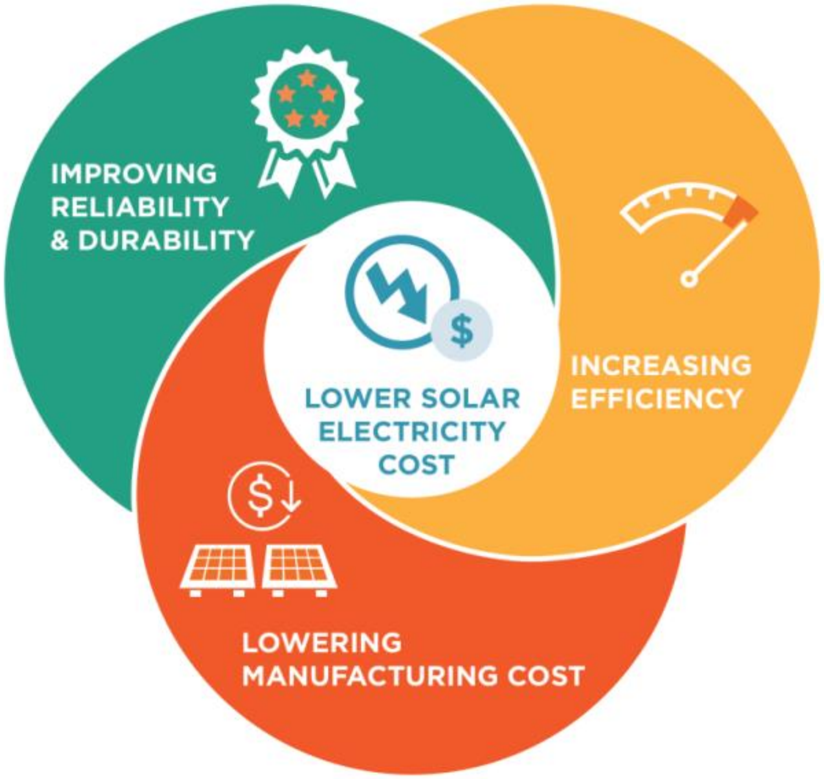
WHAT WE DO

Drive innovation in technology and soft cost reduction to make solar **affordable** and **accessible** for all Americans

Enable solar to support the **reliability**, **resilience**, and **security** of the grid

Support **job growth**, **manufacturing**, and the **circular economy** in a wide range of applications

Photovoltaics (PV) Research Area



Funds research with a 10–15-year horizon, to advance industry and deployment

Supports an innovation ecosystem that includes universities, national labs, and the private sector

Agenda

1. **SETO**
   - PV EOL Action Plan
   - PV Environmental Impact
2. **PV EOL Projects**
   - UC San Diego
   - National Renewable Energy Lab
   - SOLARCYCLE
   - EPRI
3. **Federal Agencies Update**
   - Advanced Materials and Manufacturing Technologies
   - Manufacturing and Energy Supply Chains
   - Environmental Protection Agency

"How else would I keep my solar panels in the sun all day?"

PV Impact: Waste Only Perspective

2017


ENVIRONMENTAL PROGRESS

ABOUT ENVIRONMENT ENERGY PEACE FACT CHECK NEWS GIVE

Are we headed for a solar waste crisis?

JUNE 21, 2017

2021


Harvard Business Review

Sustainable Business Practices

The Dark Side of Solar Power

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June 18, 2021

2020


WIRED BACKCHANNEL BUSINESS CULTURE GEAR MORE SIGN IN SUBSCRIBE

MADDIE STONE SCIENCE AUG 22, 2020 8:00 AM

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2023


CBS MORNINGS ›

A black eye for green energy? Renewable energy growth brings mounting waste challenge

By Ben Tracy, Analisa Novak

May 1, 2023 / 9:27 AM EDT / CBS News

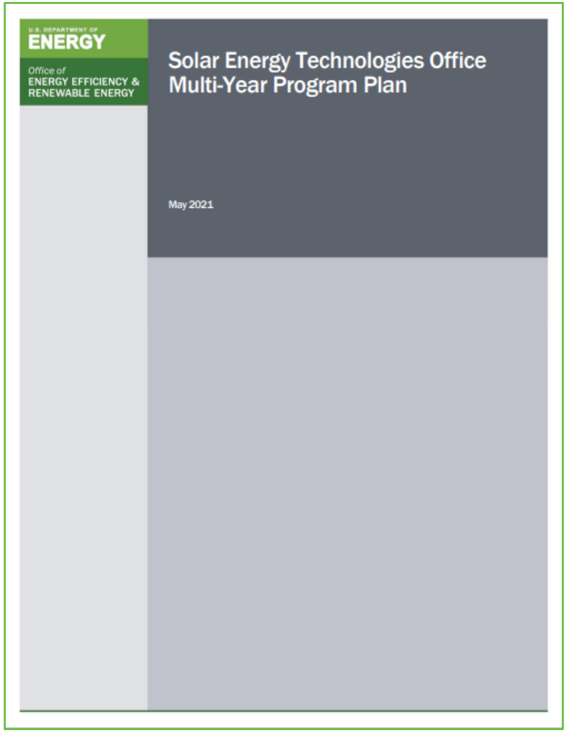
Waste Volumes

Ecological and Human Risk

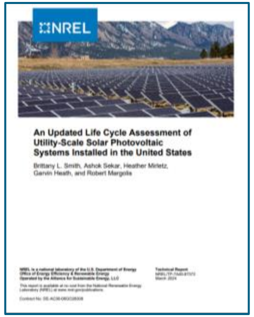
- Media stories influence public perception
  - Context, significance, and overall magnitude of impact often missing

Source: "Winter 2024 Solar Industry Update" NREL 1/25/24 nrel.gov/docs/fy24osti/88780.pdf
CBS News (5/1/23); Environmental Progress (6/21/17); Harvard Business Review (6/1821); Wired (8/22/20).

SETO Multi-Year Program Plan 2021 – PV Goals



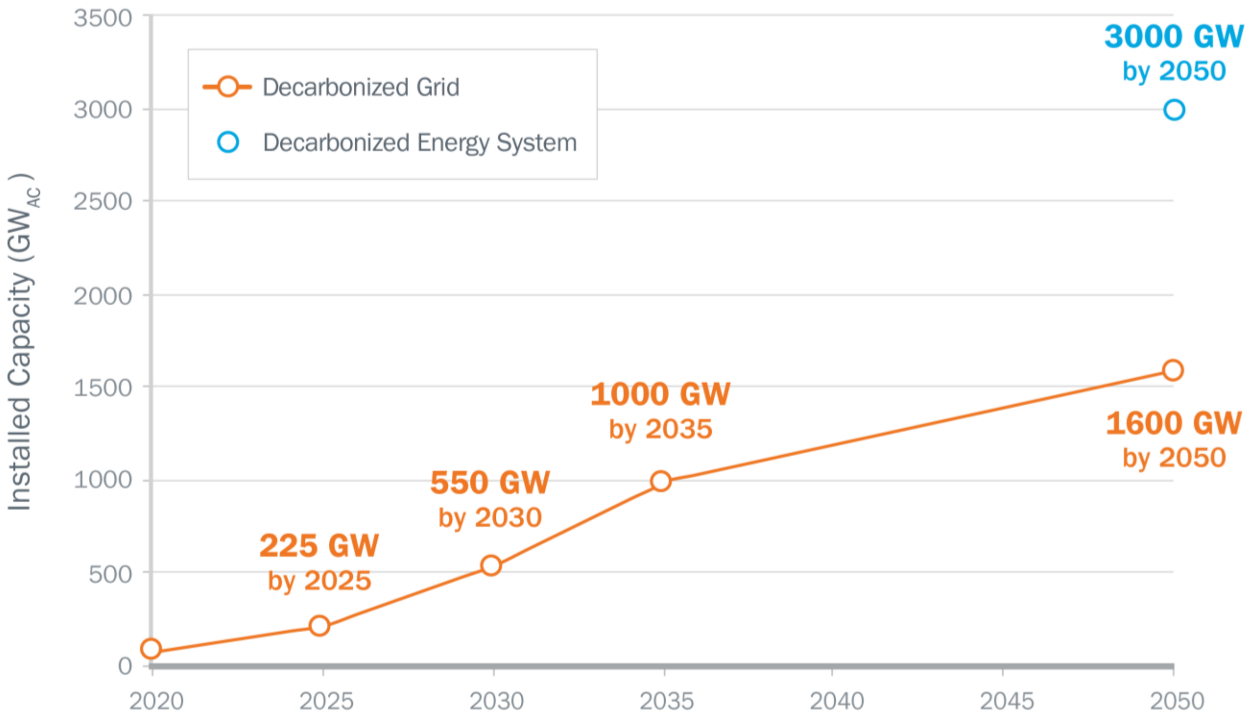
- **Lowering the cost of energy from PV**
- **Reducing the life cycle impacts of solar energy**
  - New materials, designs, and practices for reducing the environmental impact of PV technology
  - Life cycle impacts benchmark



