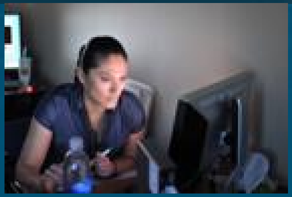
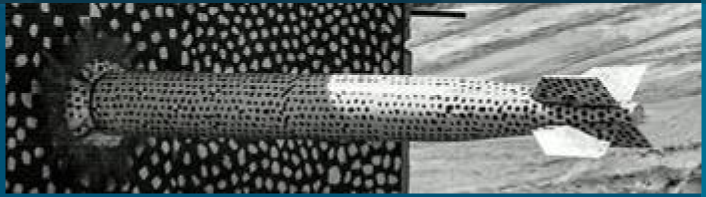
SAND2021-13545PE

Sandia National Laboratories

Solar PV Technologies – An Overview of Current and Emerging Research





PRESENTED BY

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October 28, 2021

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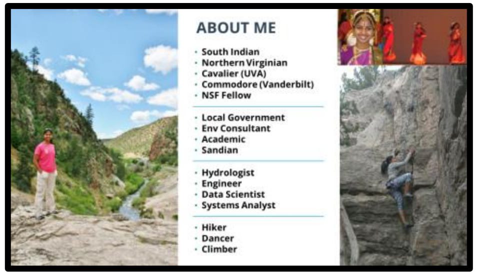
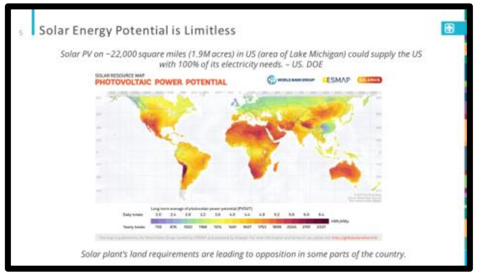
Outline

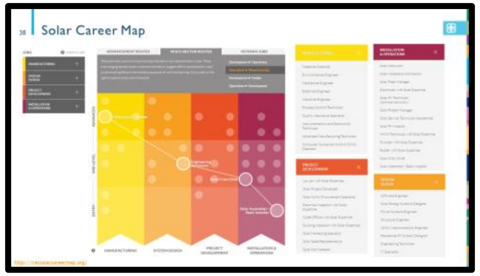


Brief Bio



Overview of PV

Research Design, Development & Deployment



Solar Careers

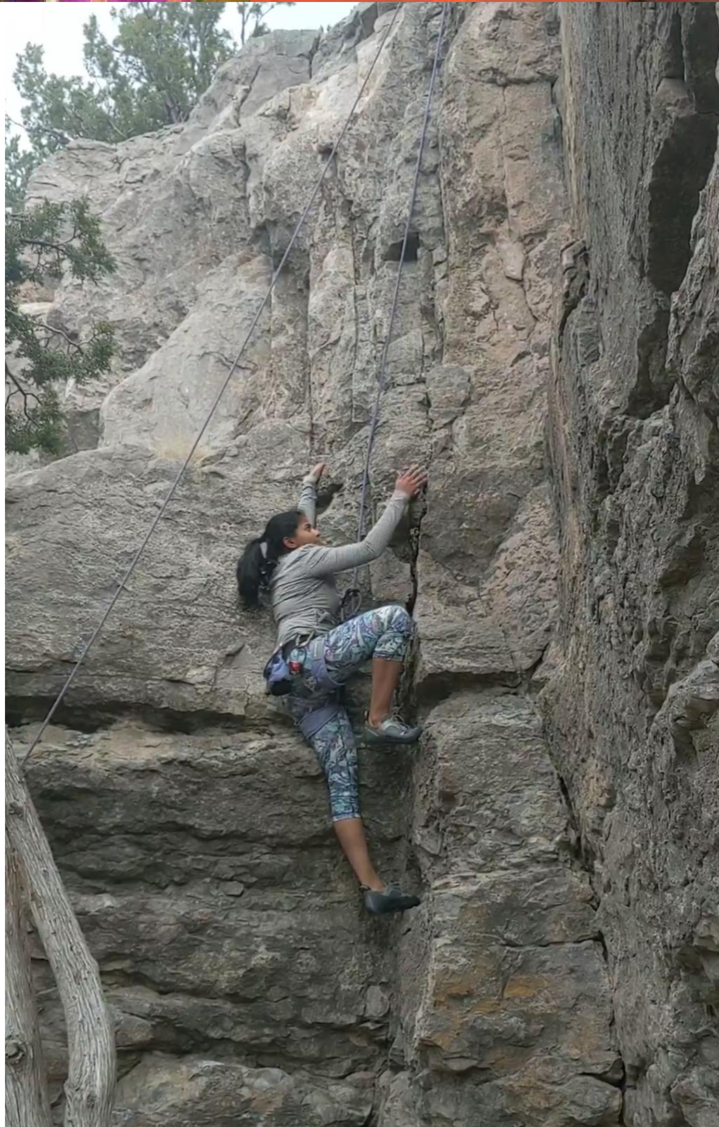
ABOUT ME

- South Indian
- Northern Virginian
- Cavalier (UVA)
- Commodore (Vanderbilt)
- NSF Fellow

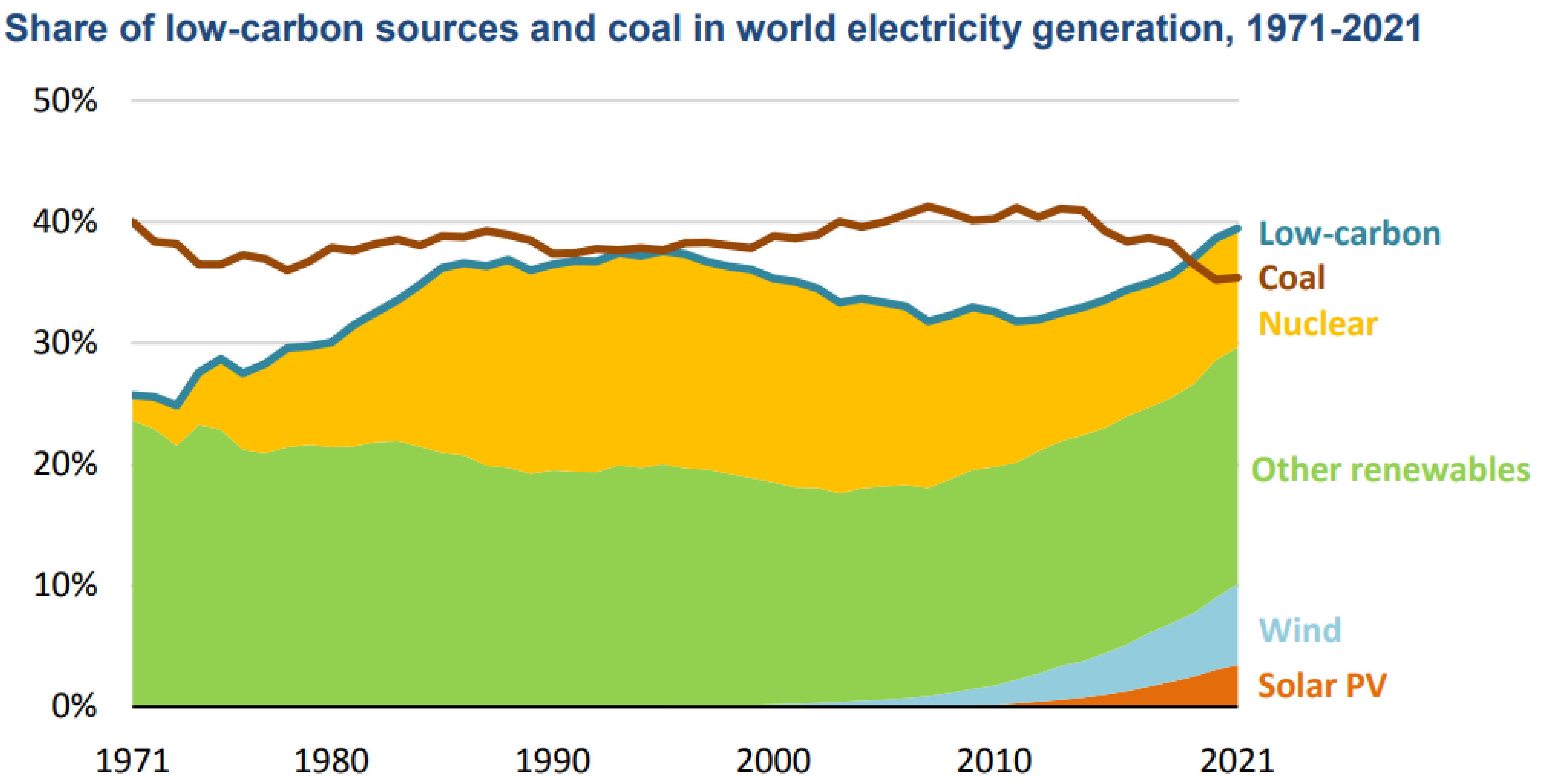
- Local Government
- Env Consultant
- Academic
- Sandian

