U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE

2022 SETO PEER REVIEW

SETO Photovoltaics R&D

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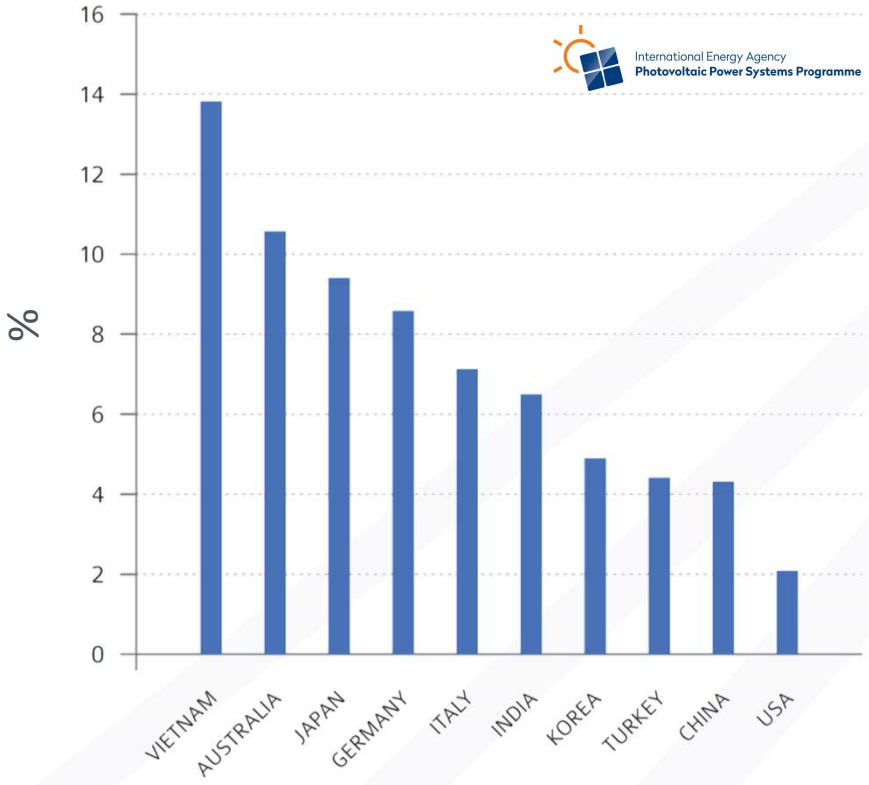
Decarbonizing the Electricity and Energy Sectors

The US is targeting a carbon-free electricity sector by 2035 and 100% clean energy economy with net-zero emissions by 2050

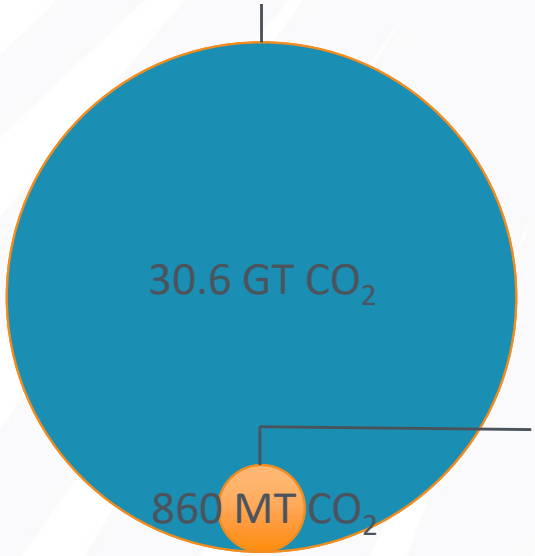
- In a fully decarbonized grid, predictions indicate that **30-50% of U.S. electricity generation would come from solar**
- To meet the 2035 goal, we need to deploy solar at **two to five times the current rate**

We're Making Progress

CO_2 emissions avoided by PV as a percentage of total emissions



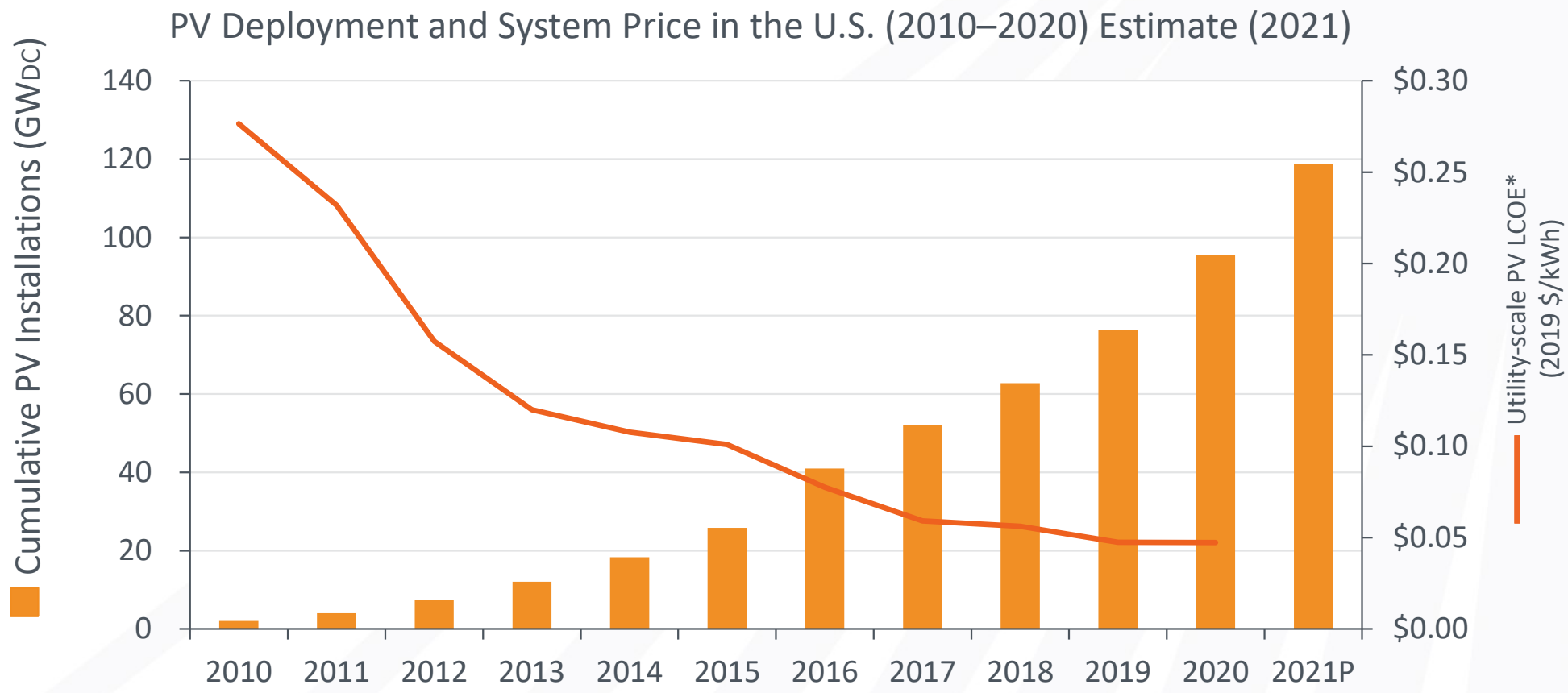
2020 Global energy sector CO_2 emissions from fuel combustion



Global emissions avoided by PV (2.8% of total emissions)

https://iea-pvps.org/trends_reports/trends-in-pv-applications-2021/

U.S. Solar: Falling Costs, Rising Deployment



*Price is depicted as levelized cost of energy (LCOE)