https://www.energy.gov/eere/solar/articles/solar-energy-technologies-office-multi-year-program-plan

https://www.nrel.gov/docs/fy24osti/87372.pdf

PV has a Significant Role to Play in Decarbonization

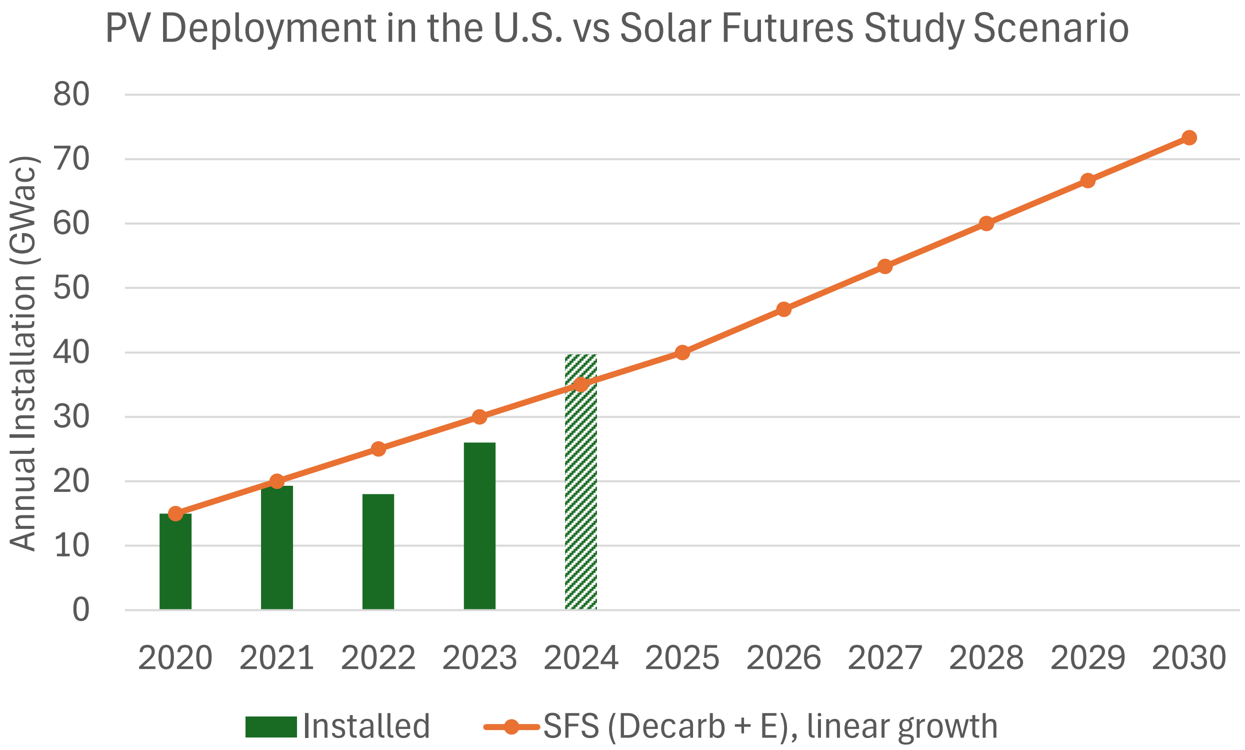


Note: The Solar Futures Study modeled the deployment of solar necessary for a decarbonized grid. Preliminary modeling shows that decarbonizing the entire energy system could result in as much as 3,000 GW of solar due to increased electrification across the energy system.

Decarbonization Goals:

- Electric grid (2035)
- Energy system (2050)

Decarbonization Goals Require a Rapid, Increasing Deployment Rate



EIA, Electric Power Monthly, Table 6.1.A. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_6_01_a

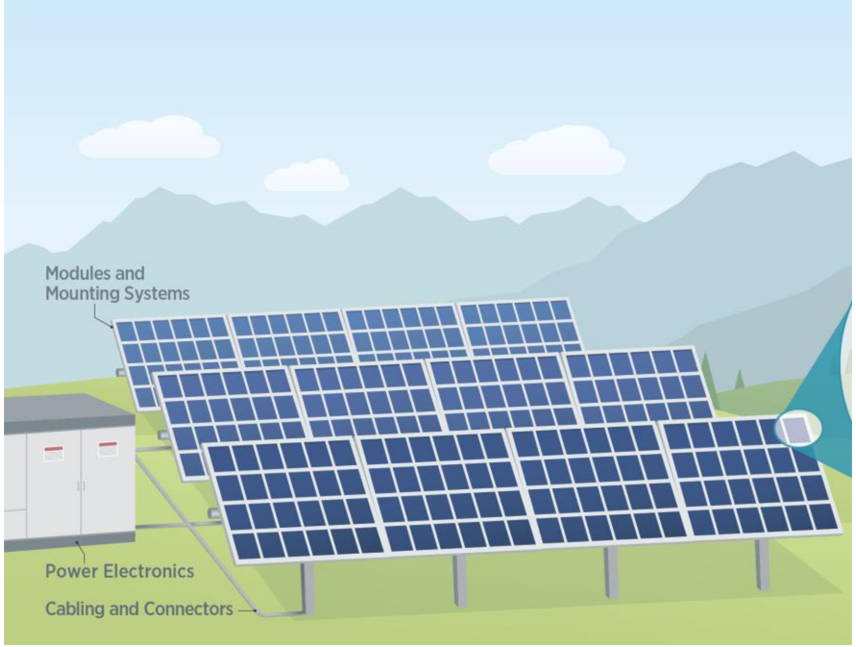
Quiz Time!

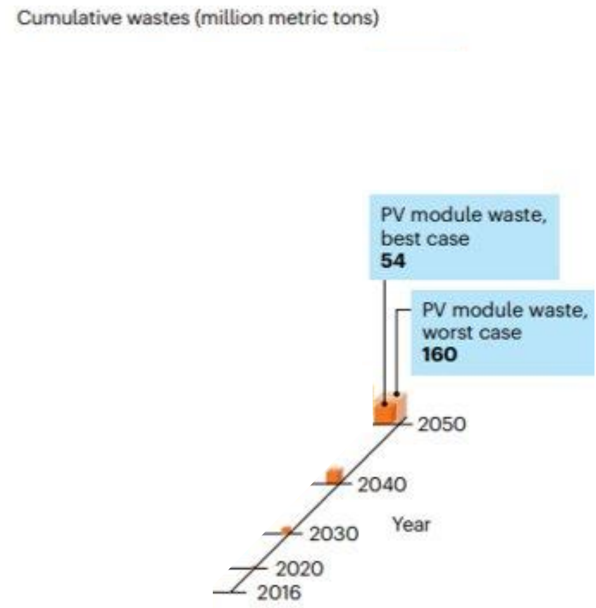
One model of PV waste estimates a cumulative amount of 160 million tons by 2050. How do you think this compares to non-PV electronic waste?

www.menti.com Code: 9606 6318

Answer: Anticipated PV waste is significantly less than electronic waste

What Does This Mean for PV EOL Volumes?