- Hydrologist
- Engineer
- Data Scientist
- Systems Analyst

- Hiker
- Dancer
- Climber



Global Electricity Production

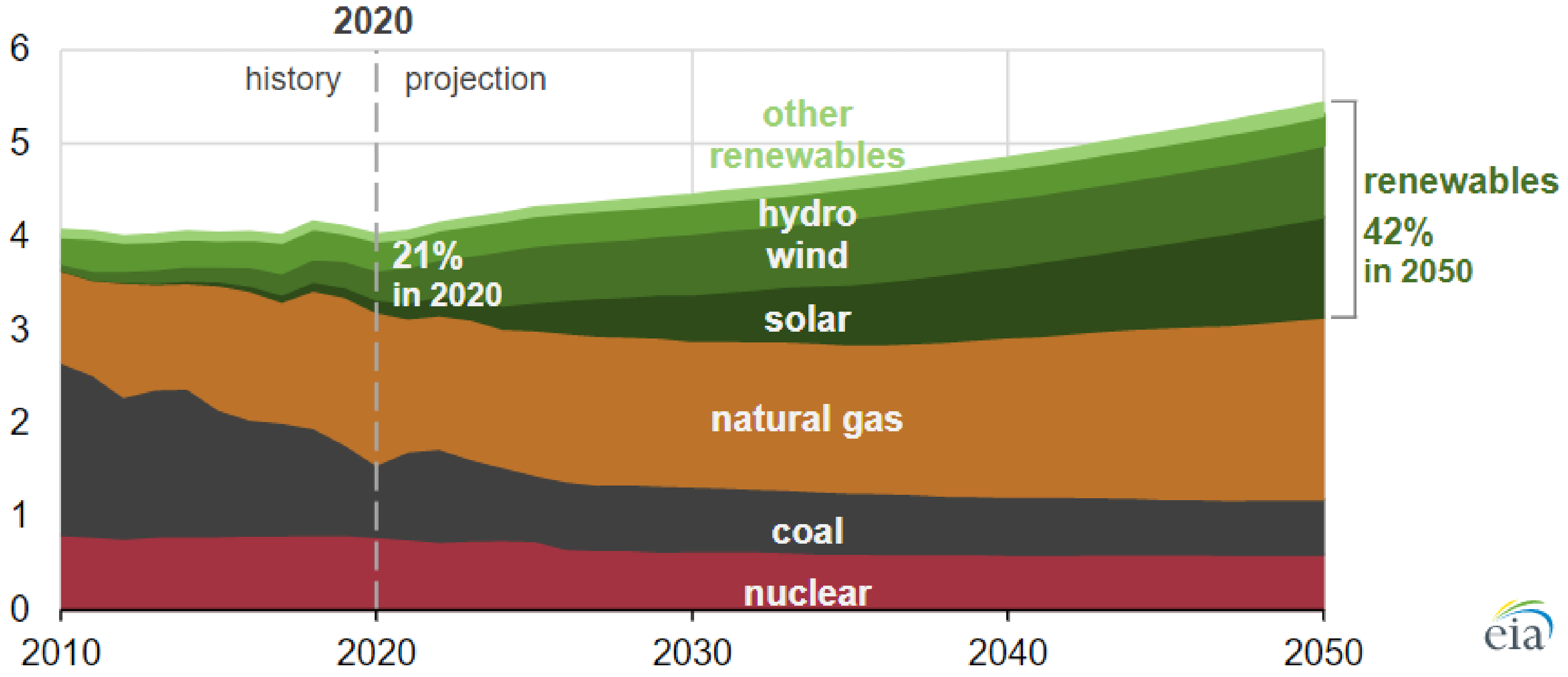


Energy Generation in the U.S.

FEBRUARY 8, 2021

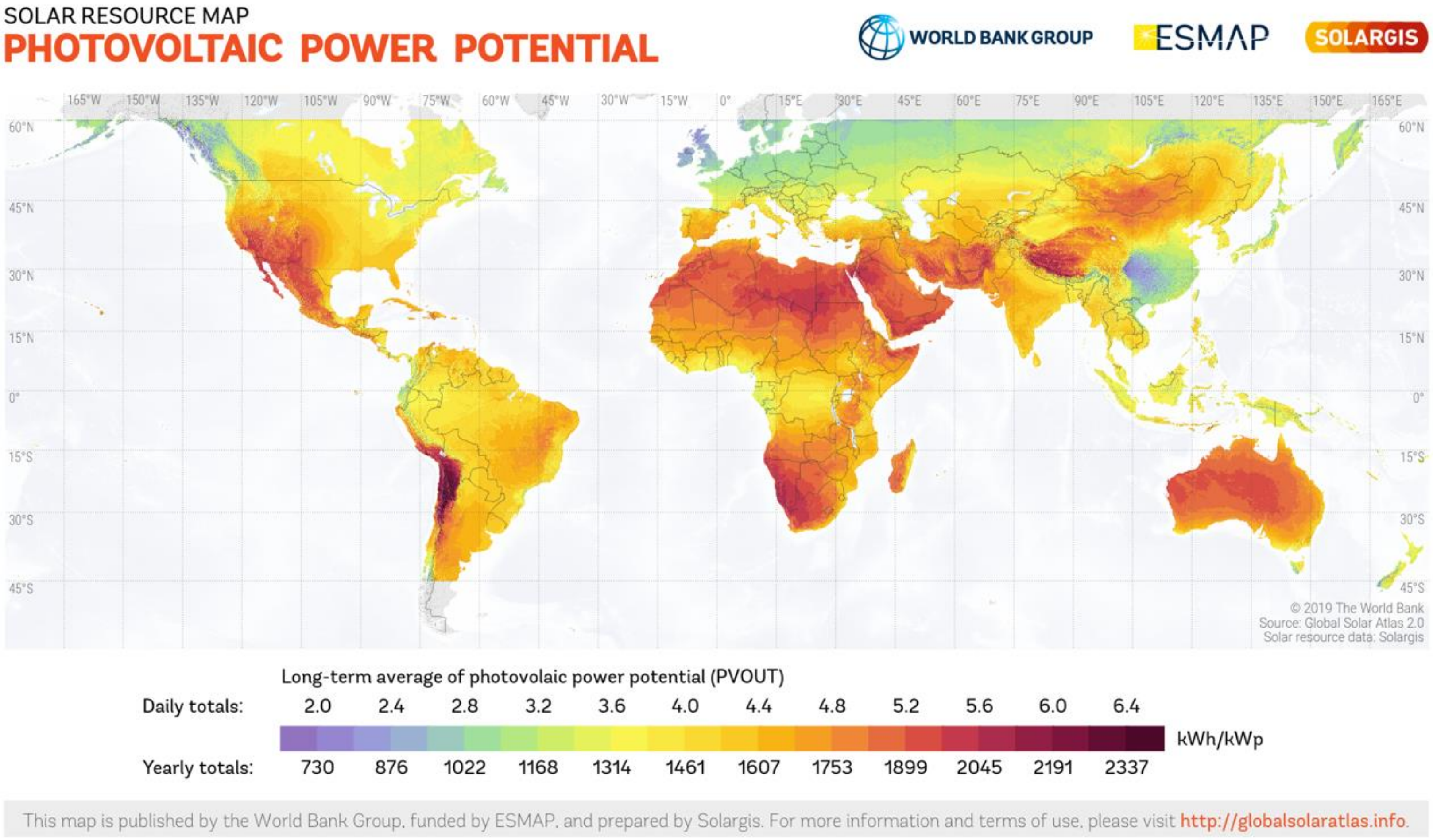
EIA projects renewables share of U.S. electricity generation mix will double by 2050

U.S. electricity generation, AEO2021 Reference case (2010–2050)
trillion kilowatthours



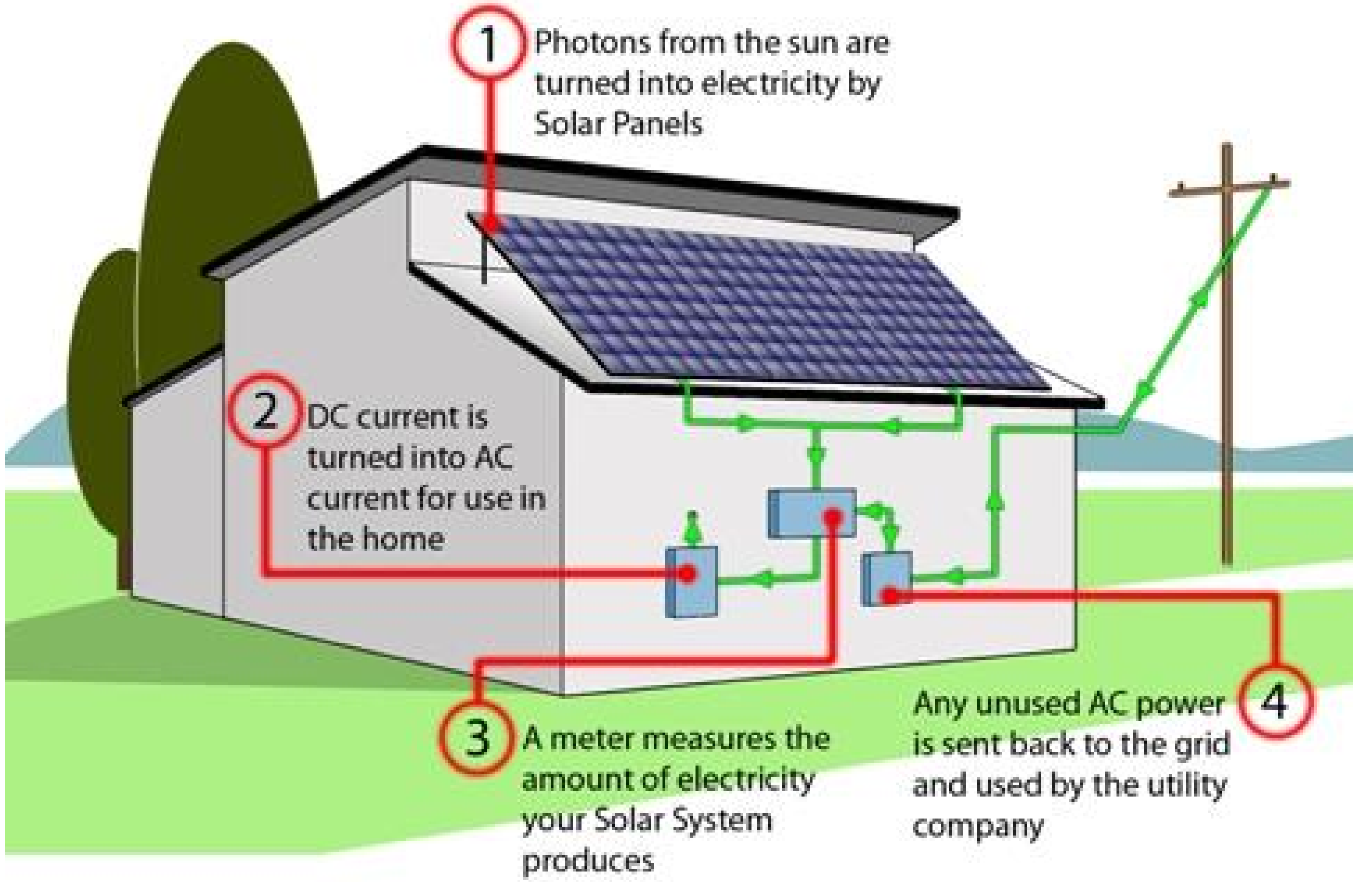
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2021* (AEO2021)

Solar Energy Potential is Limitless



Solar PV on ~22,000 square miles (1.9M acres) in US (area of Lake Michigan) could supply the US with 100% of its electricity needs. – US. DOE

Overview of PV



Source: Linc Energy

Variation: AC power is directly sent to grid and home energy cost is credited the difference

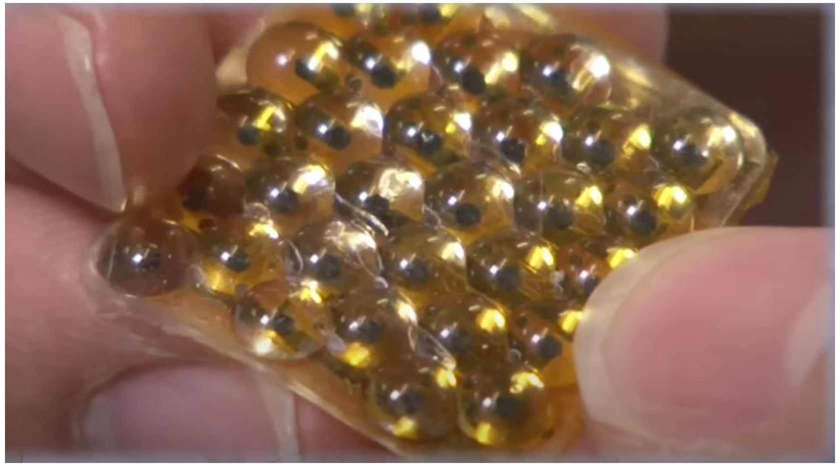
PV installations occur in varying shapes and sizes