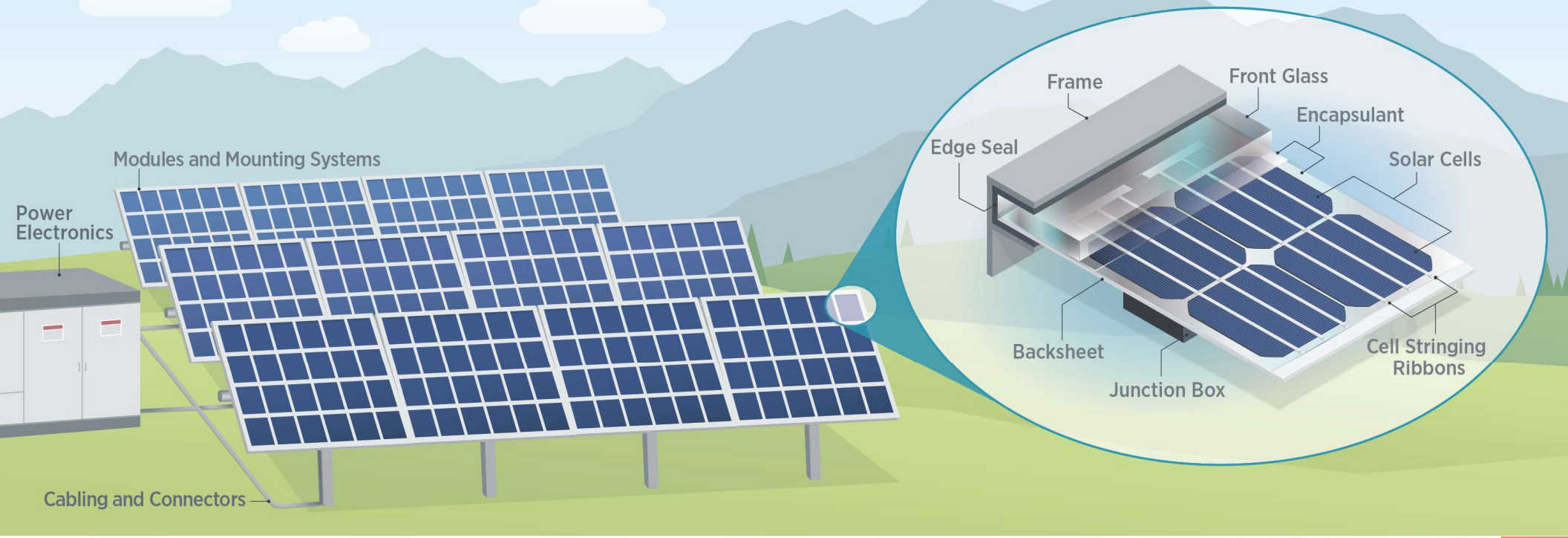
Sources: National Renewable Energy Laboratory, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2019"; Wood Mackenzie Power & Renewables/SEIA U.S. Solar Market Insight.

2030 SETO Photovoltaic Goals

Photovoltaic (PV) electricity costs less than 2 cents/kWh

Seamless integration with other land uses

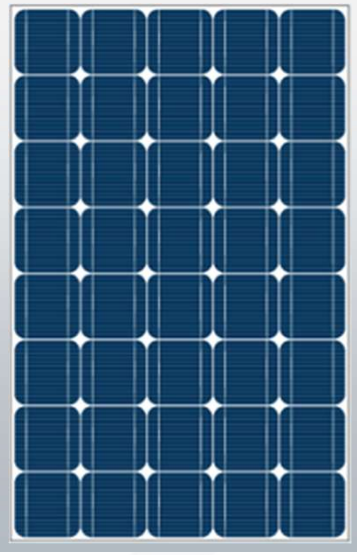
Reduced overall PV system life cycle impacts



Photovoltaic System Elements

PV Modules

37% of utility-scale system cost



Electrical & Structural BOS

21% of utility-scale system cost

Inverter

4.5% of utility-scale system cost

Source: National Renewable Energy Laboratory. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021" https://www.nrel.gov/docs/fy22osti/80694.pdf

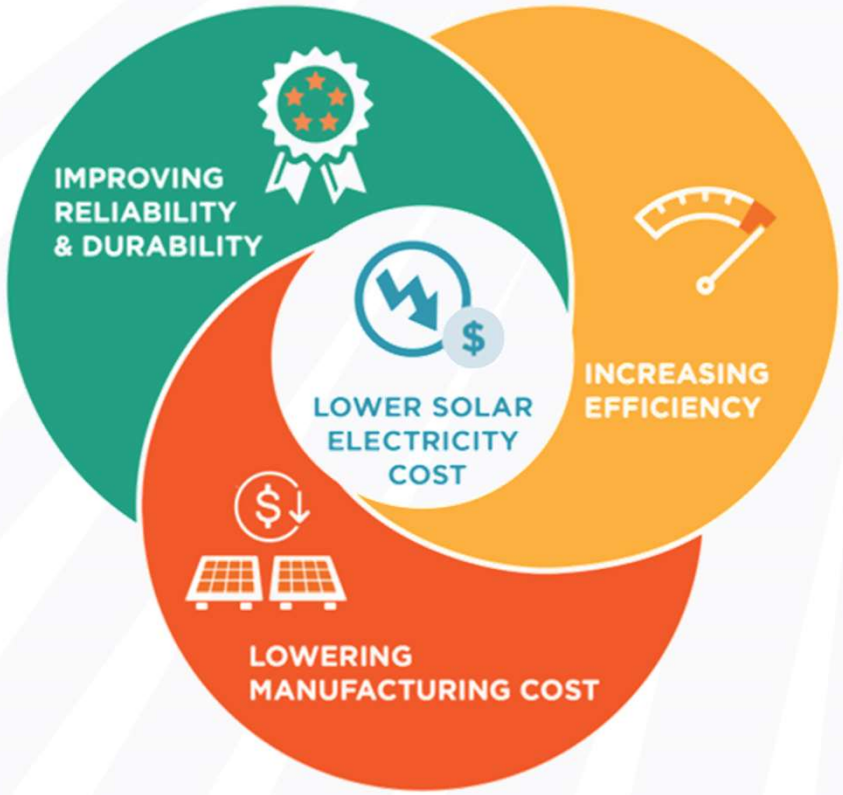
A Pathway to $0.02/kWh for Utility-Scale PV