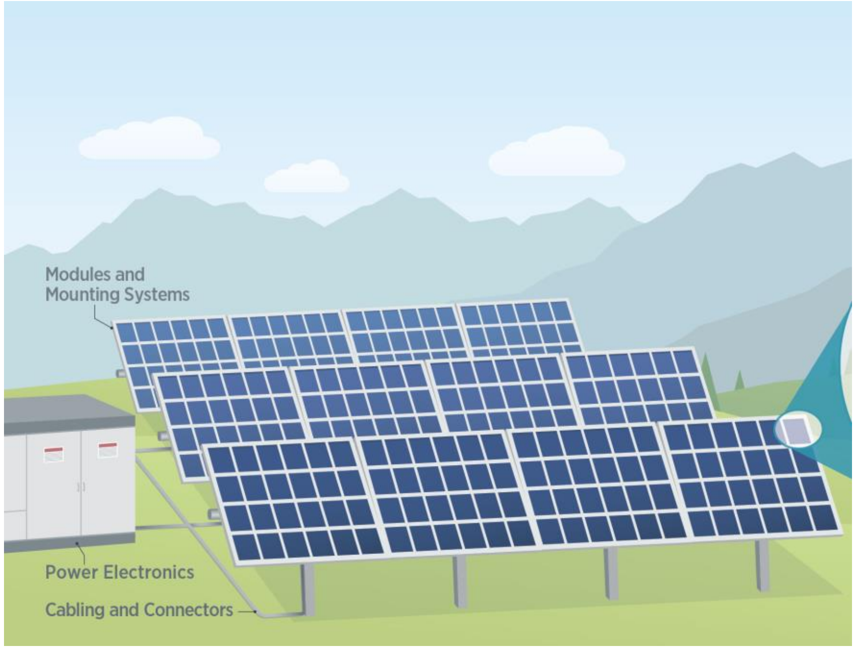


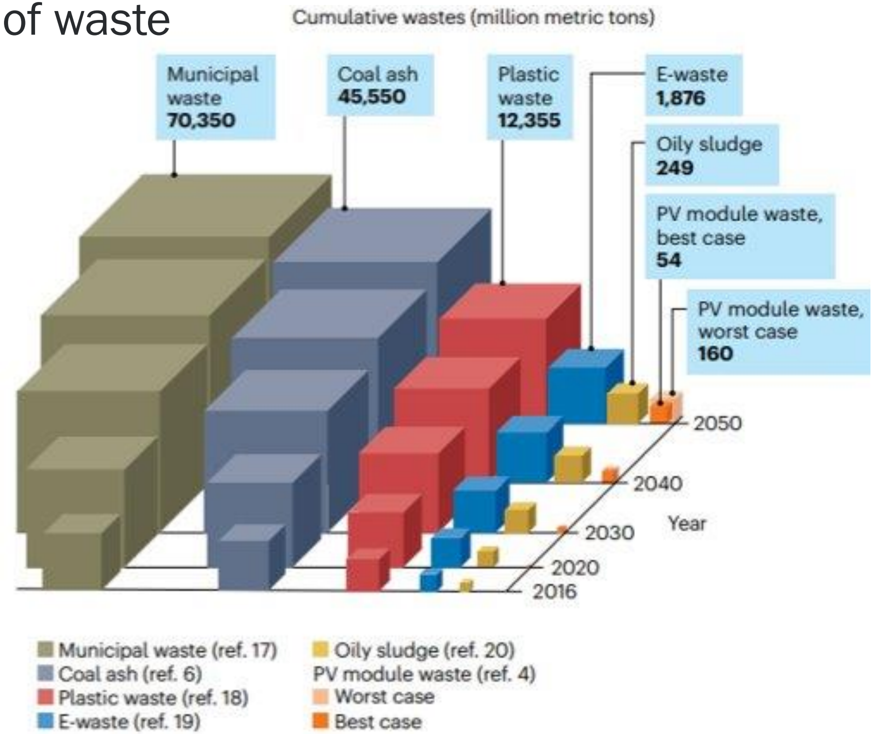


Mirletz, H., Hieslmair, H., Ovaitt, S. *et al. Nat. Phys.* **19**, 1376–1378 (2023).

What Does This Mean for PV EOL Volumes?

Forward projections estimate future volumes of waste





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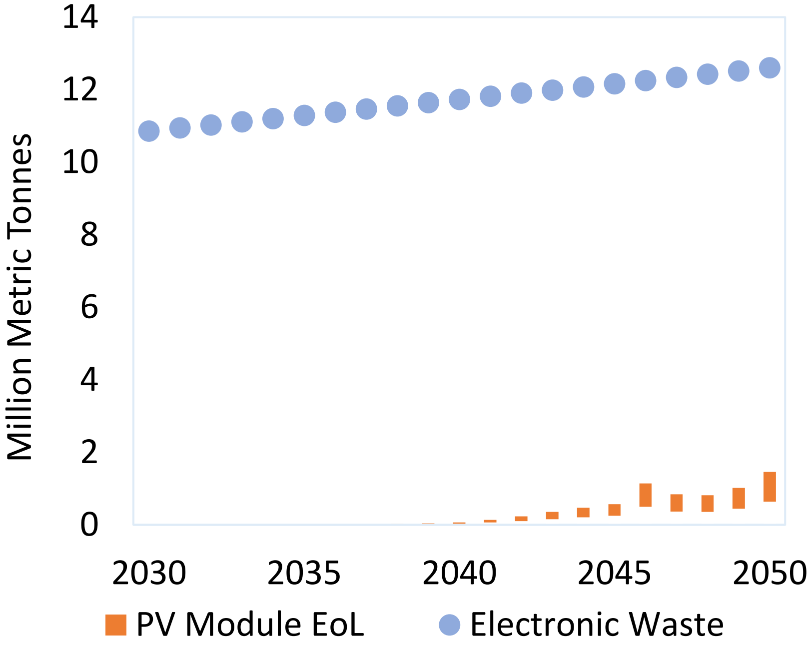
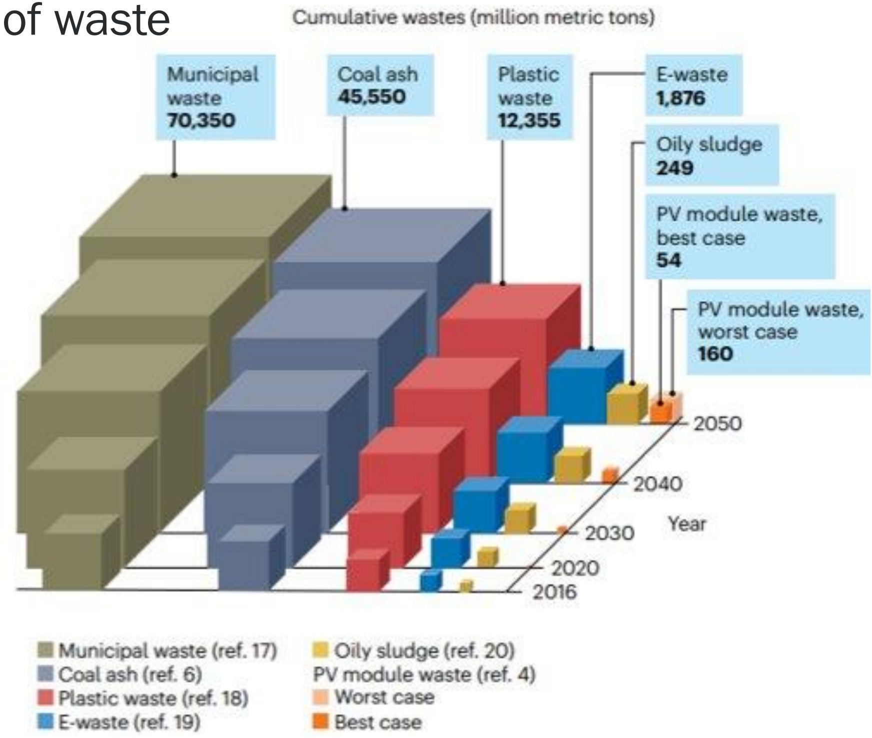


"Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan" March 2022
https://www.energy.gov/sites/default/files/2023-10/SETO-PV-End-of-Life-Action-Plan-1.pdf
Projections for PV Module EOL assume a 30 year life span