Source: PNM

Solar Farms (Utility-Scale)

Source: leisurevehicleartisan and CNN

Cars &
Camper Vans



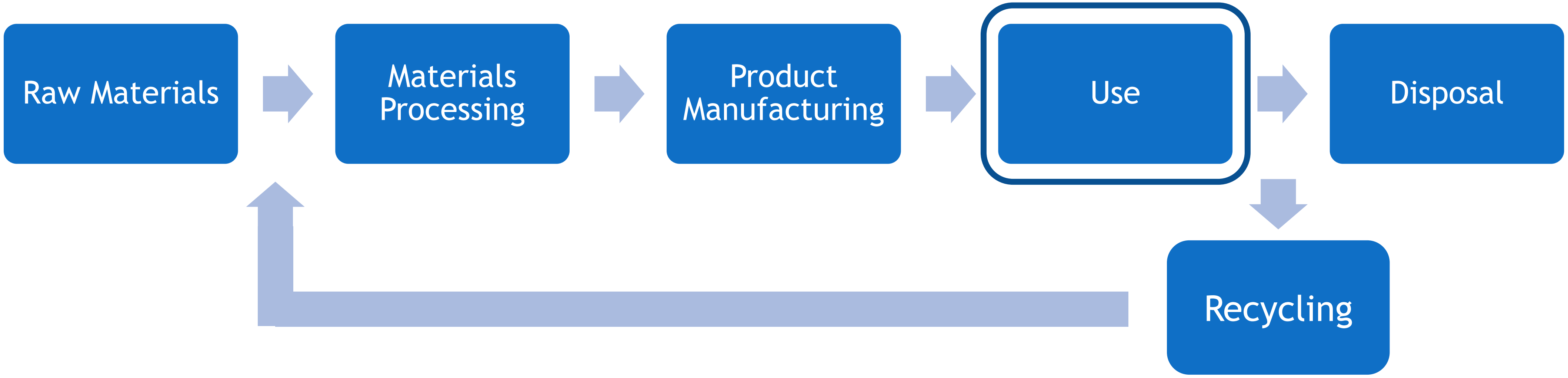
Source: Sandia

Micro-cells

What are the life cycle components for PV?

Jot down a few phases that you think that an LCA should consider

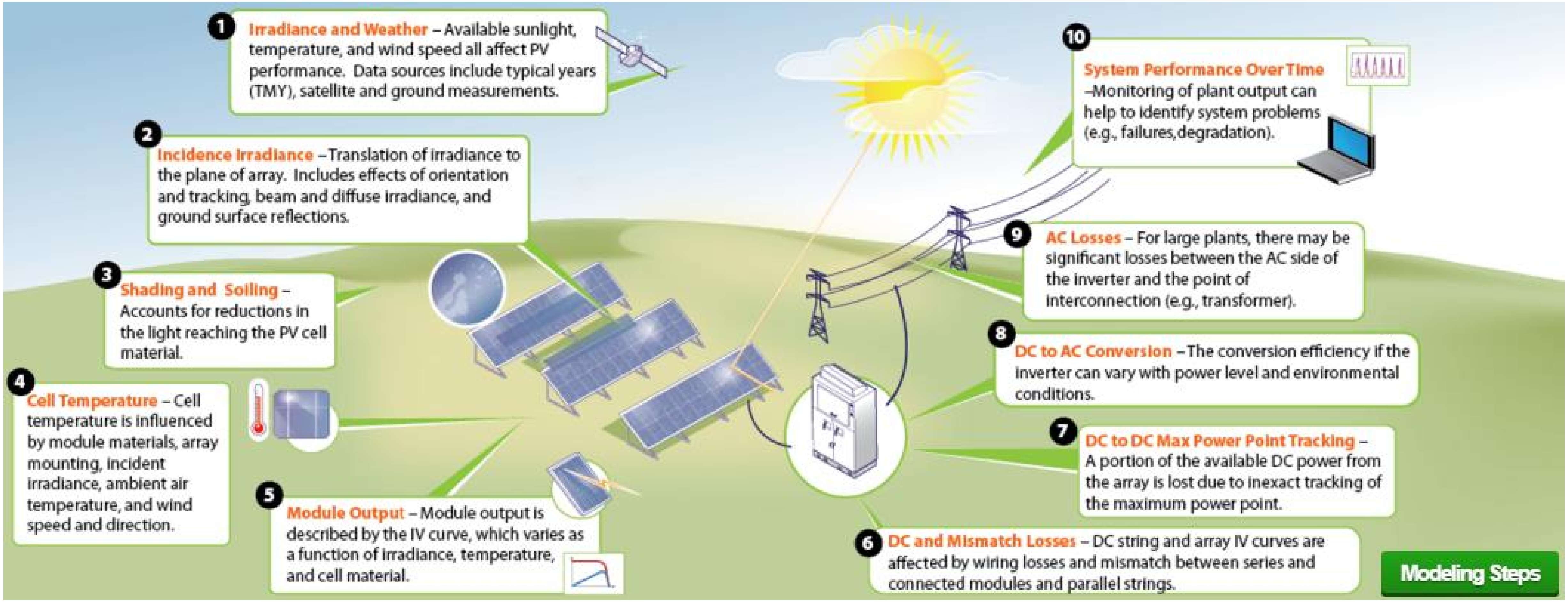
Life Cycle of PV



Source: Vellini et al., 2017

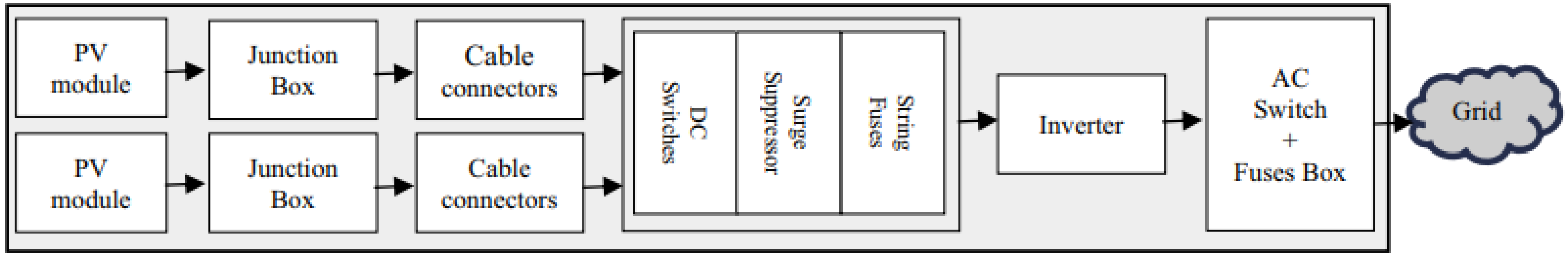
What are some challenges that PV systems may face during operations?

Performance Modeling Steps



Source: PVPMC

PV Plants as Complex Systems

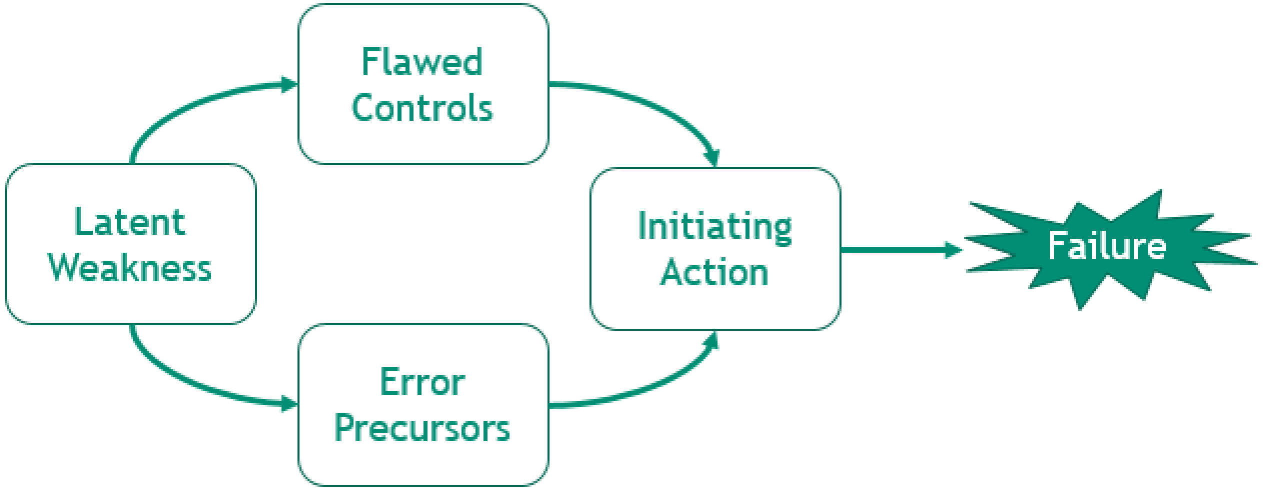


Source: Cristaldi et al., 2015

Fig. 1. Simplified schematic diagram of photovoltaic plant.