The Photovoltaics Subprogram Approach

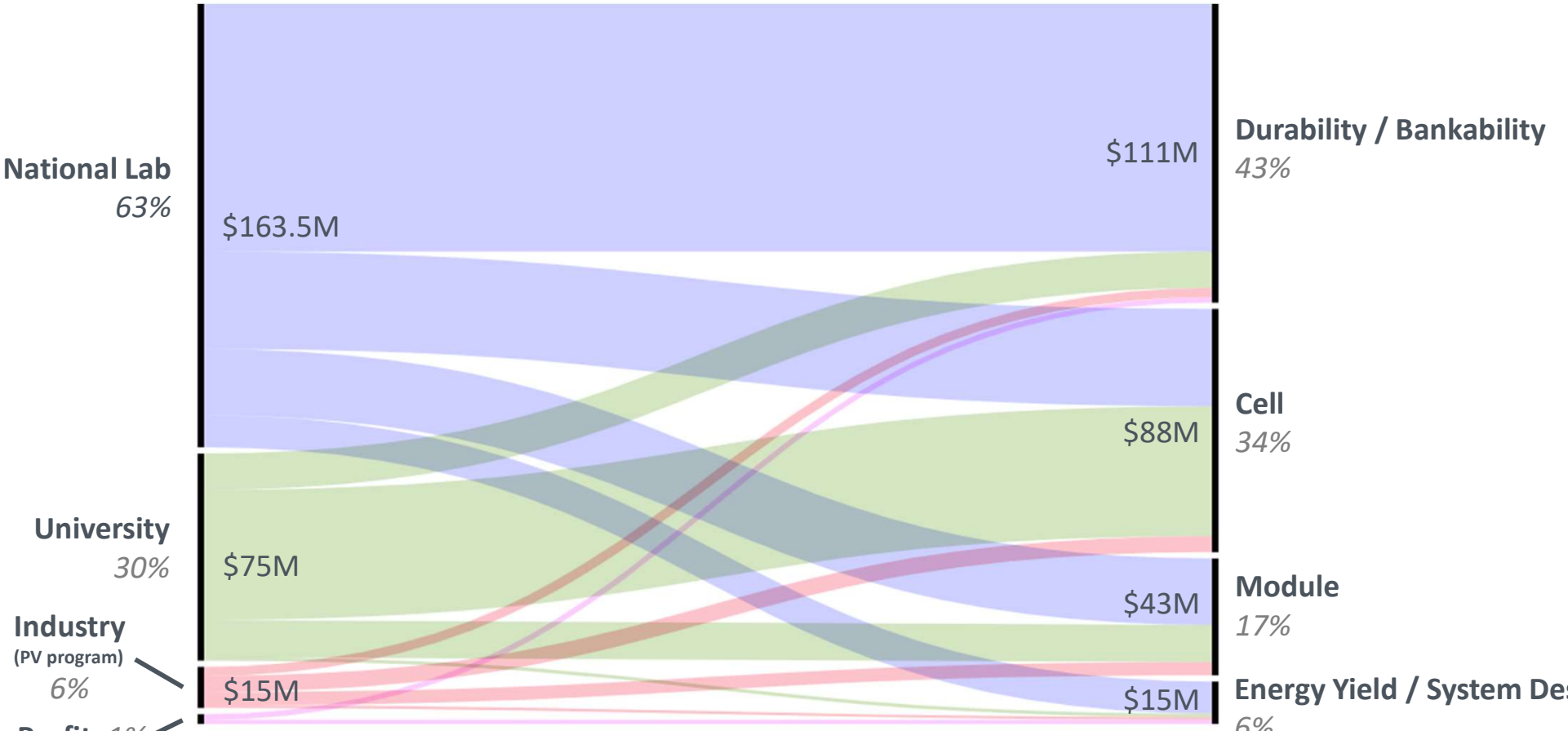
Funds research with a 3-15 year horizon, which is beyond industry focus or capabilities

Supports an innovation ecosystem that includes universities, students, professors, and the private sector

Fosters the transition of research developments into the marketplace



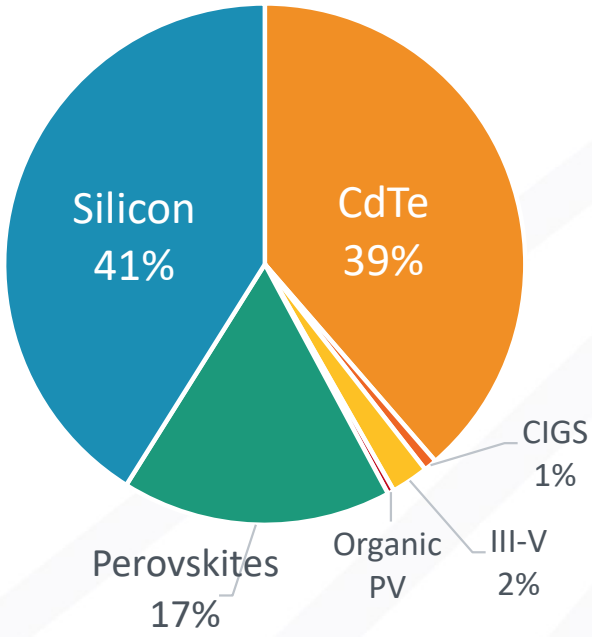
SETO PV Research Funding Allocation - 2022 ($257M)



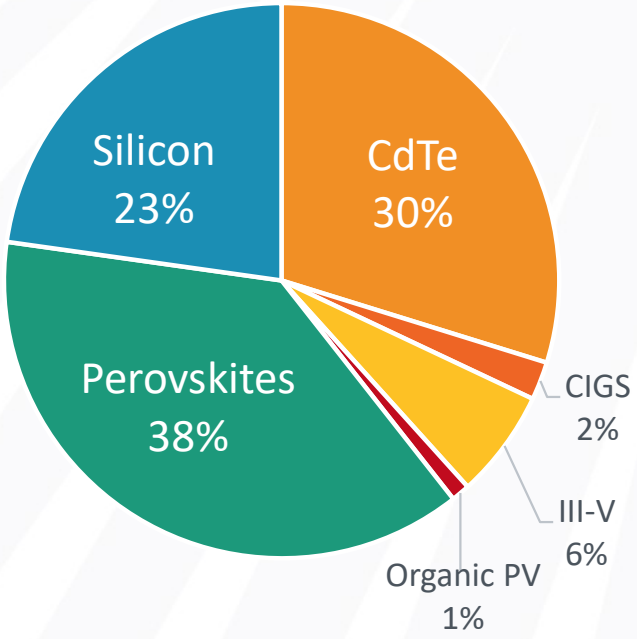
SETO PV Research Funding Allocation - 2022 ($257M)

PV Absorber Tags by Funding

Reliability, System, Cell, and Module Research



Only Cell and Module Research



Includes projects under negotiation and recent starts not formally included in 2022 Peer Review; individual projects have multiple tags

Evolutions Of Existing Commercial Technology R&D

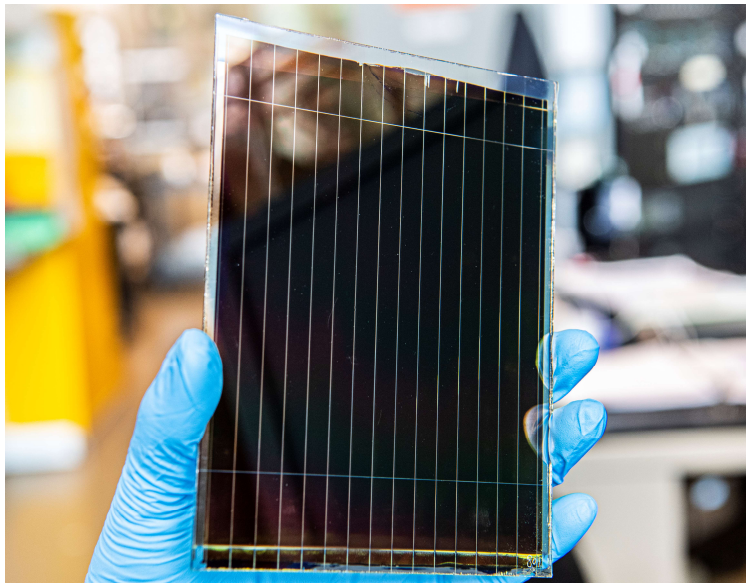
- $65M portfolio in FY2022 peer review
- Federal funds used to accelerate advancement in the most competitive technologies
- Bulk of funding directed to CdTe and Si PV

Examples:

- Passivation and heterojunction Si cells
- Understanding defects to increase CdTe performance
- Metallization and paste development
- Low-cost manufacturing processes for III-V PV technologies

Emerging Cell and Module Technology R&D

- $51M portfolio in FY2022 peer review
- Diversified R&D portfolio to enable potentially radially low-cost PV
- Focus on areas where the US could have a competitive advantage or strategic capability