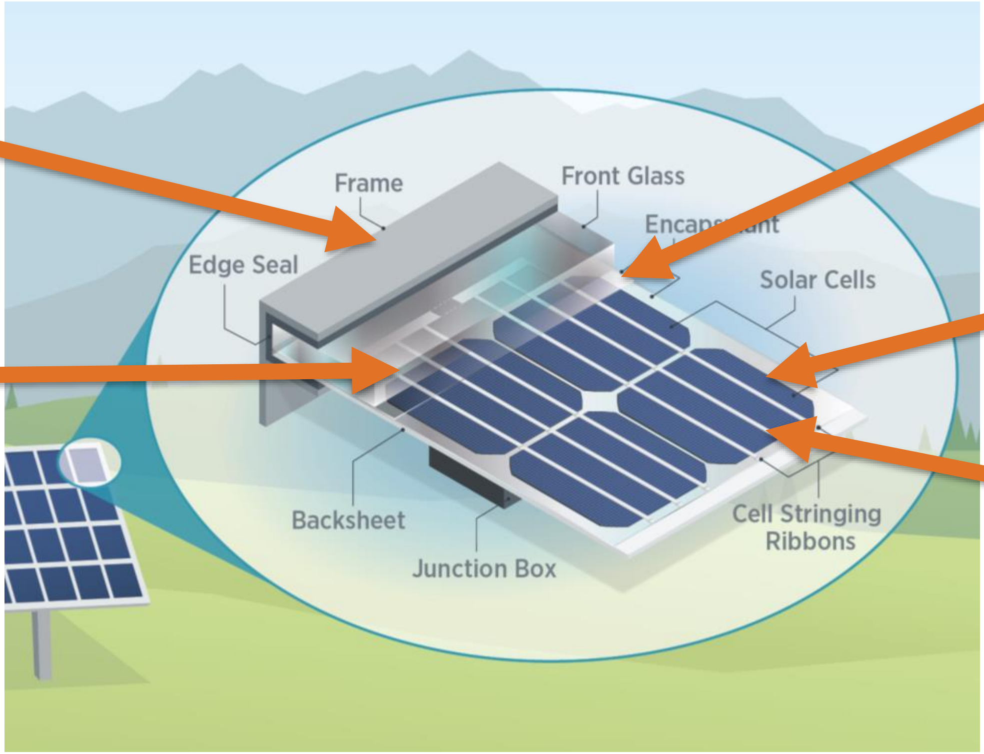
Mirletz, H., Hieslmair, H., Ovaitt, S. *et al. Nat. Phys.* **19**, 1376–1378 (2023).

Need: more decommissioning and EOL handling data

PV Modules Are Made of Many Materials

Aluminum
10%

Glass
70-80%



Polymer films
2-4%

Silicon
2-4%

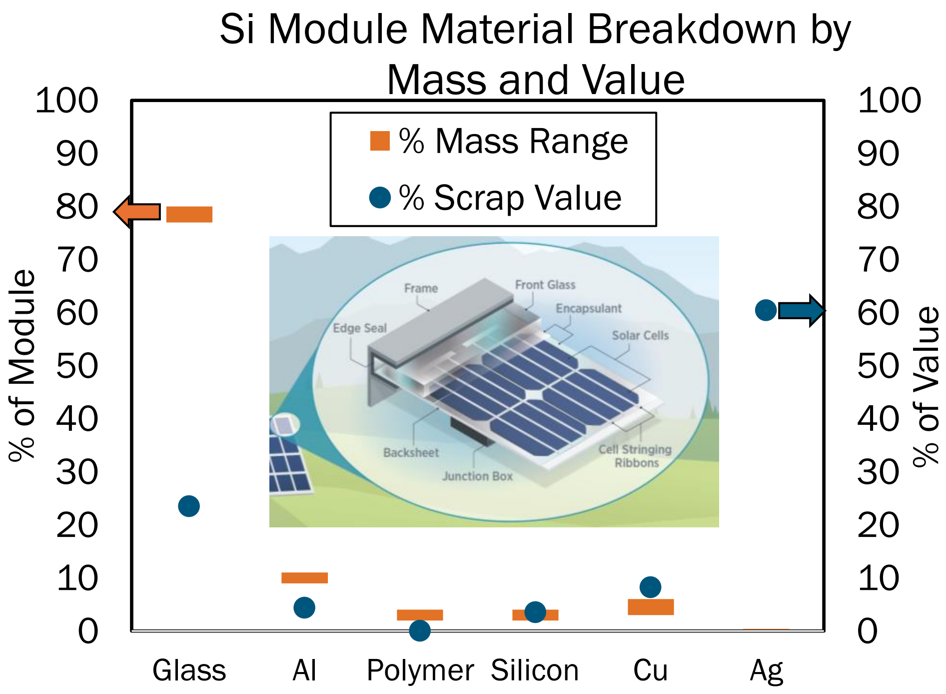
Copper
2-4%

Silver
0.4%

Tellurium
(in CdTe PV)
0.02%

"Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan" March 2022
https://www.energy.gov/sites/default/files/2023-10/SETO-PV-End-of-Life-Action-Plan-1.pdf

EOL Action Plan – Recycling Challenges



- Misalignment of material mass, ease of extraction, and value
  - 90% glass and aluminum by mass
  - 60% of recovered value from silver
- Precious metal use and recovery
- Lack of materials data
- Encapsulant removal
- Scaling and economics

Need: Technology solutions to lower recycling costs

"Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan" March 2022
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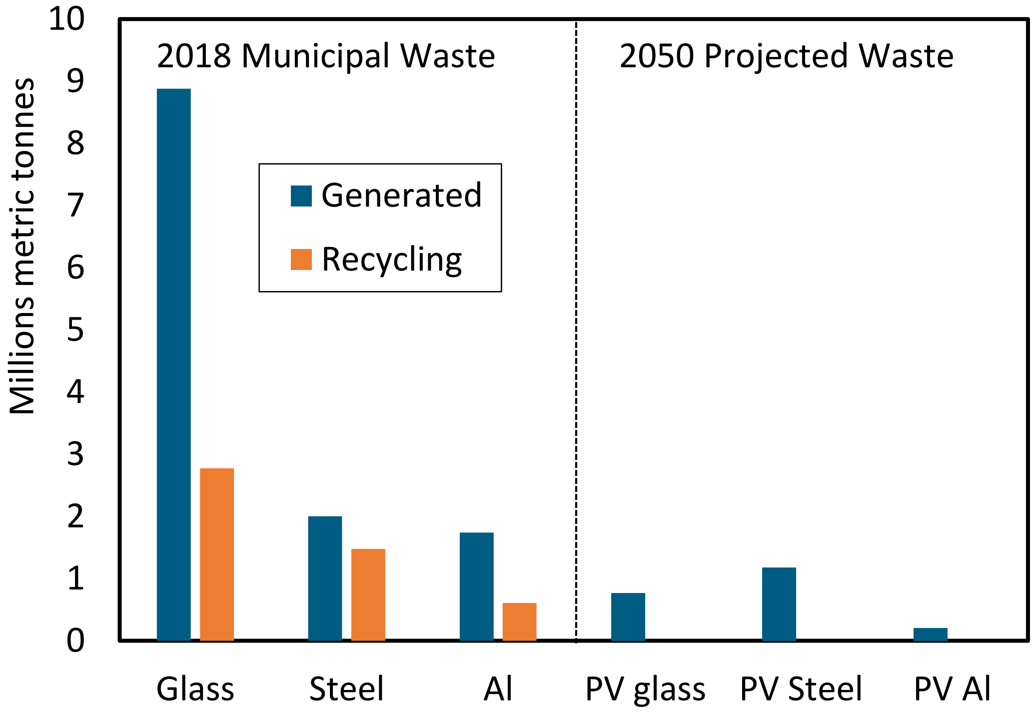
End-of-Life Action Plan – Recovered Materials Use



- Some Challenges
  - Purity levels of product and identity of impurities
  - Contamination of recovered materials
  - Off-taker market requirements
  - Volume and availability