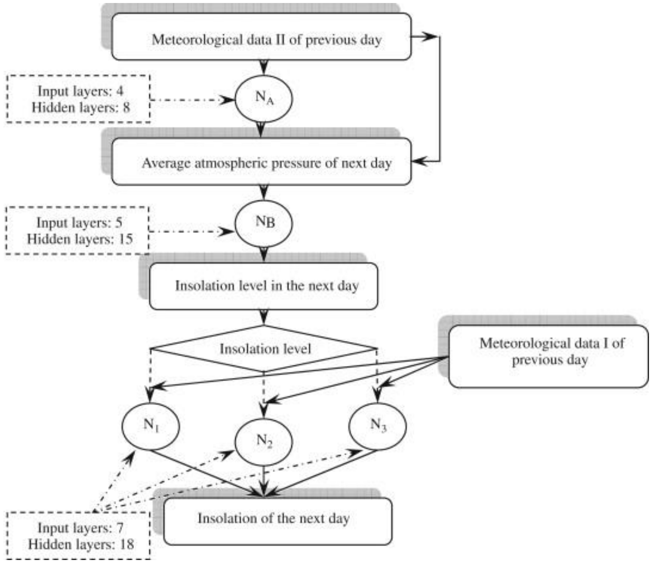
- Lots of parts and interconnections
- Both human and machine elements in laten weaknesses and controls
- Precursors can be maintenance-oriented
- Actions can be chronic or acute
- Non-linear pathways with lots of uncertainty and dynamic components

→ COMPLEX SYSTEM

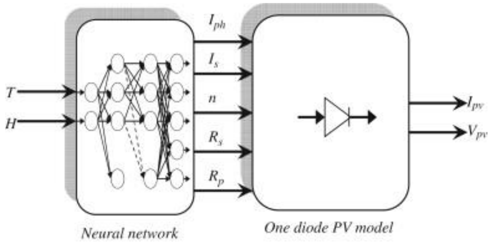


Adapted from the DOE Human Performance Improvement Handbook

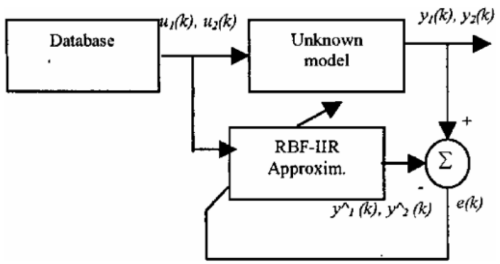
Machine Learning & Photovoltaics



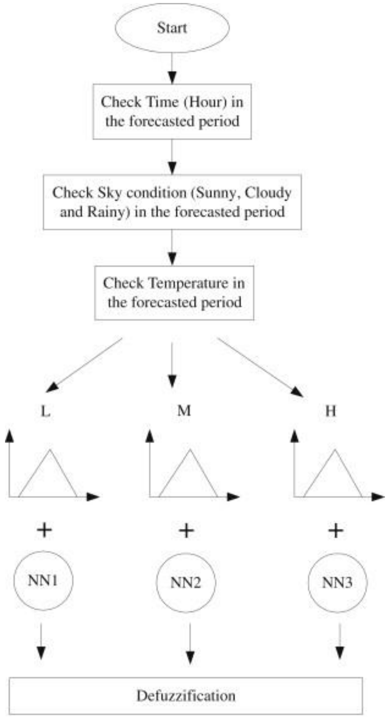
Kemmoku et al., 1999



Karatepe et al., 2006



Mellit et al., 2004

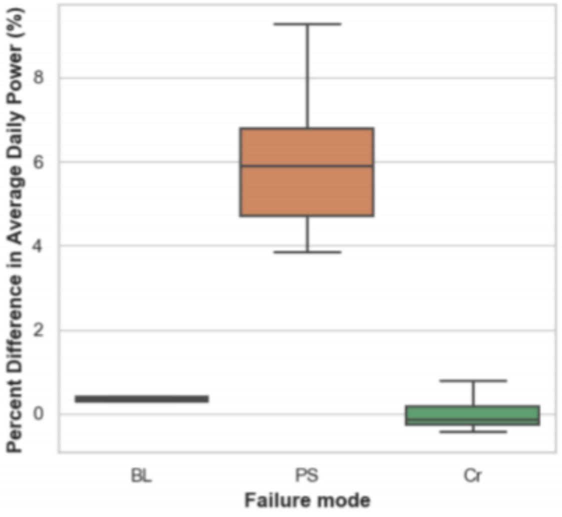


Chen et al., 2013

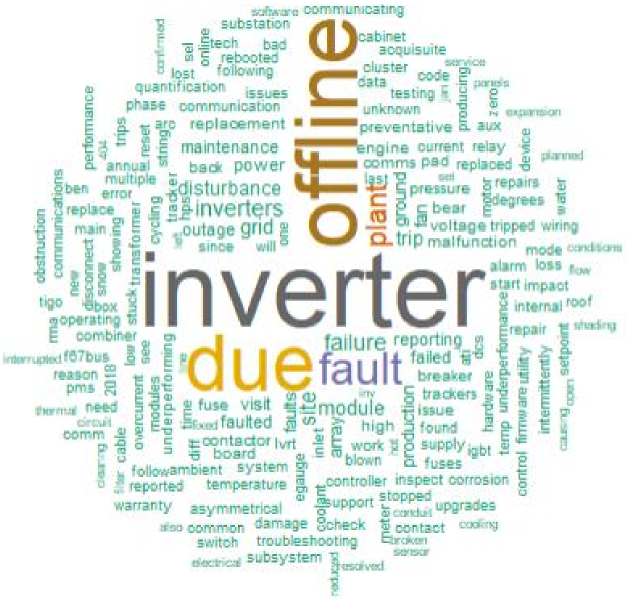
- ML has been leveraged in PV for decades
- Multiple applications, including
  - Radiation and weather forecasting
  - Sizing of PV systems
  - Simulation of PV systems and controls
- Across stand-alone, grid-connected, and hybrid systems

PV & Failures

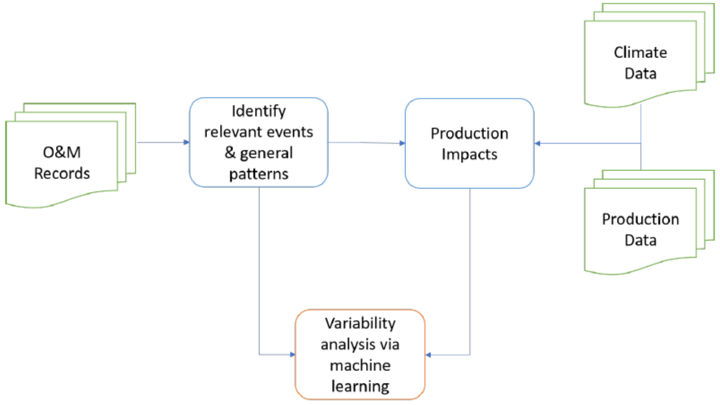
- Understanding and dealing with the PV system aging process is creating a new and unknown set of challenges
- Machine learning is being increasingly used for understanding failures within the PV industry



Failure Characterization



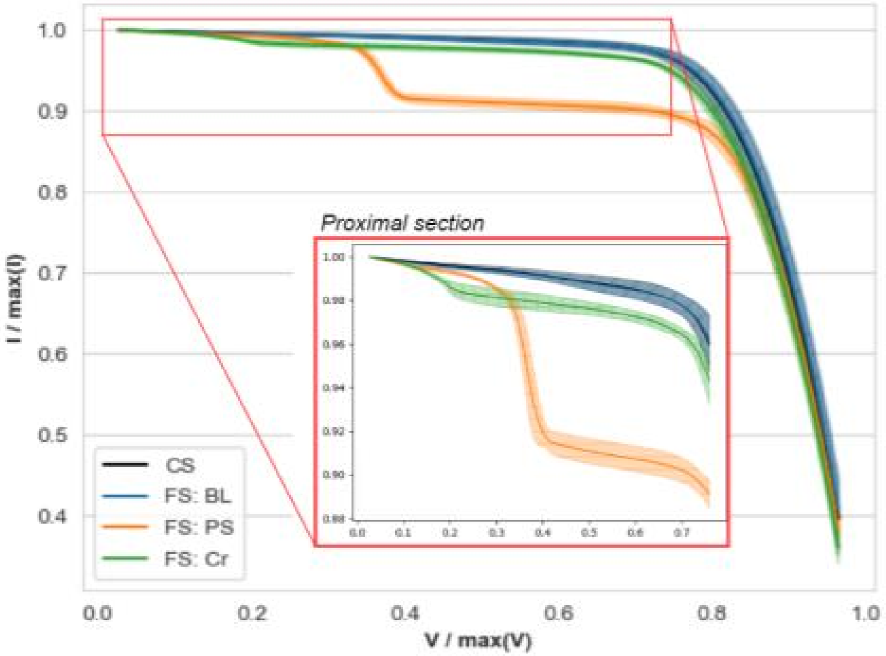
Common Failure Modes



Weather Impacts

Failure Characterization

- Extended current approaches of feature extraction to consider the entire IV trace using 3 NN architectures
- Data processing including quality checks, normalization, and interpolation
- Multi-headed LSTMs and 1D CNNs had comparable high accuracies. Single-headed LSTM outperformed when only considering proximal regions.



NN Architecture	Sampling Region	Num. Predictors	Average accuracy, % (SD) across 20 tests			
			BL	PS	Cr	Total
Multi-headed LSTM	Entire Curve	4	100.0 (0)	100.0 (0)	98.0 (2.8)	99.3 (1.0)
	Proximal	4	99.1 (2.8)	100.0 (0)	97.6 (5.1)	98.9 (1.7)
Single-headed LSTM	Entire Curve	4	74.5 (37.5)	68.2 (42.0)	23.7 (36.3)	51.8 (15.8)
	Proximal	4	70.3 (44.6)	95.0 (21.8)	76.2 (37.4)	79.0 (20.8)
1D CNN	Entire Curve	4	99.4 (2.4)	100.0 (0)	100.0 (0)	99.8 (0.8)
	Proximal	4	100.0 (0)	100.0 (0)	94.0 (10.3)	98.0 (3.2)
1D CNN	Entire Curve	2[a]	71.2 (40.8)	80.0 (40.0)	62.7 (42.7)	68.9 (27.4)

[a] Utilizing only I_{CS}, I_{FS} out of the normal set: I_{CS}, I_{FS}, ϵ_{FS}, and δ_I

Source: Hopwood et al., 2020

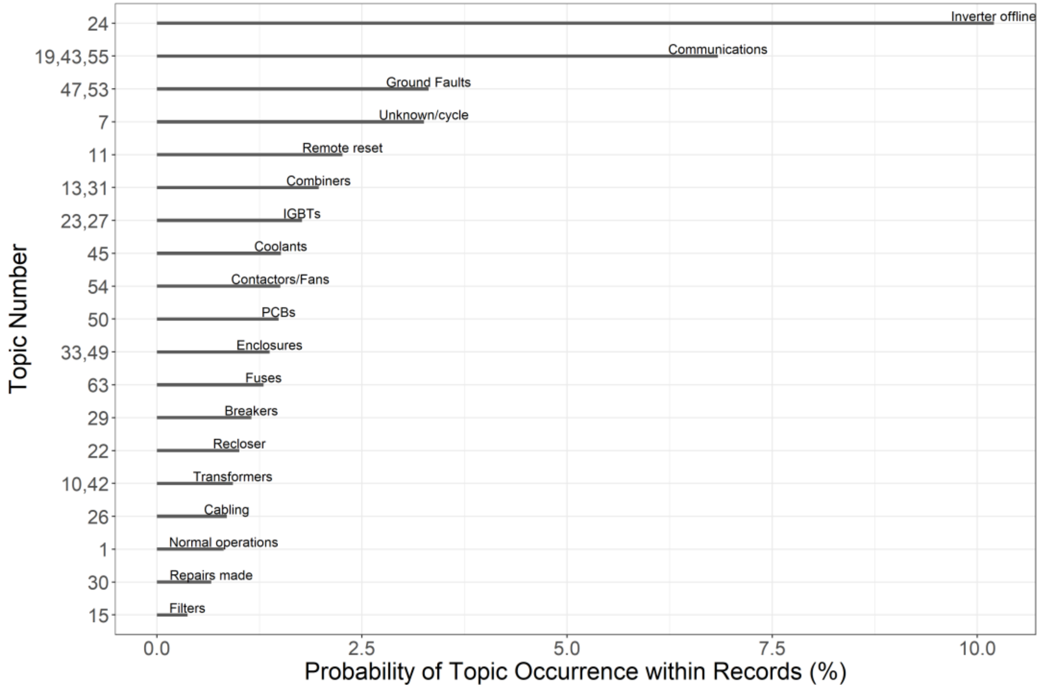
O&M Data

- Maintenance logs contain valuable contextual information
- However, significant diversity in the structure and detail of the logs makes it challenging to ascertain needed insights
- Most contain a general comment field to capture issue description