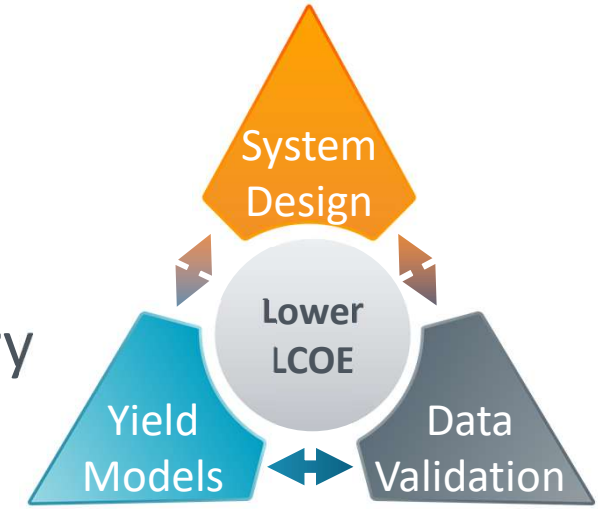


Examples:

- New Perovskite PV cell architectures to improve durability
- Tandem modules
- New materials development for advanced contacts

Research to Ensure PV Delivers as Expected

- $50M portfolio in FY2022 peer review
- System lifetime dramatically affects LCOE but systems must be reliable and financeable
- PV deployment is accelerating, and the industry needs to be able to predict, understand, and mitigate degradation



- SETO is increasing efforts on BOS system durability and best practices

Examples:

- Collecting, analyzing, and disseminating PV performance data
- Core National Laboratory work to support standard testing procedures

Advanced System Designs and Increasing Energy Yield

- $13.5M portfolio in FY2022 peer review
- R&D to increase the energy yield (kWh/kW) in a variety of climates
- Expanding PV deployment options so that the solar resource can be more fully utilized

Examples:

- Characterizing bifacial gain and creating an albedo database
- Improved performance in snowy climates
- Improved tracking designs

SETO Multi-year Program Plan Published 5/4/21

Continuing cost reductions for incumbent technologies

→ Silicon, CdTe

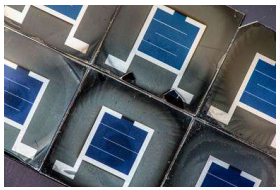
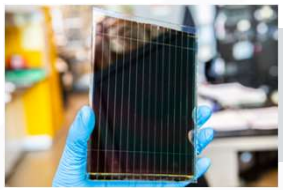


Improvements in system yield

→ Transition to bifacial, extended system operational life

Solutions that expand viable siting and improve installations

→ Varied terrain, canopy, floating

Improvement in module performance

→ Tandem modules, perovskites

Increased focus on sustainability

→ Supply chains, end-of-life considerations


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

A quick recap

- PV research will help us achieve our goals of a carbon-free electricity sector by 2035 and 100% clean energy economy with net-zero emissions by 2050
- SETO PV research focuses on reducing cost, increasing durability, and increasing performance
- Expanding research portfolio in PV balance of systems durability, as well as in PV end of life and waste mitigation
- Looking ahead to technologies such as floating solar and agrivoltaics to further accelerate deployment

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2022 SETO PEER REVIEW

Keeping up with Industry

Encouraging Collaboration and Industry Involvement in Photovoltaics R&D Projects

Brion Bob, Technology Manager

Items to Cover

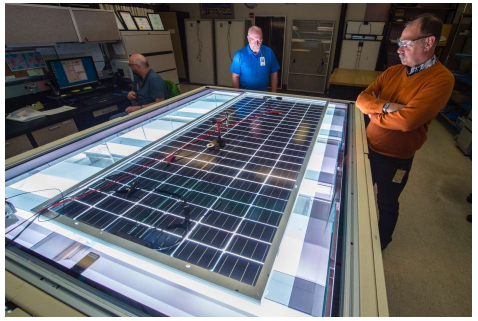
- Industry Involvement in Early-Stage Research
  - Perovskite Technology Transfer
  - CdTe PV Research Community
  - Silicon Cells, Modules, and Systems
- A Few Examples of Partnership-Focused Research Projects
  - 4 Partnership Focused Projects Focused on Cell, Module, and System Technologies
  - 2 Research Consortia in Important Research Areas

Industry Engagement in Early-Stage R&D

Previous Designs

State of the Art Technology

Future Technology

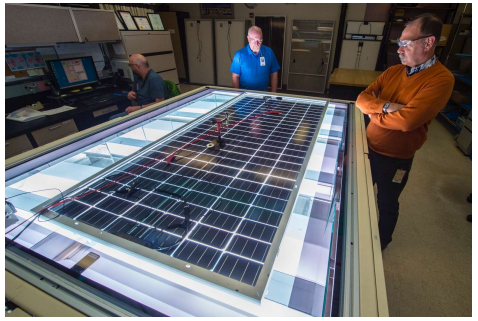


Industry Engagement in Early-Stage R&D

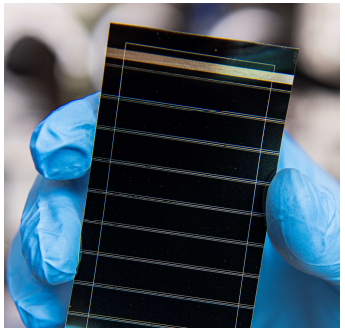
Previous Designs

State of the Art Technology

Future Technology



Next Gen Innovations



State of the Art Deposition Systems and Materials

Perovskite Technology Development and Validation

Cell Design and Materials

State of the Art Deposition Technology

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

NREL Transforming ENERGY

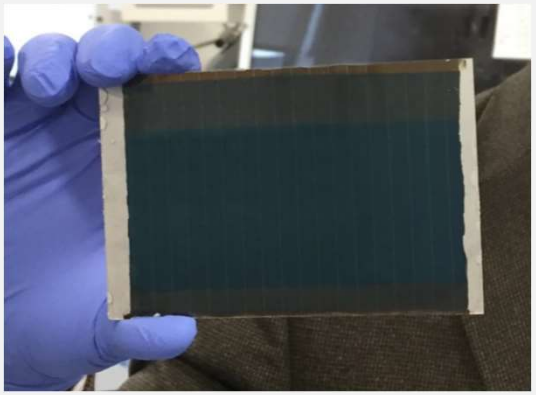
Arizona State University

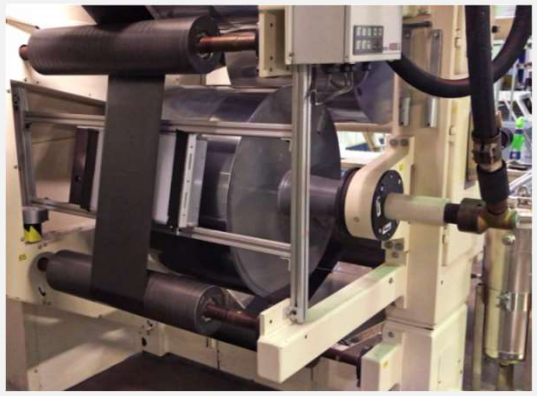
SLAC

EMC

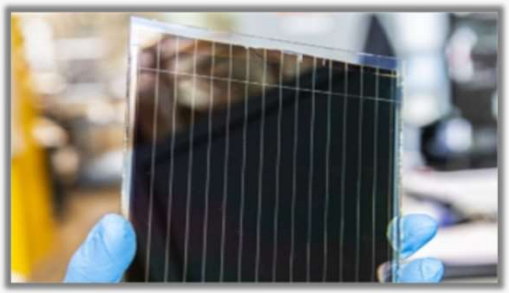
SWIFTCOAT

Other Collaborators:
Eastman Kodak
Corning





Project Goals: GW-scale Production at 90% Reduced CapEx from a Single Roll-to-Roll System