Need: Optimized second use and markets for PV materials

"Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan" March 2022
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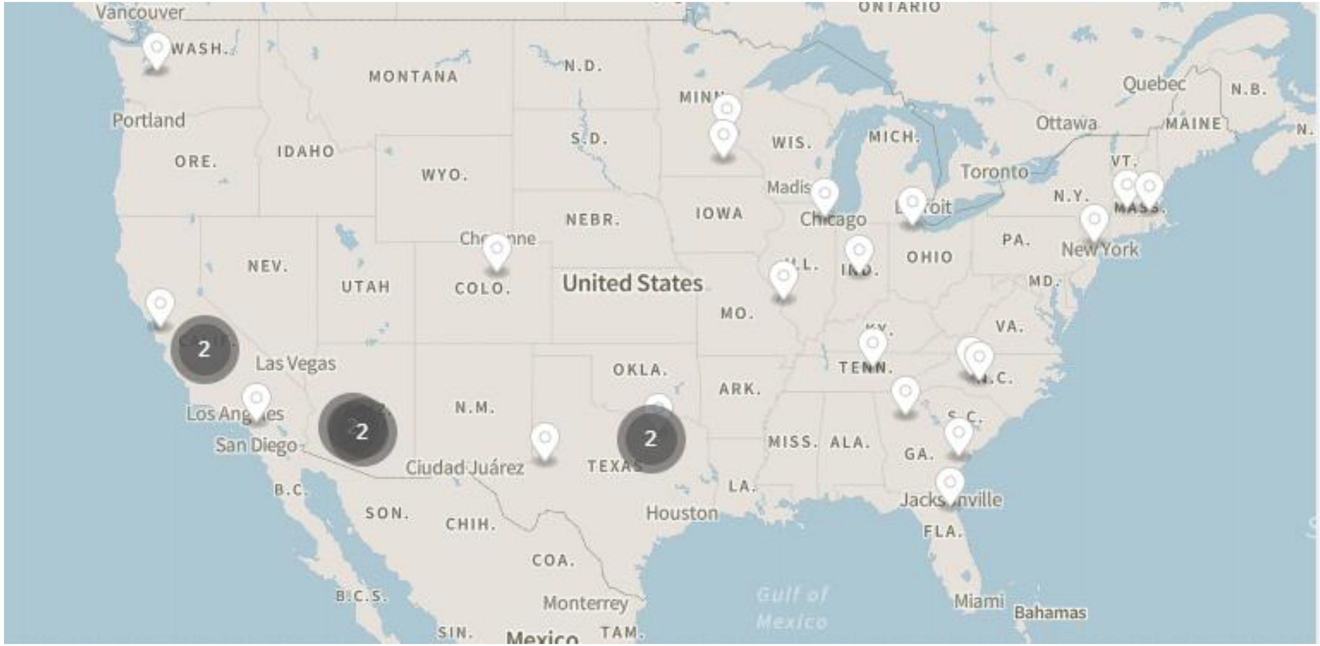
End-of-Life Action Plan – Collaboration and Outreach

- Industry
  - Materials, supply chain
  - Manufacturers
  - Installers, developers, operators
  - Recyclers, waste management
- Government and Communities
  - Policy makers, regulators, funding agencies
- University and Research Lab

End-of-Life Action Plan – Research Areas

- **Database**
  - *Target: 10 MW of PV EOL data by 2025*
  - Data from generators, waste management
  - Materials in PV modules and systems
- **Extend PV life spans**
  - Durability, reuse, refurbishing
- **Recycling**
  - *Target: Module recycling costs < $3/module (or < $150/ton) by 2030*
  - Designs to balance recycling and life span
  - High throughput, low-cost processing
  - Greater recovery of valuable materials
  - Optimized use of recovered materials
- **Disposal**
  - Safety and environmental considerations

U.S. PV Recycling



https://www.energy.gov/eere/solar/solar-manufacturing-map

Capacity: ~ 620 ktons/year

(20-30 million panels/year)

Moving Beyond "Waste Only" Perspectives

2017

ENVIRONMENTAL PROGRESS

ABOUT ENVIRONMENT ENERGY PEACE FACT CHECK NEWS GIVE Search

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By Ben Tracy, Analisa Novak

May 1, 2023 / 9:27 AM EDT / CBS News

Waste Volumes

Ecological and Human Risk

- Waste at end-of-life is one aspect to consider
- Zoom out to assess the most critical issues and overall environmental impact

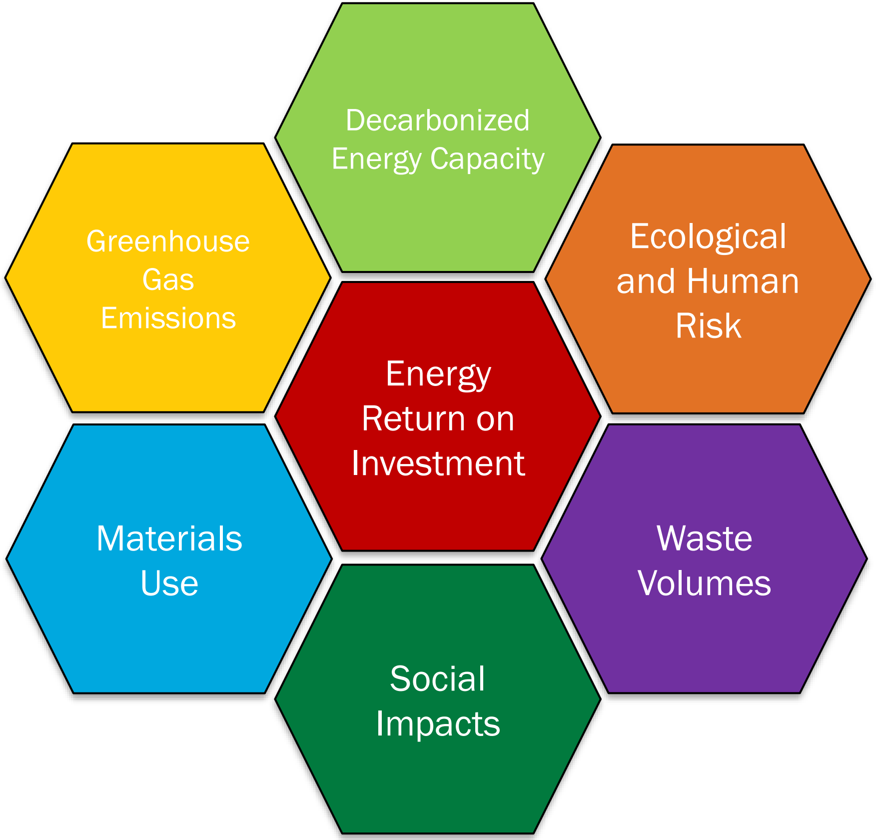
Source: "Winter 2024 Solar Industry Update" NREL 1/25/24 nrel.gov/docs/fy24osti/88780.pdf
CBS News (5/1/23); Environmental Progress (6/21/17); Harvard Business Review (6/1821); Wired (8/22/20).

A More Holistic Approach to Environmental Impact

- Decarbonization will require
  - Rapid PV deployment
  - Continued innovation for future technologies

Optimize

$$\frac{\text{Energy Output}}{\text{Energy or Material Input}}$$



Pop Quiz

From the "Reduce, Reuse, Recycle" framework, rank the "R" strategies from most to least impactful.

www.menti.com Code: 9606 6318

Answer:

1. Reduce
2. Reuse
3. Recycle

Standard Re-X Strategies for Circularity

Increasing Circularity Impact

Strategy	Description	PV Specific
Design		
R0 Refuse	Is product needed?	Refuse fossil fuels
R1 Rethink	Increase usage intensity	High energy yield PV
R2 Reduce	Reduce inputs	Reduce inputs/W_{dc}
Operations		
R3 Reuse	Reuse good condition products	Continued use, Resell
R4 Repair	Repair defects	Maintenance, repair
R5 Refurbish	Restore and update old product	
R6 Remanufacture	Use parts in new product for same function	
R7 Repurpose	Use product for different function	Repower
End-of-Life		
R8 Recycle	Process to extract materials	
R9 Recover	Energy recovery	

J. Potting, M. Hekkert, E. Worrell, and A. Hanemaaijer, Circular economy: measuring innovation in the product chain. The Hague: PBL Publishers; 2017.