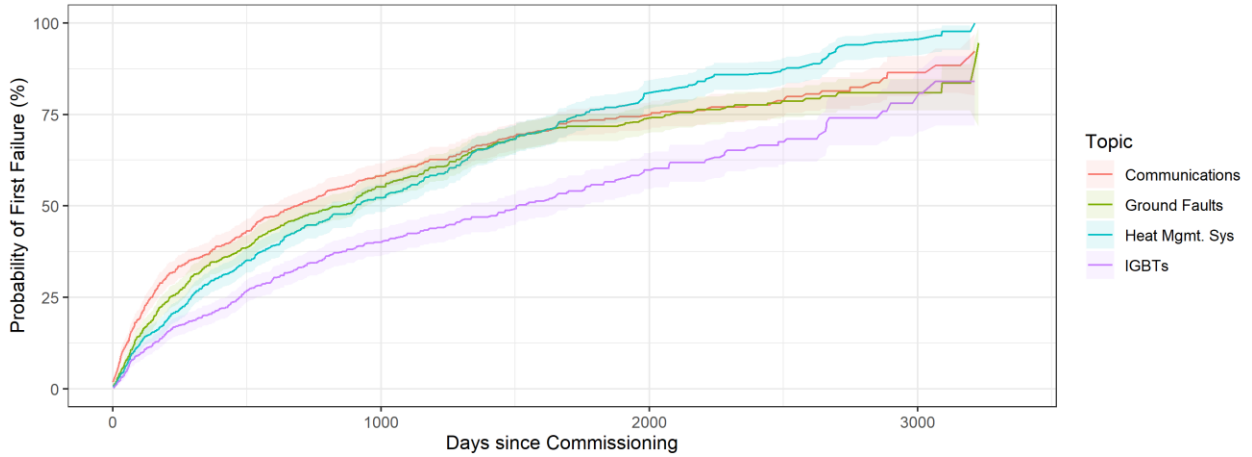
Context	Where	What	When	Why	How
WO type	Site ID	General desc.	Event Start	Priority	Completion desc.
WO Status	Asset	Failure cat.	Event End	Production impact	Effort (labor)
Warranty info				Impact level	

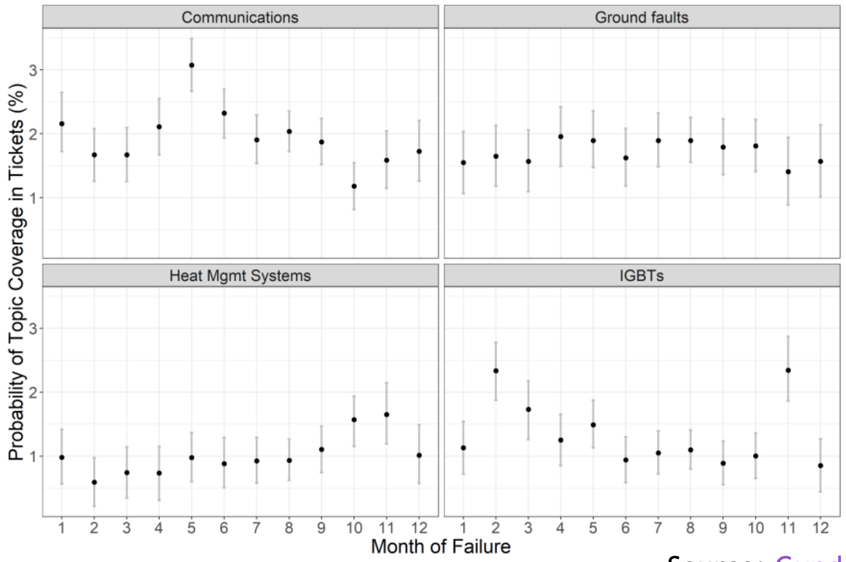
randid	WOType	WONumber	FailureCategories	Cause	ImpactLevel	FullDesc	CompletionActivity
C2S16	Corrective	17_014989	Hardware Malfunction	NA	Partial	Circuit 2 trackers stuck in flood	Hardware Adjustme
C2S1	Corrective	17_017409	Software Problem	NA	Partial	Trackers going into flood stow	Software/Firmware
C2S16	Corrective	17_015278	Hardware Malfunction	NA	Partial	Circuit 2 Trackers went to Flooc	Power Cycle
C2S16	Corrective	17_015727	Software Problem	NA	Partial	Circuit 2 in flood stow due to m	Power Cycle
C2S16	Corrective	17_018812	Hardware Malfunction	NA	Partial	Circuit 2 in flood stow. Power C	Power Cycle
C2S1	Corrective	17_019236	Hardware Failure	NA	Mixed	All trackers in intermittent floo	Hardware Replacem
C2S1	Corrective	17_025187	Software Problem	NA	Partial	Tracker NCUs indicate in flood	Software/Firmware

Identification of Common Failure Modes



- Focused on inverters – one of the leading causes of PV system failures
- Used ML in 2 ways:
  - Single Vector Decomposition to identify inverter-related records
  - Latent Dirichlet Allocation to group “like” records
- Temporal patterns in clustered records were evaluated using survival analysis and estimateEffects

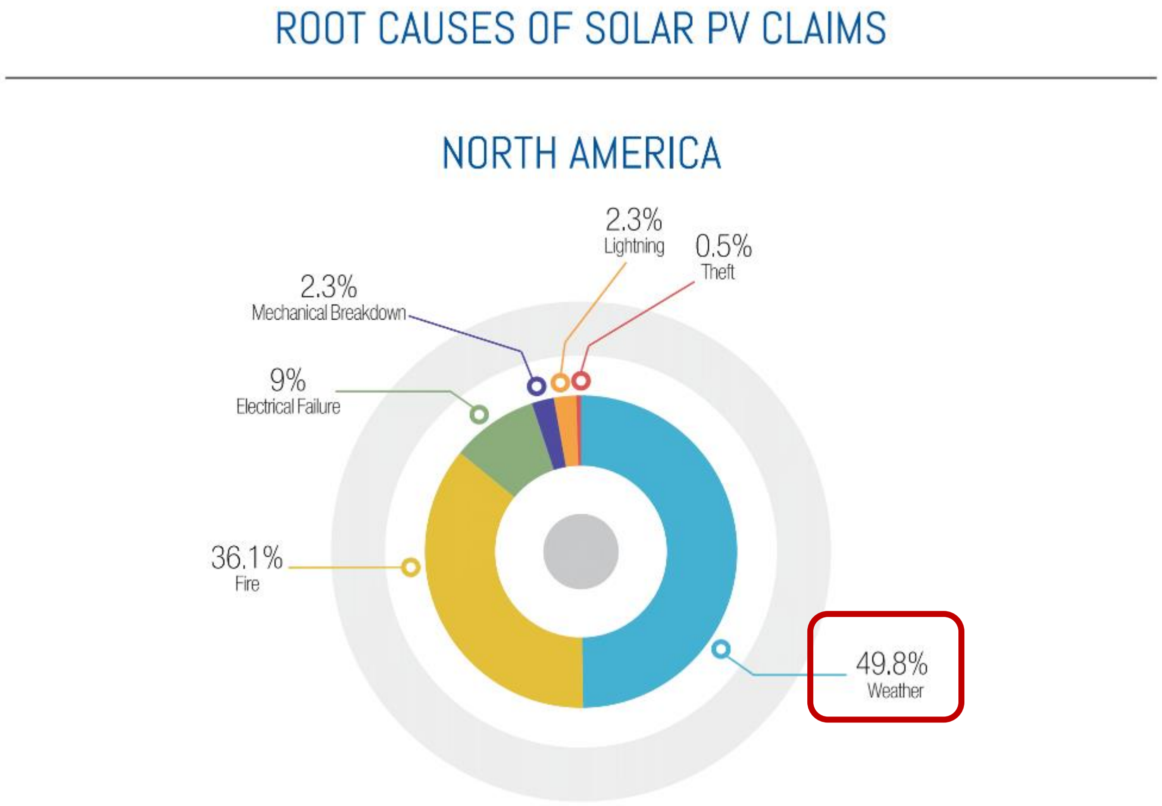




Source: Gunda et al., 2020

PV plants can be exposed to disruptions due to weather events that can have financial implications.