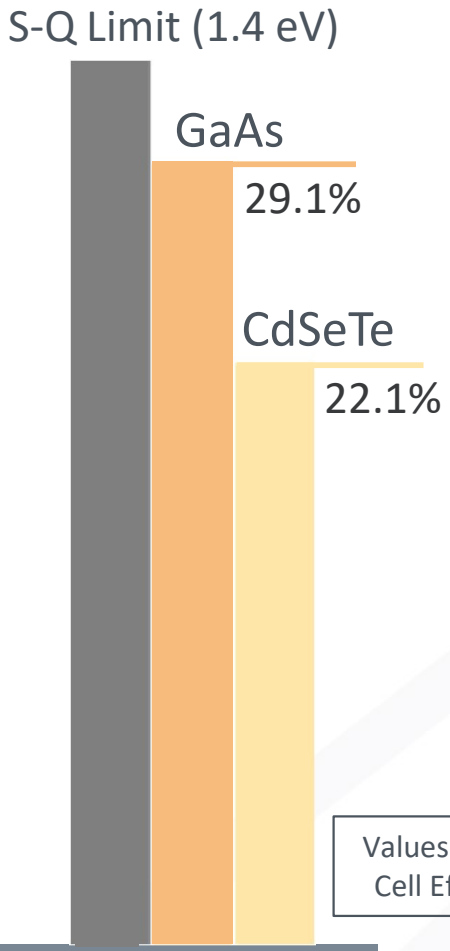


PV PACT

- Focused on Validating Perovskite Cell and Module Reliability
- Prototype Testing and Analysis Available

pvpact.sandia.gov

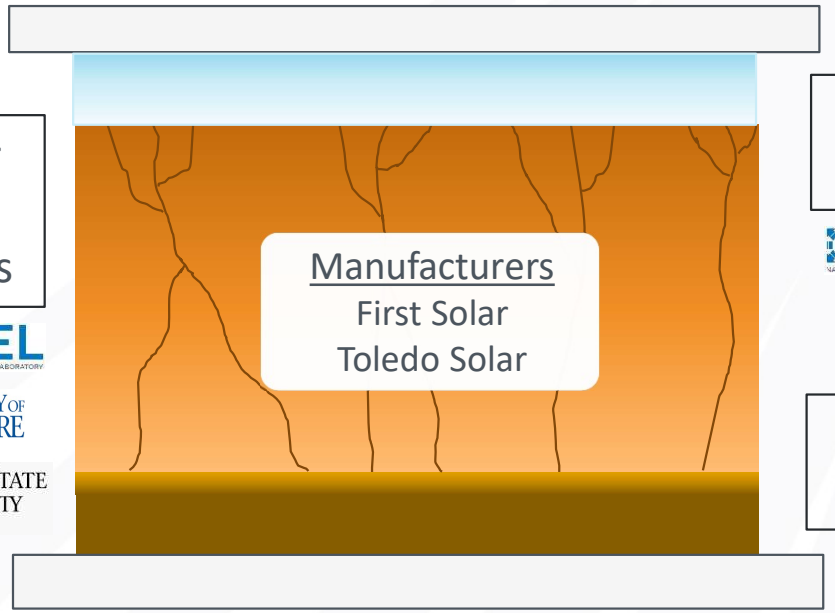
The Cadmium Telluride PV Community



Values from the NREL Cell Efficiency Chart

Absorber Layer Deposition and Post-Treatments

The University of Toledo · NREL · Colorado State University · University of Delaware · The University of Alabama · Washington State University



Manufacturers
First Solar
Toledo Solar

Front Contact and Junction

NREL · Colorado State University · The University of Toledo

Rear Contact and Metallization

Colorado State University · NREL · The University of Toledo · The University of Utah

Loss Mechanism Analysis and Material Characterization

Arizona State University · Ohio State · UIC · Drexel University · BGSU · NREL

FY21 CdTe PV Accelerator Consortium

$13.5M solicitation released by NREL to support the initial 3 years of a consortium to enhance domestic technology leadership and the long-term competitiveness of CdTe PV

- Focus on cell performance, with expected goals of 24% efficiency by 2025 and 26% efficiency by 2030.
- The consortium will also work to advance and grow domestic CdTe PV production and maintain sustainable module prices that are competitive with imported PV modules.

The Consortium Will:

- Convene domestic research and guide new solicitations to address CdTe R&D goals.
- Maintain technology roadmaps outlining CdTe research priorities
- Assess opportunities to expand the US CdTe manufacturing base

Stay Tuned for Further Announcements

Selected Projects Focused on Partnering

Total Active Cycle Funding across all Four Programs: $52M

PV Foundry

- Provides Silicon Cell and Module Fabrication Support and Collaboration

Arizona State and Georgia Tech

PV Proving Grounds

- Operates the Regional Test Centers to Validate New Technologies

rtc.sandia.gov

PV Fleet Data Initiative

- Studies System Performance Data and System Power Loss at the Fleet Level

pvfleetdata@nrel.gov

DuraMAT
Durable Module Materials Consortium

The DuraMat Consortium

- Focused on improving PV module materials, design, and overall reliability
- Able to fund research projects to accomplish its goals

More Information: Duramat.org

Thank You!

The SETO newsletter highlights the key activities, events, funding opportunities, and publications that the solar office has funded.

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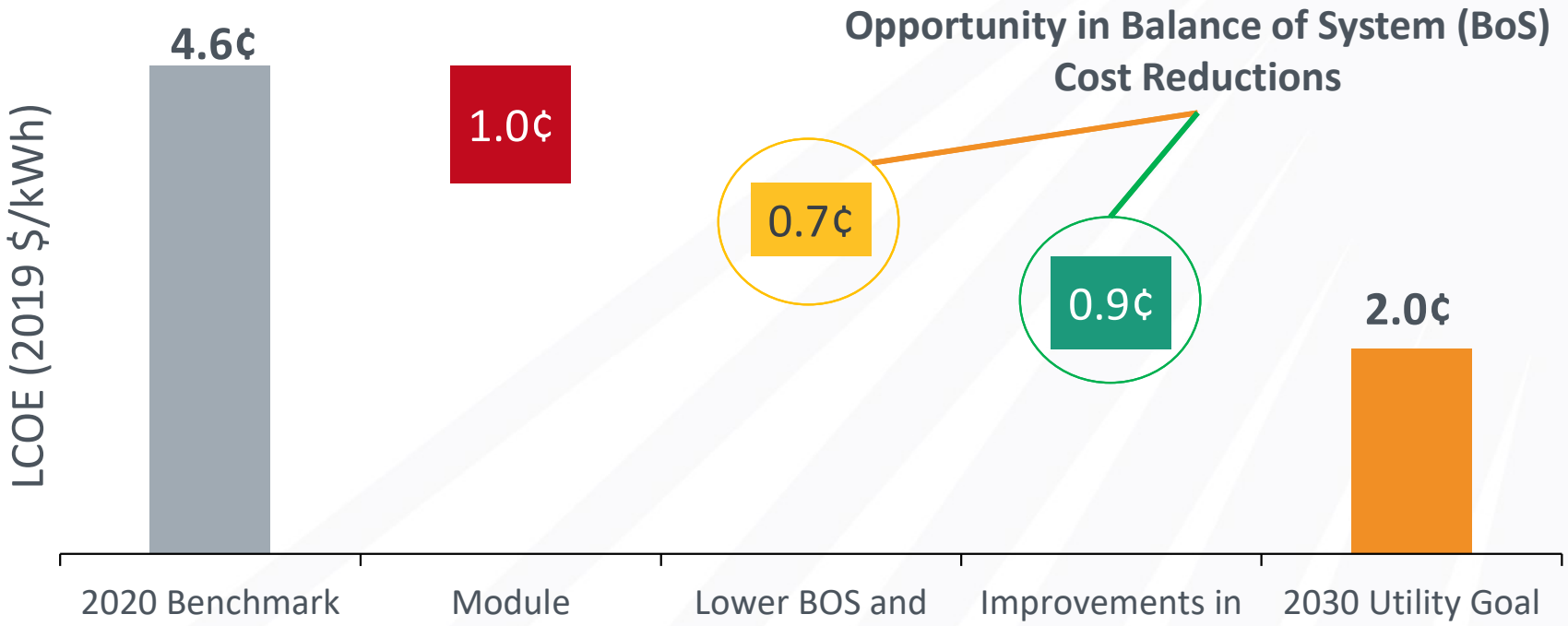
PV Balance of System