H. Mirletz et al., Energy in the Balance: PV Reliability to Power the Energy Transition. PV Reliability Workshop; 2023.

Design: Consider Changes at the Beginning

Strategies

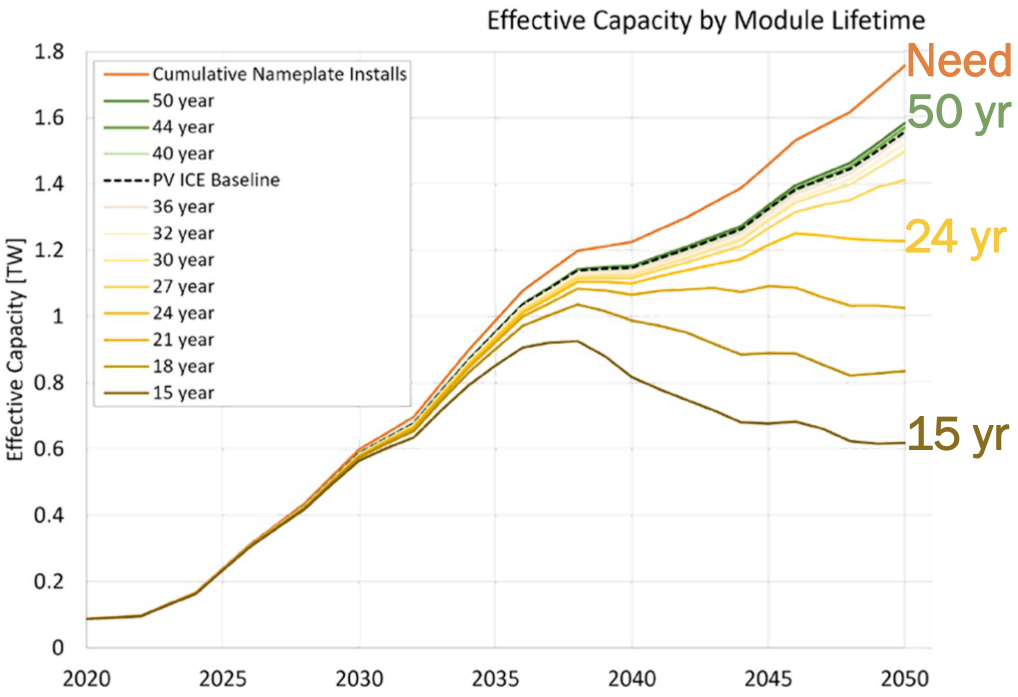
- Refuse
- Rethink
- Reduce

Challenges

- Field performance
- New design derisking
- Intergenerational compatibility

Balance: Solutions that maintain reliability and durability needs, while **optimizing & maximizing the overall positive impact of PV**

Operations: Maintaining and Extending Useful Life



Mirletz H, Ovaitt S, Sridhar S, Barnes T, (2022) Circular economy priorities for photovoltaics in the energy transition. PLoS ONE. 17(9): e0274351. https://doi.org/10.1371/journal.pone.0274351

Strategies

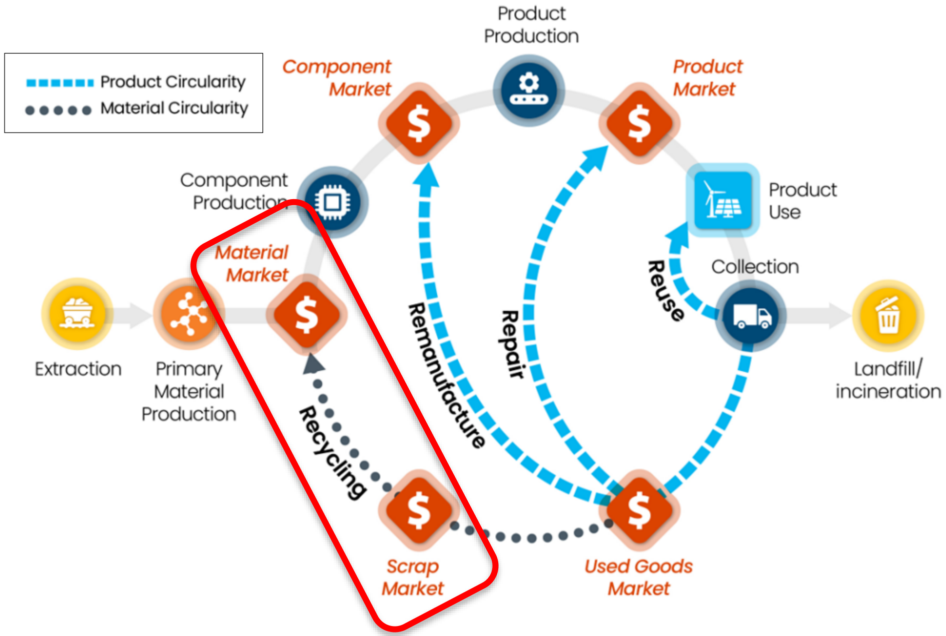
- Reuse
- Repair
- Refurbish
- Repurpose

Challenges

- Reducing degradation & failure
- O&M costs and practicality
- Safety and standards
- Accurate performance tests

Need: Extend module lifetime to grow & maintain effective capacity

End-of-Life: Recovering Materials & Secondary Markets



“Circularity for Secure and Sustainable Products and Materials: A Draft Strategic Framework” October 2024: https://www.energy.gov/sites/default/files/2024-10/circularity-for-secure-sustainable-products-materials-report.pdf

Strategies

- Recycle
- Recover

Challenges

- Recovering high purity materials
- Establishing secondary markets
  - In and out of PV
- Economics and scaling

Need: Technology solutions to lower recycling costs and materials markets for next use

Final Round: Quadruple Points!!

What percent of the US PV Fleet was installed less than 5 years ago?

www.menti.com Code: 9606 6318

Answer: ~65%

SETO Funding Programs Overview

SETO has numerous, diverse programs and prizes working on improving the positive environmental impact of solar

Projects and submissions often have criteria that benefits go to the broader community.

Research Projects: https://www.energy.gov/eere/solar/solar-energy-research-database
Prizes: https://www.energy.gov/eere/solar/american-made-challenges
2024 Peer Review: https://www.energy.gov/eere/solar/2024-seto-peer-review

Community Benefit Plans: https://www.energy.gov/infrastructure/about-community-benefits-plans

Photovoltaics Research and Development (FY22)

Topic Area 1: Low-Cost Solutions to Reduce Environmental Burden and Materials Supply Chain Vulnerability

Funding: $10 million*

- From cell design to EOL
- 8 projects selected on:
  - Precious metal minimization
  - Encapsulant challenges
  - Key material recovery
  - Lifecycle tracking

*Bipartisan Infrastructure Law Appropriations

https://www.energy.gov/eere/solar/seto-fiscal-year-2022-photovoltaics-research-and-development-pvrd-funding-program

Photovoltaics Research and Development (FY22)

- 8 projects innovating on technical challenges
- From design to optimizing materials recovery

Precious Metal Minimization

electroninks

Georgia Institute of Technology

UNIVERSITY OF CENTRAL FLORIDA

Encapsulant Challenges

Speaker

UC San Diego

KU THE UNIVERSITY OF KANSAS

Precious Metal Recovery

Speaker

SOLARCYCLE

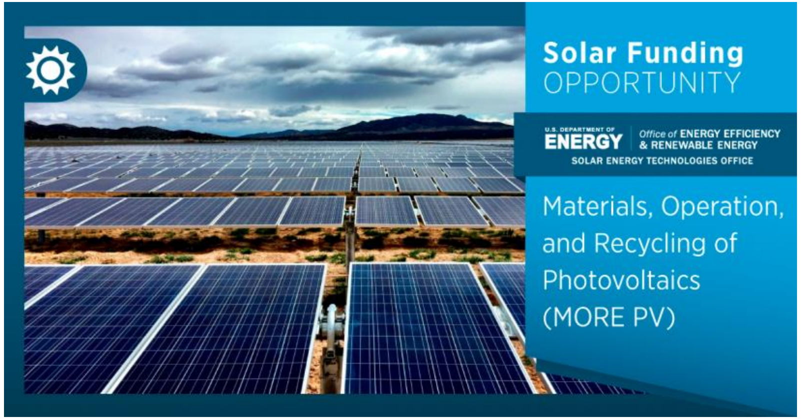
Berkeley UNIVERSITY OF CALIFORNIA

Lifecycle Tracking

LOCUSVIEW

https://www.energy.gov/eere/solar/seto-fiscal-year-2022-photovoltaics-research-and-development-pvrd-funding-program

MORE PV: Materials, Operations, and Recycling of PV (FY23)



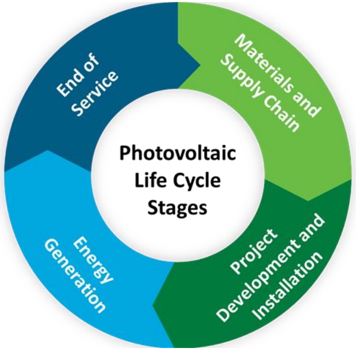
Funding: $7.7 million

- PV lifecycle with generative AI and spatiotemporal graphs
- Data-driven standards for increased resiliency
- Contactless multi-curve tracer for installation, operations, and performance