Source: BMR Energy



Source: GCube

Although economic impacts are apparent, quantitative evaluation of PV production impacts are currently lacking

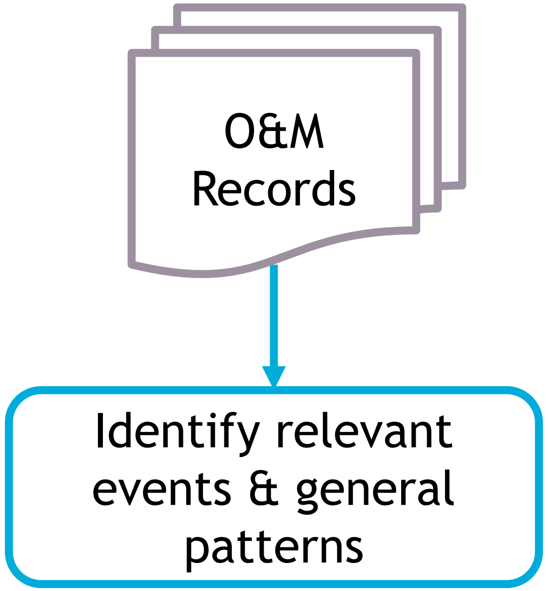
Studies to date have focused on

- Analysis of annual performance reports,
- Field evaluations of post-hurricane damages, and
- Experimental investigations of different PV architectures on snow-related losses

However, few studies have systematically quantified the impact of extreme weather events on PV performance and evaluating characteristics that could be contributing to these variations

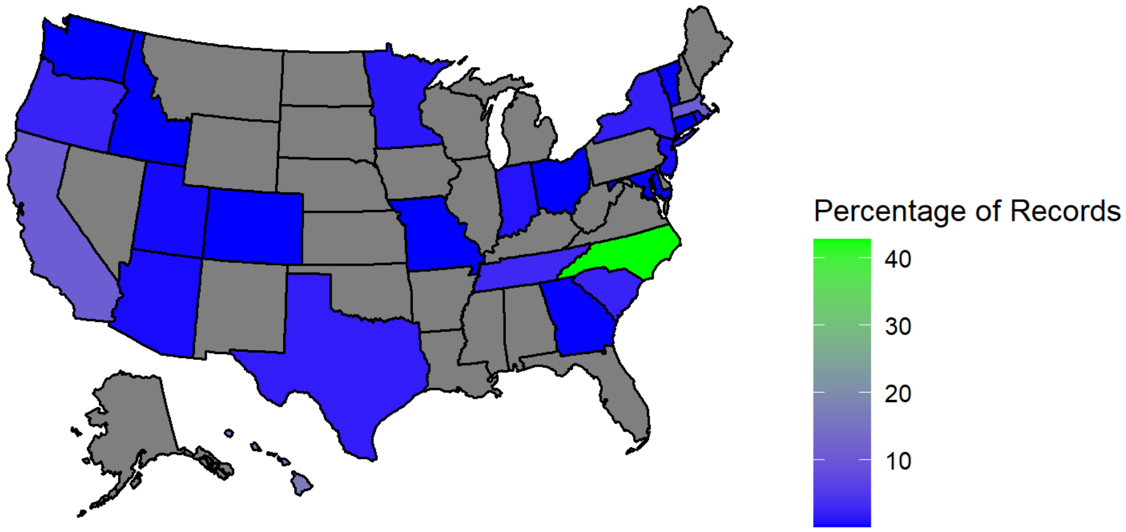
Study Objective: *Conduct an integrated assessment of PV plant performance considering maintenance records, production information, and weather events.*

Our analysis approach consisted of leveraging diverse datasets, starting with O&M tickets to identify relevant weather events



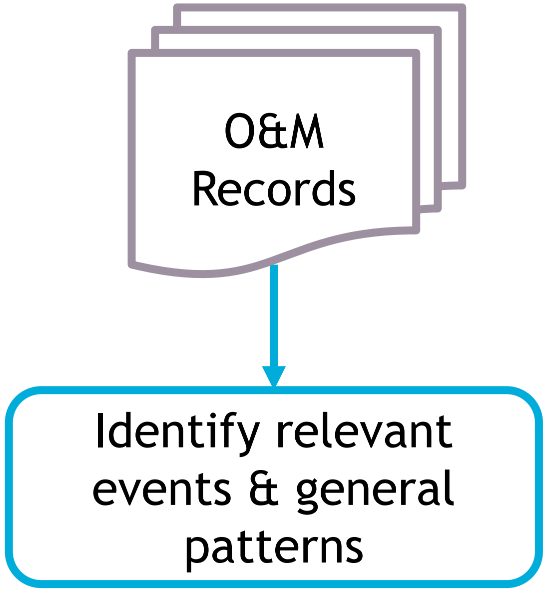
PVROM represents 14.9% of utility-scale generation in the United States

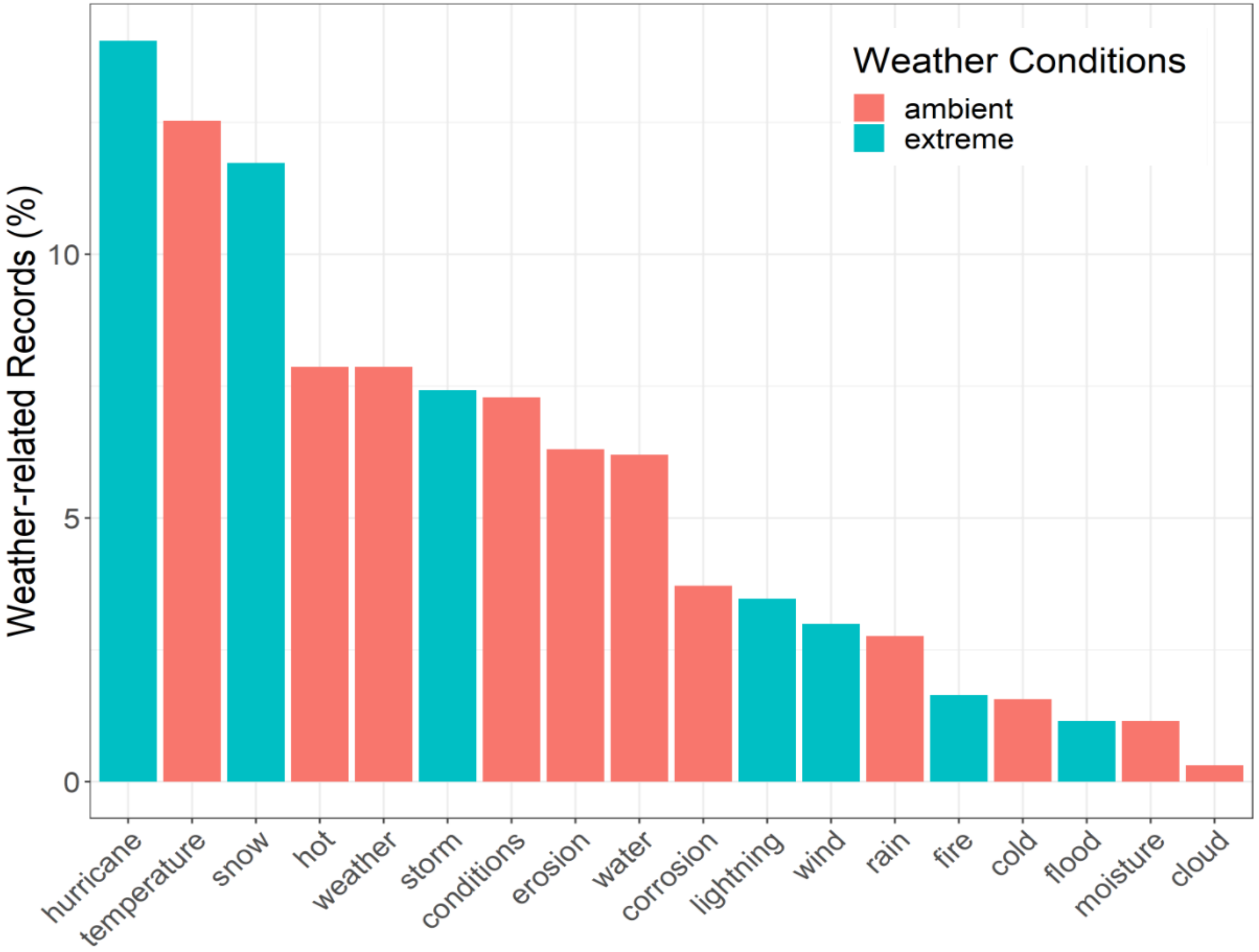
O&M ticket data



	O&M Records
Number of Industry partners	6
Number of Sites (Utility-Scale Sites)	837 (547)
Total Capacity of Sites: GWDC (GWAC)	5.1 (3.9)
Record Ranges	Aug 2014 – Feb 2020
Number of Records	54,000

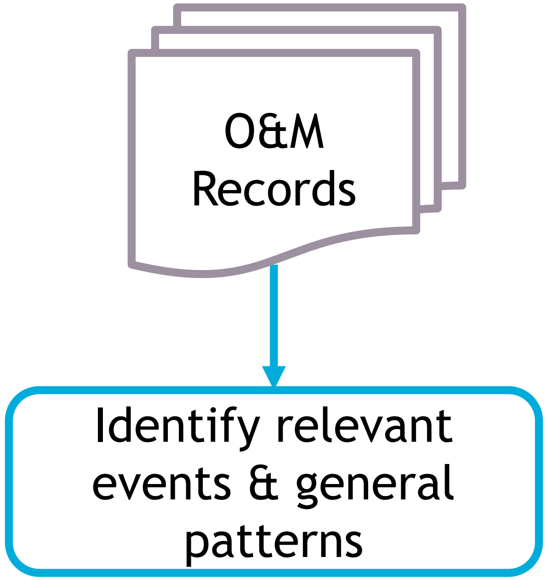
Text analysis of PVROM's O&M records helped identify the most prevalent weather events

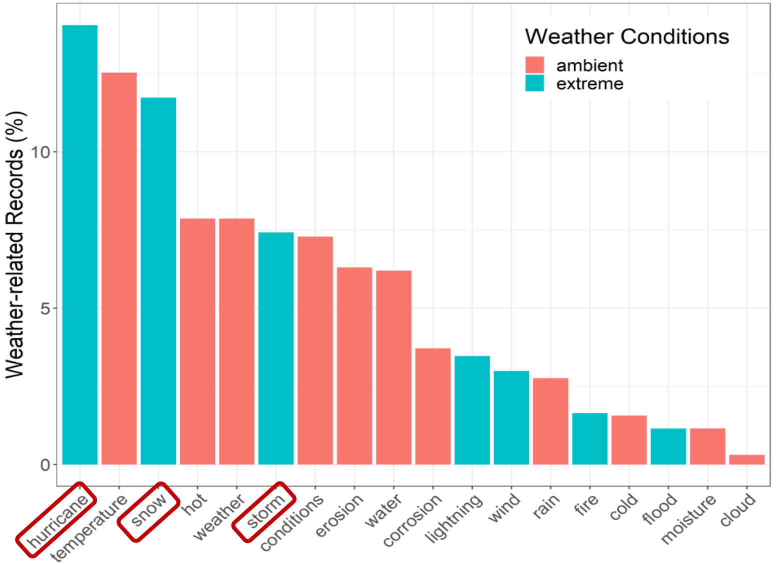




12% of O&M tickets referred to either ambient or extreme weather conditions

Key term searches revealed complexity of capturing weather events



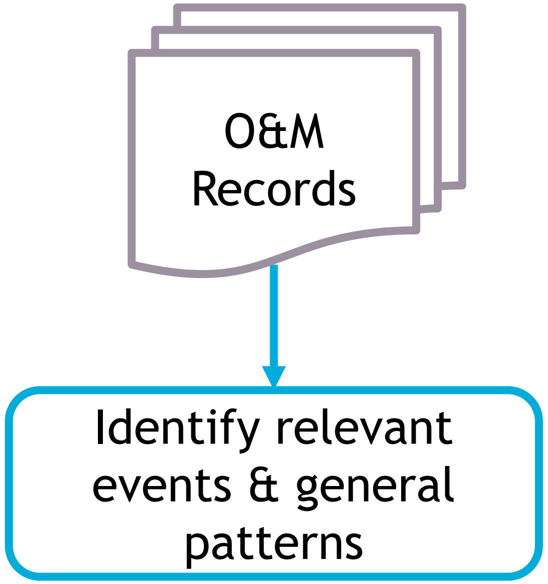


- Characteristics vs. Event
  - Lightning and high winds can occur during storms or hurricanes
  - Distinction between "storm" and "snow" is typically rooted in the type of precipitation observed
- Colloquial vs. meteorological language
  - "Superstorm Sandy" vs. "Hurricane Sandy"
  - Group tickets into "parent" categories
  - Reconcile information using NOAA Storm Events database and state weather warnings