Durability, Resilience and Cost Improvement

Allan Ward

A Pathway to $0.02 per kWh for Utility-Scale PV



PV Balance of System (BoS) Areas of Focus ($24M)

Durability

- Quality-Driven Failures
- 50-Year Service Life

Resilience

- Rapid Fault Detection
- Extreme Weather Recovery

Machine Learning

- O&M Optimization
- Multiscale Analysis

Inverter Reliability

- Root-Cause Analysis
- Predictive Analysis

PV BoS Focus Area: Durability

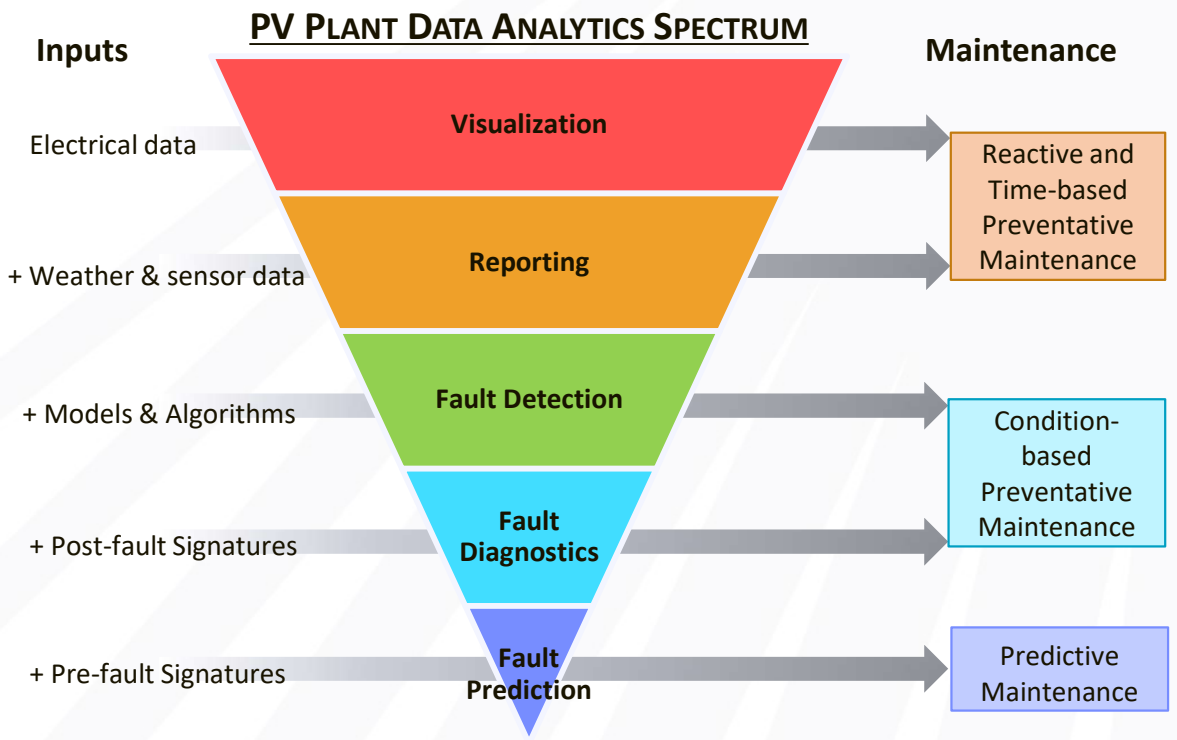
- Connectors and cabling installation quality and 50-year durability
- Fastener installation quality and 50-year durability for racking
- Latent damage effects from extreme weather (snow, wind)

PV BoS Focus Area: Resilience

- Automated fault detection and localized under-performance identification
- Rapid O&M detection, response, and recovery after extreme weather events
- Modular power block development for inverters

PV BoS Focus Area: Machine Learning

- Automated detection and diagnostics to optimize O&M costs
- Multi-scale, multi-climate data analytics for future energy output prediction



Sources: *Data Analytics for PV Systems: Fault Detection and Diagnostics.* EPRI. Palo Alto, CA: 2019. 3002015051.

PV BoS Focus Area: Inverter Reliability

- Digital twin and Physics-of-Failure modeling for energy prediction and inverter design optimization
- Electrical impedance identification of emerging inverter faults

PV BoS Principal Awardees

Thank You!

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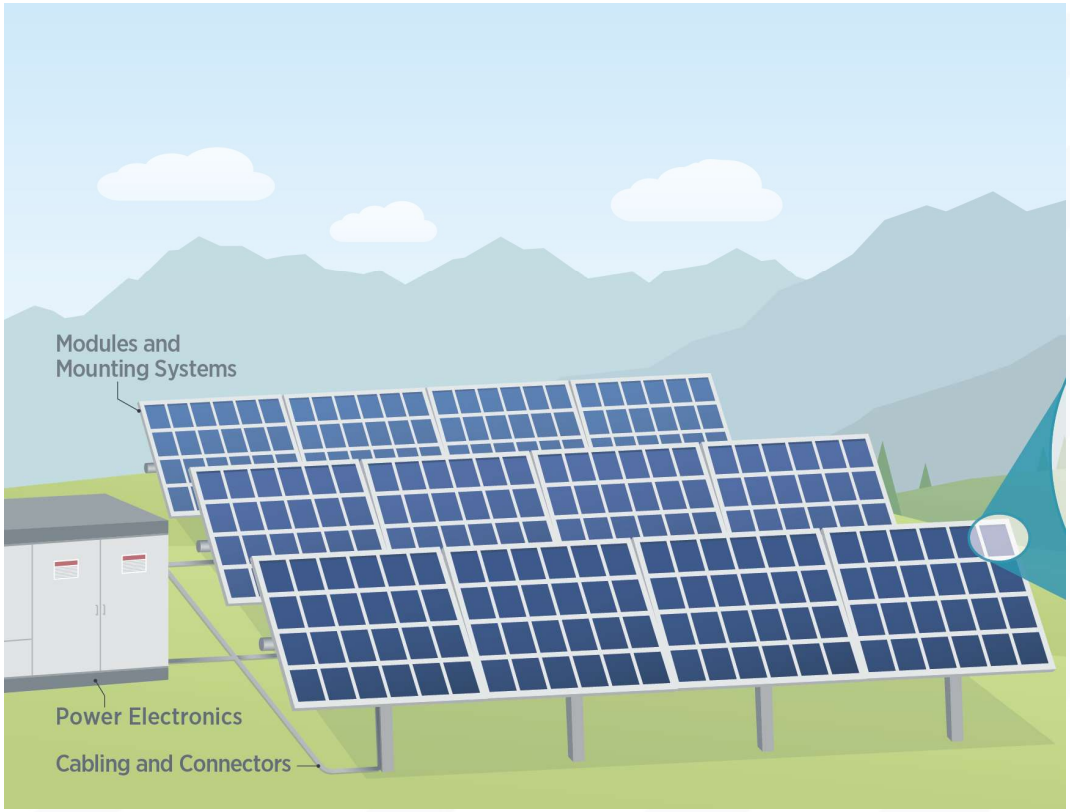
Photovoltaics End-of-Life