CASE WESTERN RESERVE UNIVERSITY

kWh analytics

UNIVERSITY OF NORTH CAROLINA CHARLOTTE



https://www.energy.gov/eere/solar/materials-operation-and-recycling-photovoltaics-more-pv-funding-program

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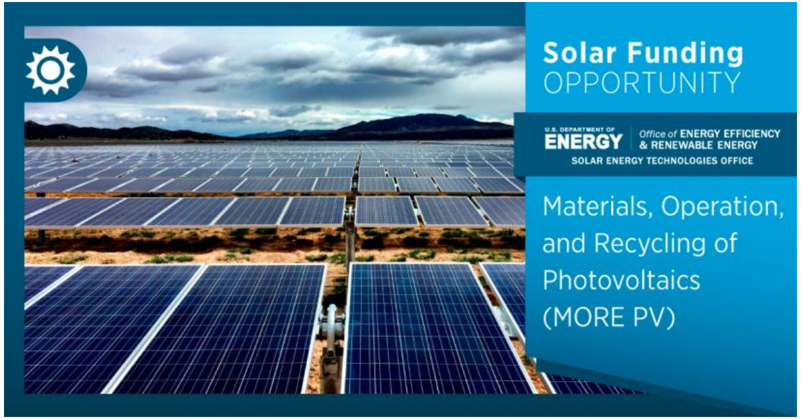


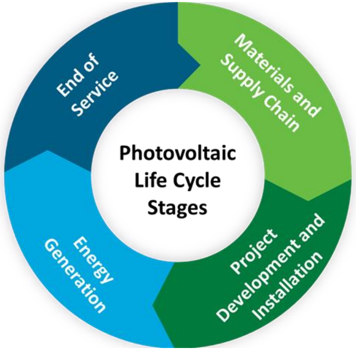
Funding: $8 million*

- 1 research partnership
- Convene researchers, technicians, manufacturers, asset owners, recyclers, and government entities

*Bipartisan Infrastructure Law Appropriations

Speaker

Breaking Barriers to Enable Solar Technology Circularity (BBEST Circularity)



https://www.energy.gov/eere/solar/materials-operation-and-recycling-photovoltaics-more-pv-funding-program

Small Innovative Projects in Solar (SIPS)

Funding: $250K/project

- 1-year projects on innovative topics

Reuse and Repowering	Lower Carbon Silicon Ingots	Recycling
NREL (Speaker)	NREL	University of Virginia

FY22 Projects: https://www.energy.gov/eere/solar/seto-small-innovative-projects-solar-2022-concentrating-solar-thermal-power-and
FY23 Projects: https://www.energy.gov/eere/solar/seto-small-innovative-projects-solar-2023-concentrating-solar-thermal-power-and
FY24 Projects: https://www.energy.gov/eere/solar/fiscal-year-2024-small-innovative-projects-solar-sips-concentrating-solar-thermal-0

Additional Programming

PV RESOLVE (Reliable Entire-System Operations and Lifecycle Value Evaluation)

PV Sustainability: IEA PVPS Task 12 Management and Stakeholder Engagement

Electrolytic Metal Recovery from Photovoltaic Waste (SBIR)

Technical Assistance

SETO Lab Call FY2025-27: https://www.energy.gov/eere/solar/solar-energy-technologies-office-lab-call-fy2025-27
Small Business Innovation Research: https://legacy.www.sbir.gov/sbirsearch/detail/2476507

Decarbonization: Upstream Silicon and Ecolabels

Funding: up to $10 million

- Technical pathways to reduce carbon and energy intensity to fabricate modules
- Low-carbon synthesis of metallurgical-grade silicon

https://www.energy.gov/eere/solar/funding-notice-fiscal-year-2024-photovoltaics-research-and-development-pvrd
DOE. September 2022. Industrial Decarbonization Roadmap. www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

Funding: $2.7 million

- Increase registration of PV modules and inverters with EPEAT ecolabel

https://www.energy.gov/eere/solar/american-made-promoting-registration-inverters-and-modules-ecolabel-prime-prize

Large-Scale Solar Siting and Permitting

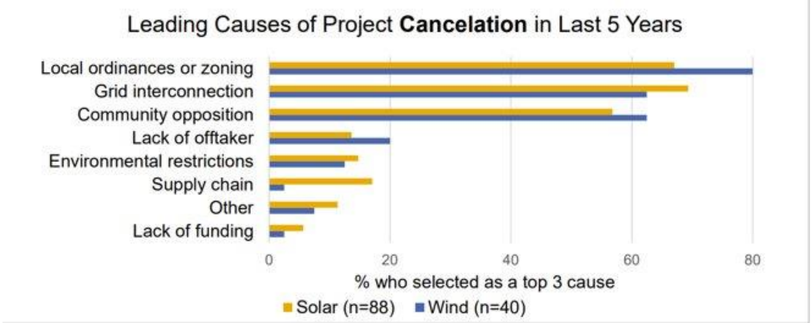
Achieving a 100% clean energy sector is likely to require >90% of new electricity through 2030 to come from solar, wind, and batteries – **annual deployment rates need to increase 2-3x**

Lawrence Berkeley National Laboratory conducted a survey of solar neighbors and solar and wind developers.

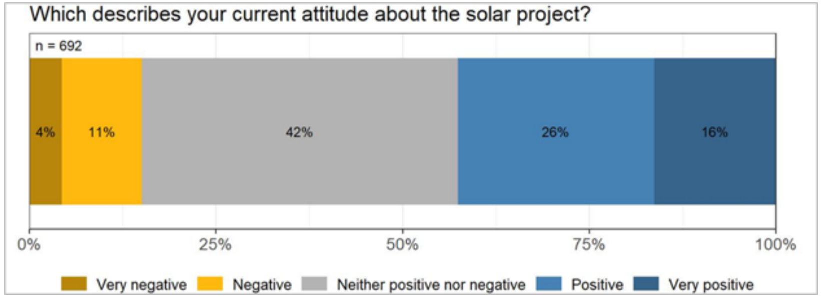
- **Developers:** Local ordinances and local opposition identified as two of the top three reasons for project cancellations
- **Neighbors:** Among large-scale solar neighbors, “positive” attitudes outnumber “negative.” However, perceptions relating to aesthetic, economic, and quality of life impacts are strongly correlated with attitudes.

Communities have expressed concerns about the management of PV panels at their end of life.

LBNL Developers Survey



LBNL Solar Neighbors Survey

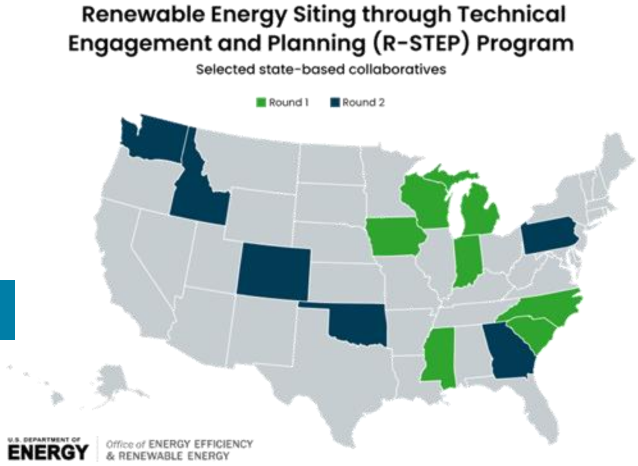


R-STEP (Renewables Siting through Technical Engagement and Planning)

Goal: To improve large-scale renewable energy planning, siting processes, and outcomes for host communities, local governments, and developers

Challenge: State and local governments with authority to permit large-scale renewable energy projects may lack the sufficient resources (staffing capacity, expertise, funding).