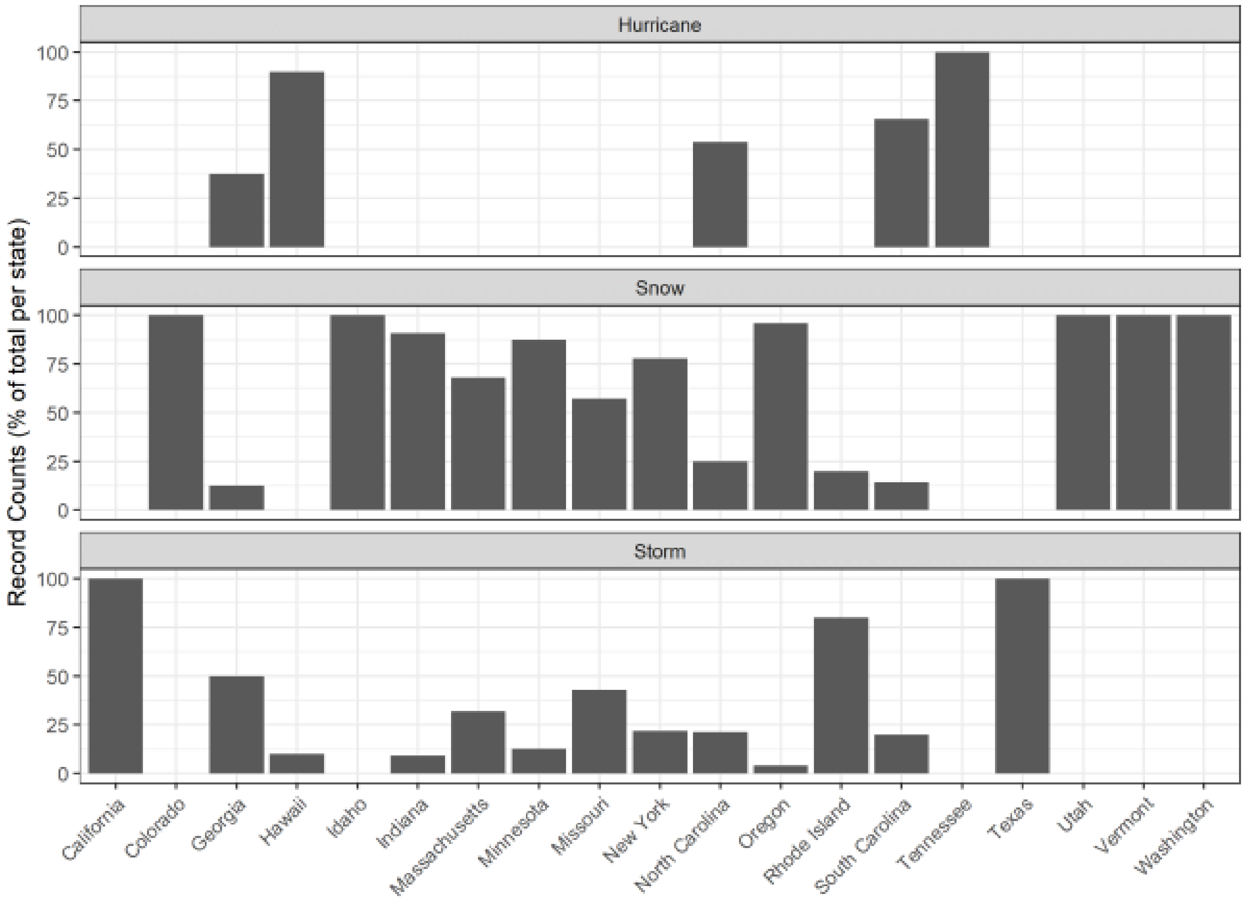
Parent category	Terms	Percentage of event category
Hurricane	Hurricane + Storm	55%
Hurricane	Hurricane + Storm + Flood	4%
Hurricane	Hurricane + Wind	3%
Hurricane	Hurricane + Flood	0.7%
Hurricane	Hurricane + Storm + Lightning	0.4%
Storm	Storm + Lightning	21%
Storm	Storm + Flood	2%
Storm	Storm + Wind	5%
Snow	Snow + Storm	9%

NOAA Storm Events Database

Regional concentrations in extreme weather event discussions

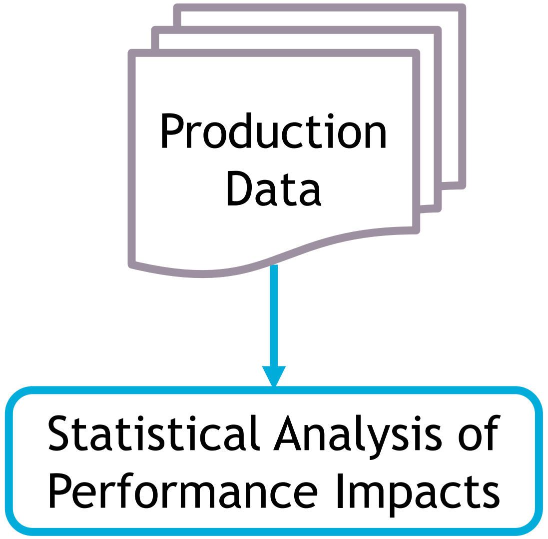


- Hurricane-related tickets were concentrated in eastern U.S. and Hawaii
  - Preparation (10%)
  - Post-event inspections (61%)
  - Post-event damages (29%)
- Most sites observed multiple issues, with module damages and plant trips dominating records



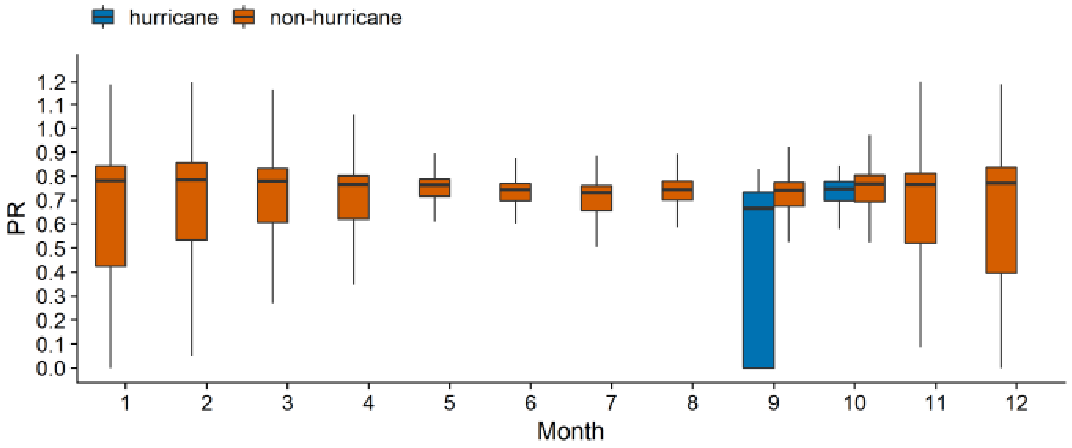
- Snow and storm impacts documented in almost all states analyzed
  - Snow events mostly related to underperformance and some racking damages
  - Storm events dominated by tripping of devices