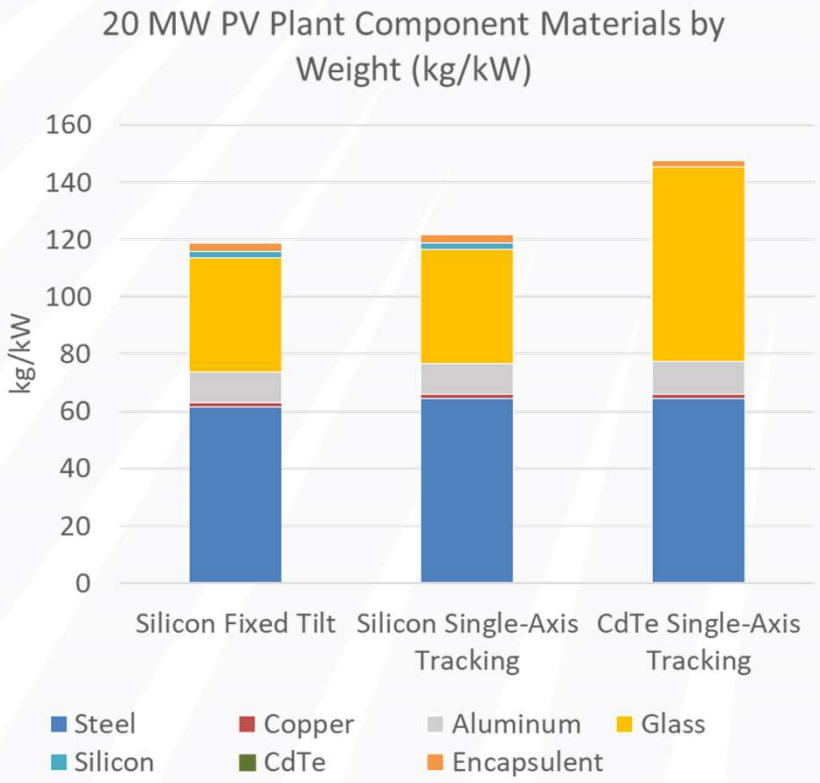
Susan Huang

Technology Manager

Materials in Plants

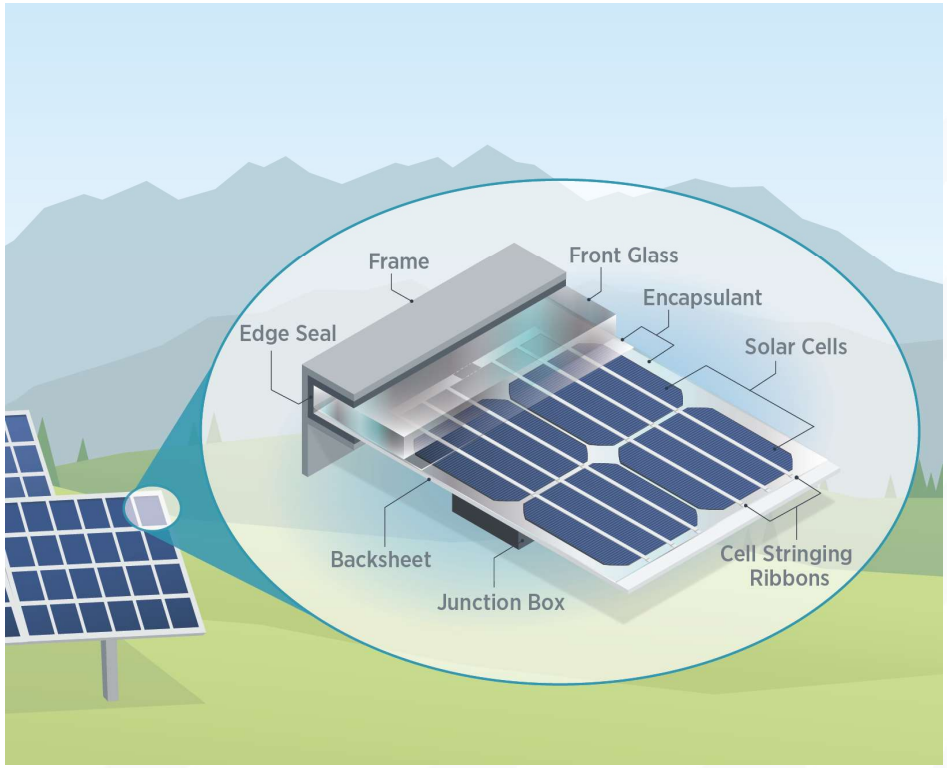
- At end-of-life (EOL), majority of plant material is recyclable

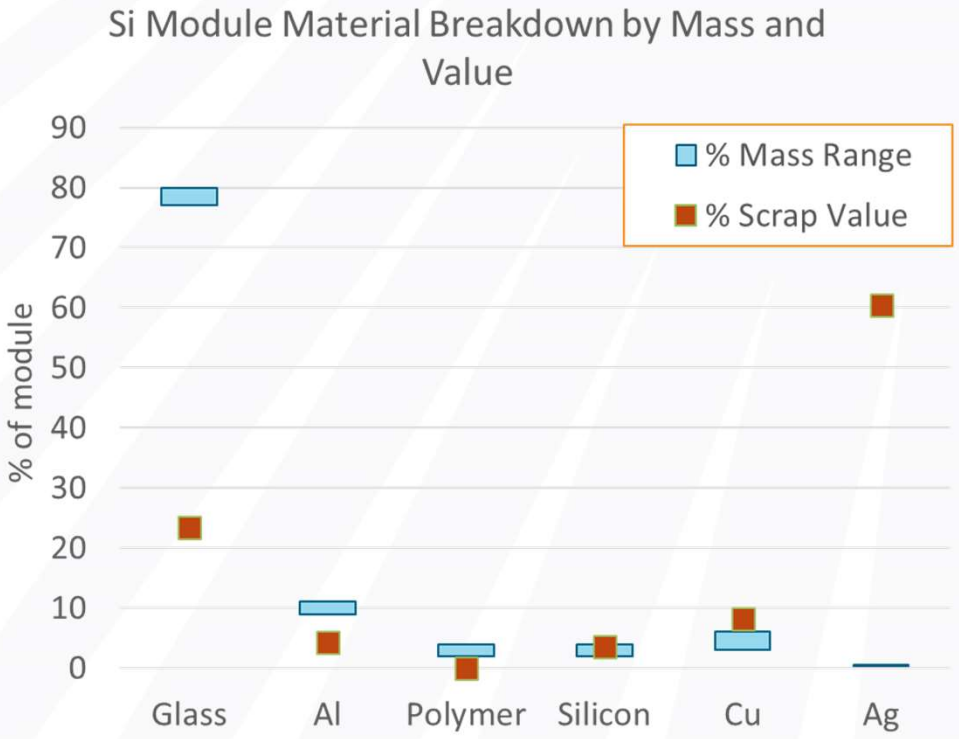




EOL PV Modules

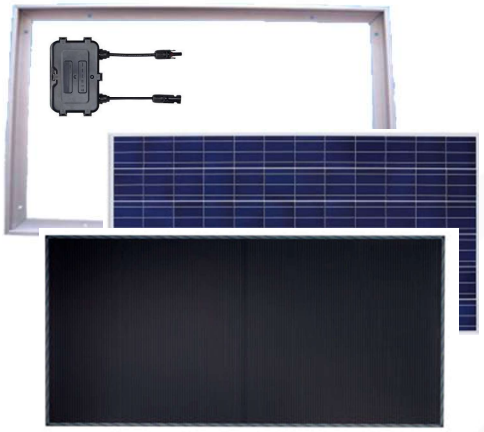
- Recycling can be improved to recover materials and lower cost