- Capacity will be further stretched as renewable energy deployment increases.
- Siting and permitting authority varies by state
- Permitting authorities need help maximizing benefits to host communities by addressing community concerns



R-STEP Components

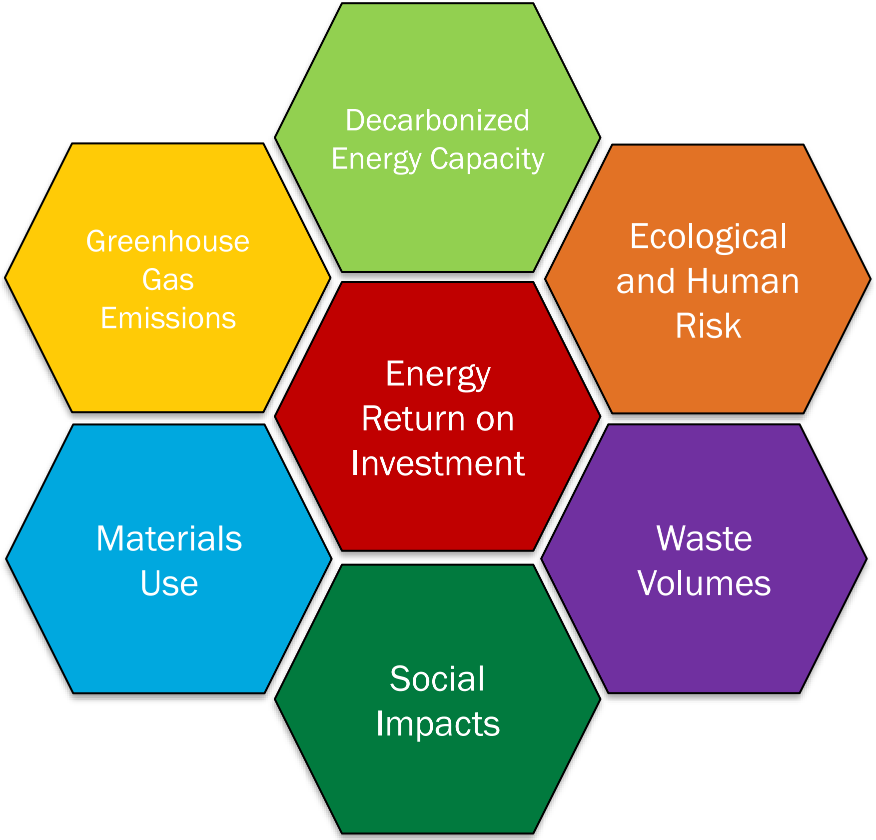
- **Funding:** Up to $2M awards (up to 3 years/award) to develop renewable energy siting programs that increase local capacity
- **DOE-Funded Technical Assistance:** From leading experts to collaboratives
- **Dissemination and Convenings:** Share collaborative successes and best practices with other states and communities, and federal offices and agencies

PV Environmental Impact

- PV is essential to decarbonization
- Optimize

$$\frac{Energy\ Output}{Energy\ or\ Material\ Input}$$

- DOE investing in technical programming to further improve positive PV impacts



Learn About Upcoming Funding Opportunities

EERE Funding Opportunity Updates

Promotes the Office of Energy Efficiency and Renewable Energy's funding programs.

SIGN UP NOW:

energy.gov/eere/funding/eere-funding-opportunities

SETO Newsletter

Highlights the key activities, events, funding opportunities, and publications that the solar program has funded.

SIGN UP NOW:

energy.gov/solar-newsletter

ORISE Science, Technology, & Policy Fellowship

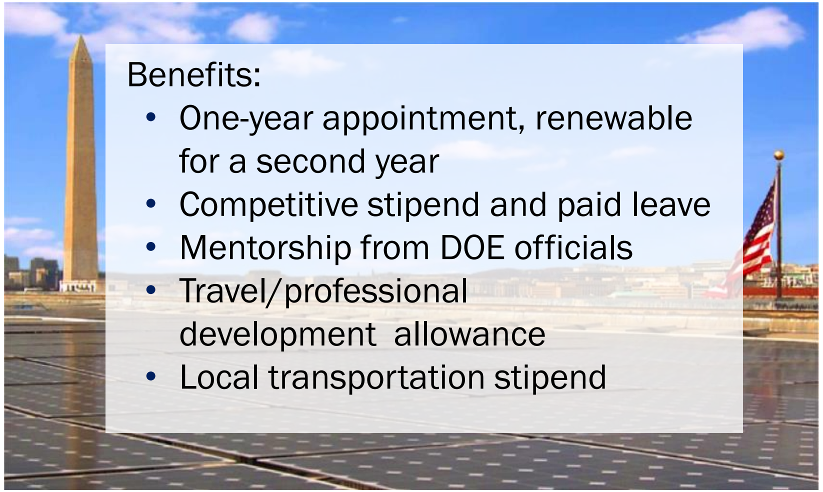
Develop leadership skills in science, technology, and policy by designing and implementing national research and development programs

Strategic Areas:

- Photovoltaic technologies
- Concentrating solar-thermal power technologies
- Grid systems integration technologies
- Solar siting, permitting, interconnection, and market analysis
- Manufacturing and technology transfer
- Energy and environmental justice
- Access to financing, capacity building, and technical assistance
- Workforce development
- Scaling and accelerating deployment with meaningful benefits
- Communications, graphic design, and stakeholder engagement

Eligibility:

Candidates with backgrounds including but not limited to physical and natural sciences, social science, engineering, policy, entrepreneurship, community and equity work, and others with bachelor's, master's, or doctoral degrees, as well as established professionals with relevant post-degree experience. SETO is also interested in bilingual candidates. Must be a U.S. citizen or have Permanent Resident (Green Card) status.



Benefits:

- One-year appointment, renewable for a second year
- Competitive stipend and paid leave
- Mentorship from DOE officials
- Travel/professional development allowance
- Local transportation stipend

Applications are accepted on a rolling basis with two annual review dates: **January 15 | July 15**

VISIT: bit.ly/SETO-Fellowships • EMAIL: DOE-RPP@orau.org

Additional resources shared in Q&A

- Programs for students to get involved in PV EOL Research:
  - https://science.osti.gov/wdts/suli
  - https://orise.orau.gov/stpf/
- NREL reports related to decommissioning and circularity
  - https://www.nrel.gov/pv/pv-circular-economy.html
  - https://www.nrel.gov/docs/fy21osti/78678.pdf
- IEA PVPS Task 12
  - https://iea-pvps.org/research-tasks/pv-sustainability/
- Solar polymer materials
  - https://graham.umich.edu/media/pubs/Facts-about-solar-panels--PFAS-contamination-47485.pdf
- R2 standards for recyclers:
  - https://sustainableelectronics.org/welcome-to-r2v3/document-library/

Project Spotlight

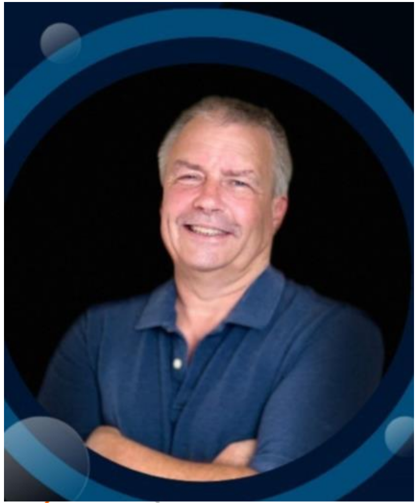
Design
David Fenning

UC San Diego

Extending Lifetime
Silvana Ovaitt

NREL

Recycling
Gerald Feldewerth



SOLARCYCLE

Re-X, Lifecycle
Cara Libby

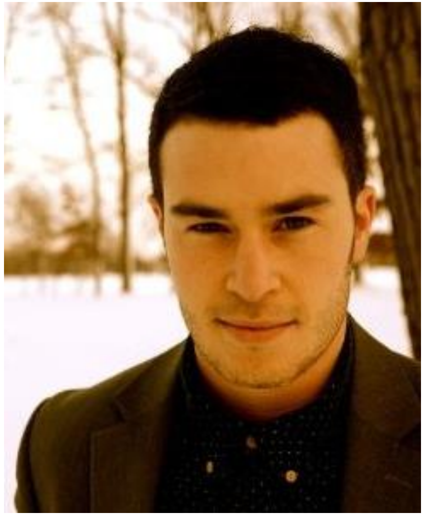
EPRI

Agency Spotlight

Advanced Materials & Manufacturing Technologies Office (AMMTO)
Allison Robinson Turner

U.S. DEPARTMENT OF ENERGY

Manufacturing and Energy Supply Chains (MESC)
Robert Sozanski



U.S. DEPARTMENT OF ENERGY

Environmental Protection Agency (EPA)
Phoebe O'Connor

EPA United States Environmental Protection Agency