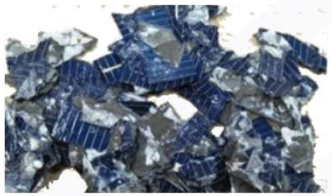
Current PV Module Recycling Processes

- Cost to generator: Recycling is ~10X more than landfilling



Remove frame, cables, and junction box

Cut and grind



Silicon

Sifting eddy current removes metals

Mechanical separation of glass and silicon

CdTe Thin Film

Chemical film removal, Glass and polymers

Ion exchange, Precipitate Cd and Te

EOL PV Modules

- Need to ensure safe disposal

TABLE 2: TCLP TEST RESULTS FOR ONE C-SI MODULE BY SAMPLING APPROACH: PROPORTIONAL, REPRESENTATIVE OR RANDOM (ND = NOT DETECTED)

Analyte	Result mg/l			Reported Detection Limit mg/l	Limit mg/l
	Proportional method	Representative method	Random method		
Arsenic	ND	ND	ND	0.1	5
Barium	ND	ND	ND	0.1	100
Cadmium	ND	ND	ND	0.1	1
Chromium	ND	ND	ND	0.1	5
Lead	2.96	2.48	4.01	0.1	5
Mercury	ND	ND	ND	0.01	0.2
Selenium	ND	ND	ND	0.1	1
Silver	ND	ND	ND	0.1	5

G. TamizhMani, et al., "Sampling Methods for Toxicity Testing of PV Modules for End-of-Life Decisions", 48th IEEE PVSC Proceedings, 2021.

PV EOL Policies

EPA United States Environmental Protection Agency

Toxicity Characteristic Leaching Procedure

Takeback Program
- WA: 2017

Universal Waste
- CA: October 2015
- HI: June 2021

Pending Policies
- NJ: Recycling Commission
- NC: Management and Decommissioning of Renewable Energy

SETO PV EOL Activities

2019 → 2020 → 2021

PV Recycling FOA Topic

DOE, EPA Collaboration

SIPS Project

PV EOL RFI & Workshop

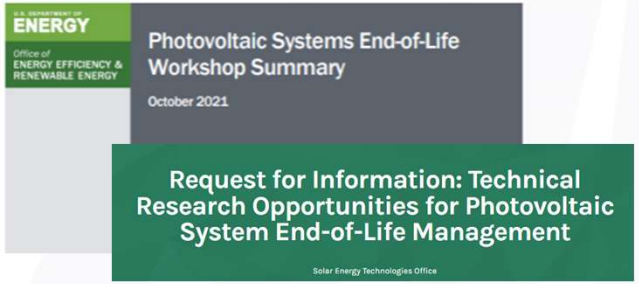
SIPS Project

IEA Task 12

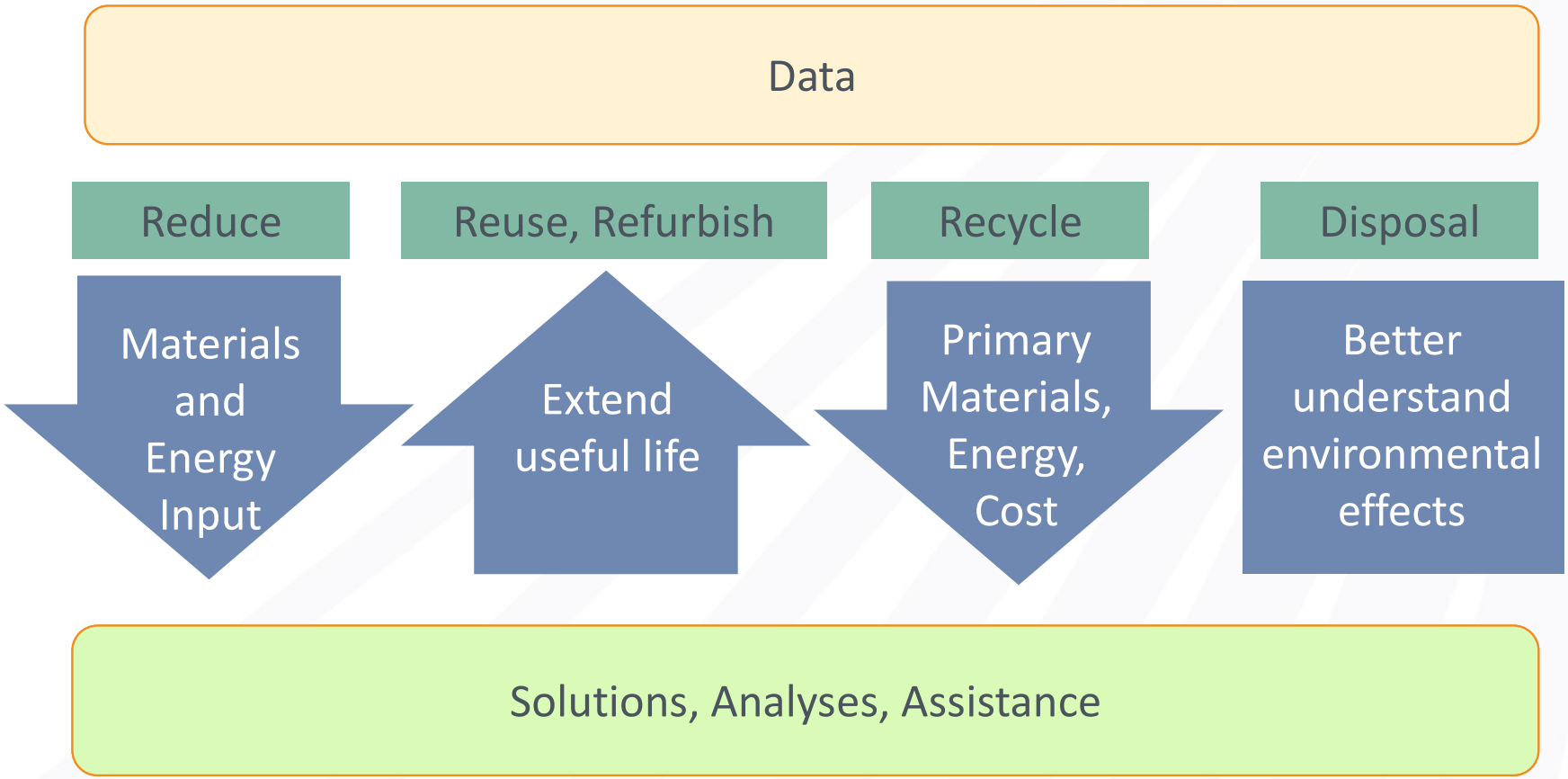
Solar Energy Technologies Office
FY2019
FUNDING OPPORTUNITY

EPA United States Environmental Protection Agency

Advanced Manufacturing Office



PV EOL Research Opportunities



PV EOL Future Work

- Infrastructure Investment and Jobs Act
  - $20M for PV Recycling and Safe Disposal
- EOL Database
- EOL Research Projects
  - Recycling cost target: 50% reduction
  - Industry engagement
- Continued collaborations with government and industry