Production impacts are variable across months and event types

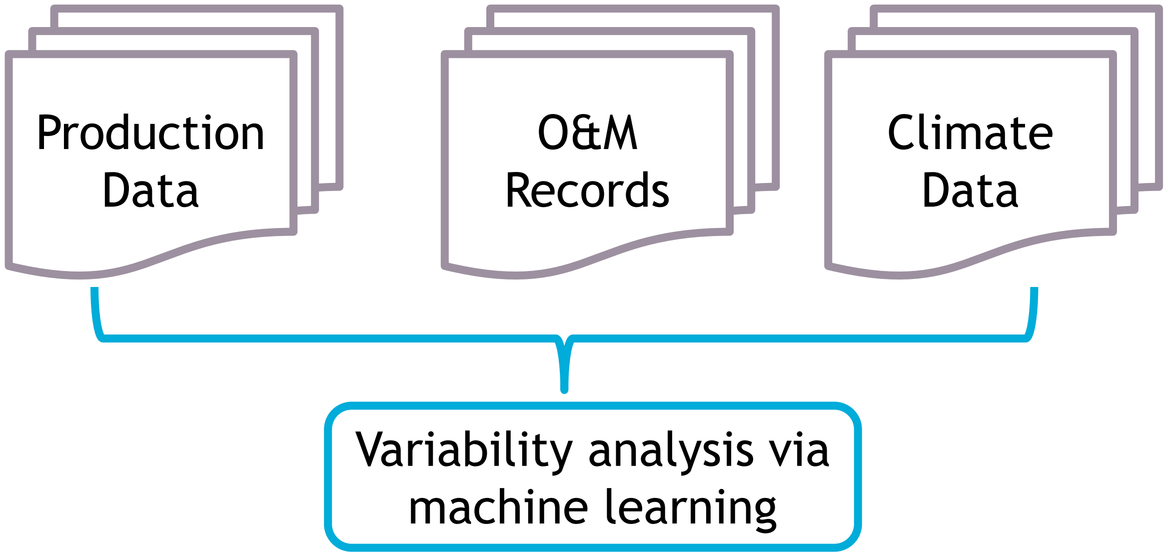


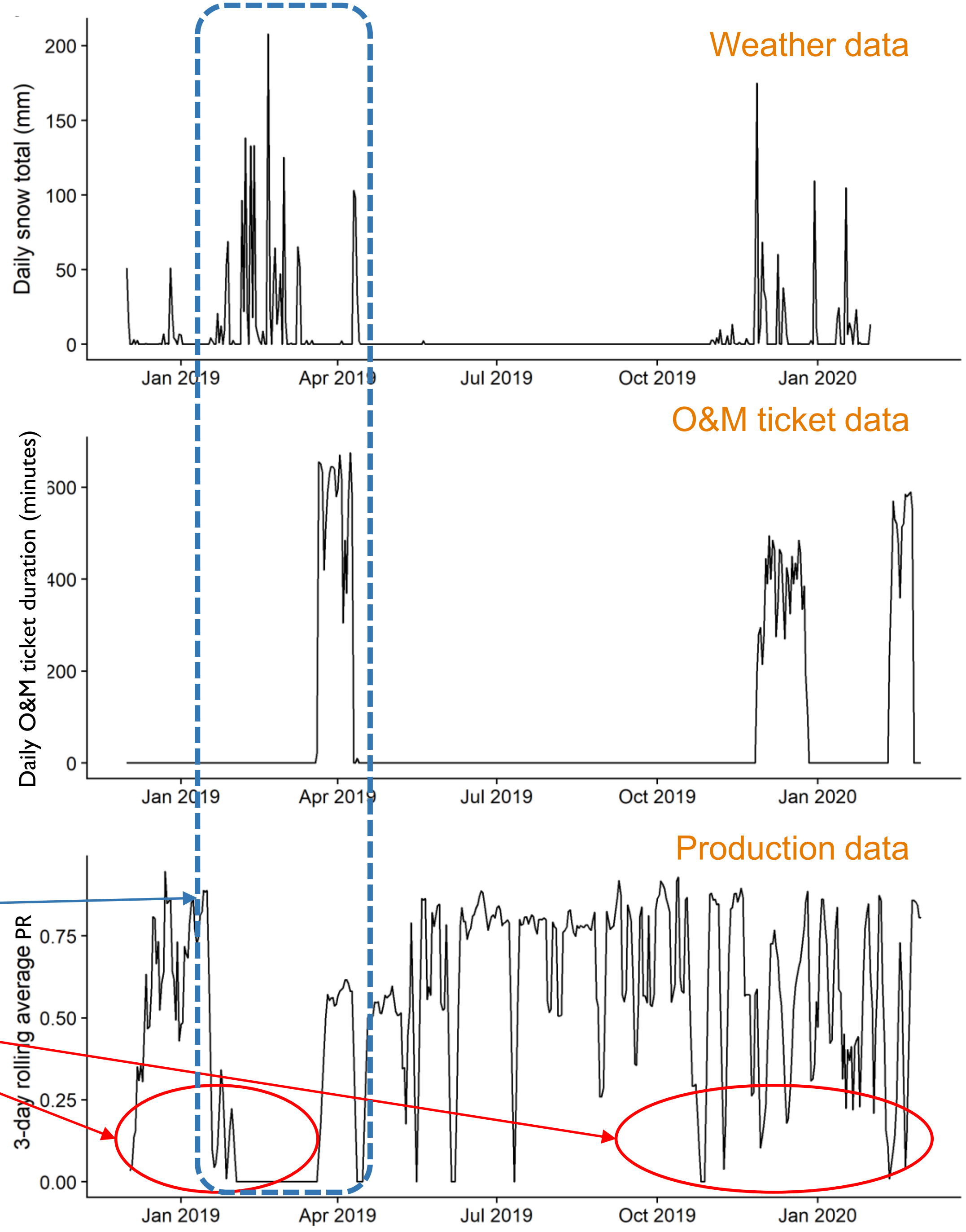
- Performance reductions greatest for snow than hurricanes and storms
- Significant variance in impacts observed, with marginal increases during some months for storms

	Hurricane	Snow	Storm
Event	0.594	0.296	0.627
Non-event	0.669	0.650	0.634

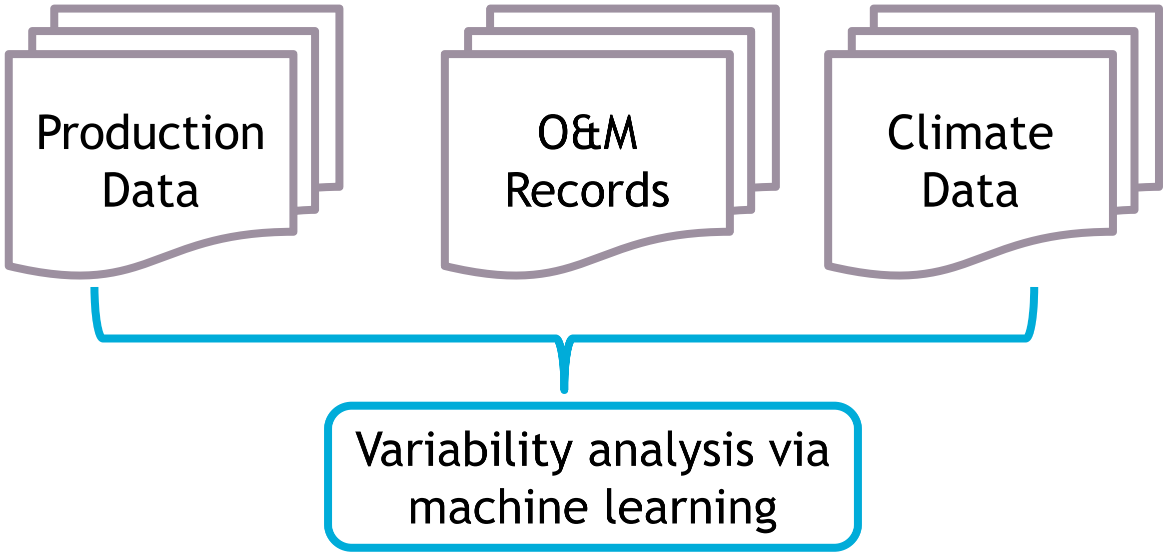


Data fusion of snow, production, and O&M data to understand unique features

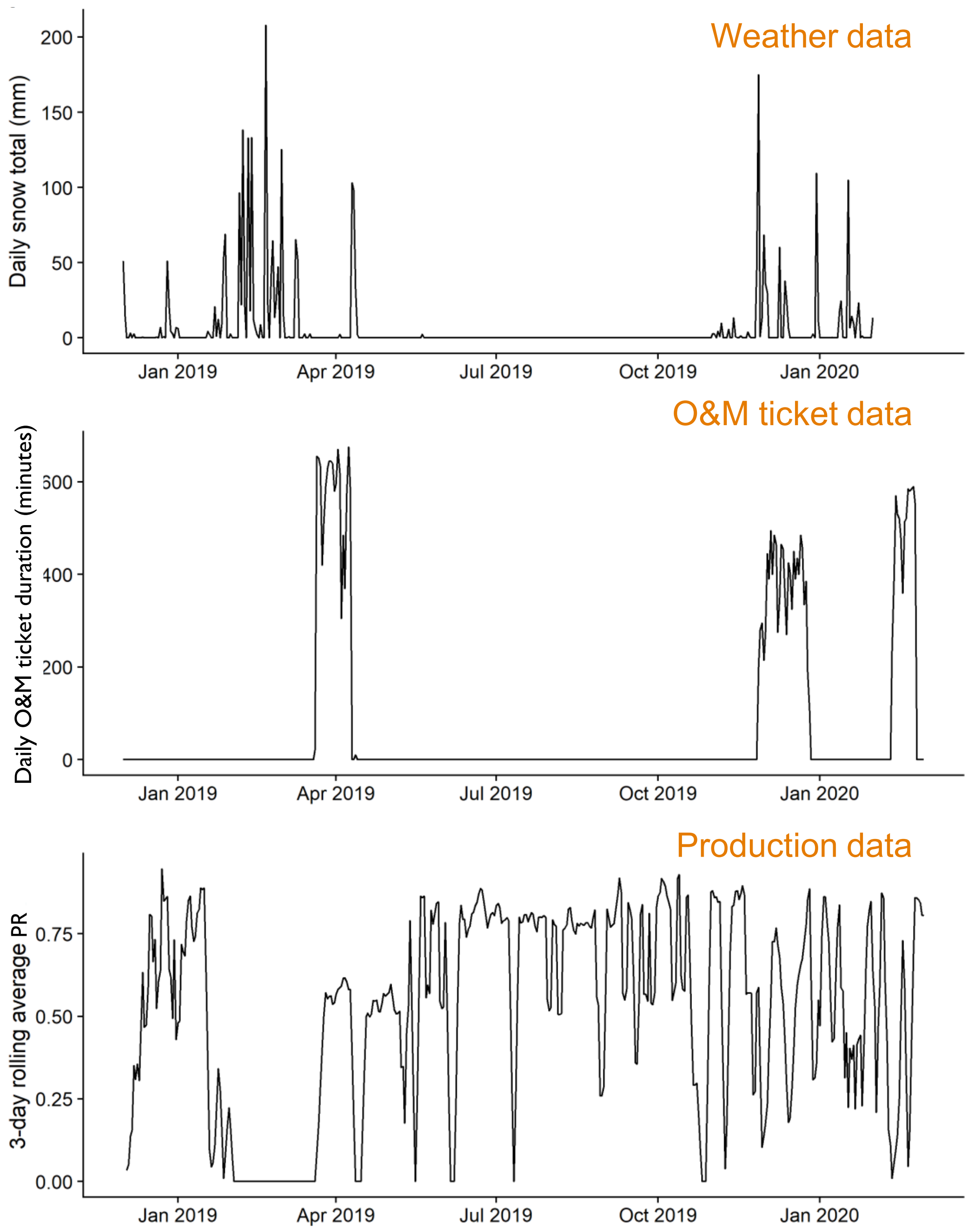




Data fusion of snow, production, and & O&M data to understand unique features

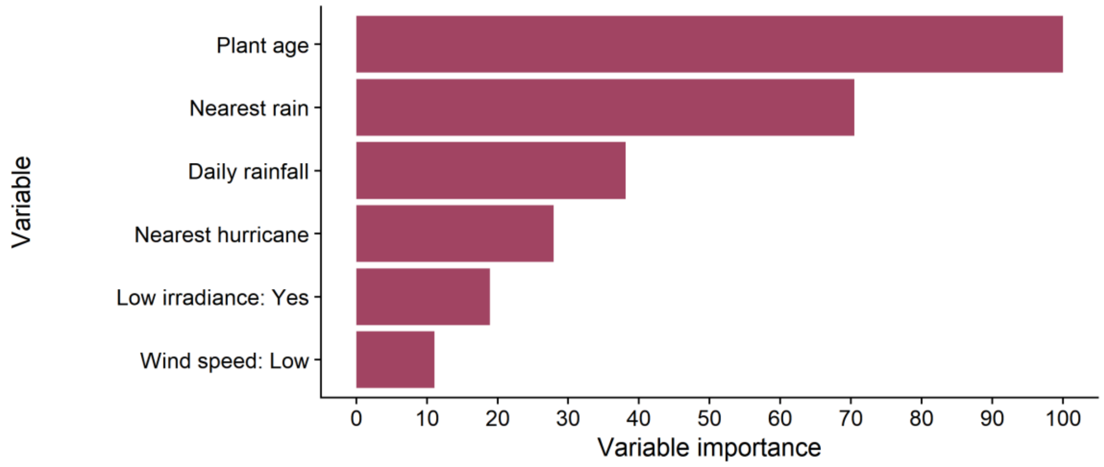


Open-source Python package to support fusion of text and timeseries data (on GitHub!)

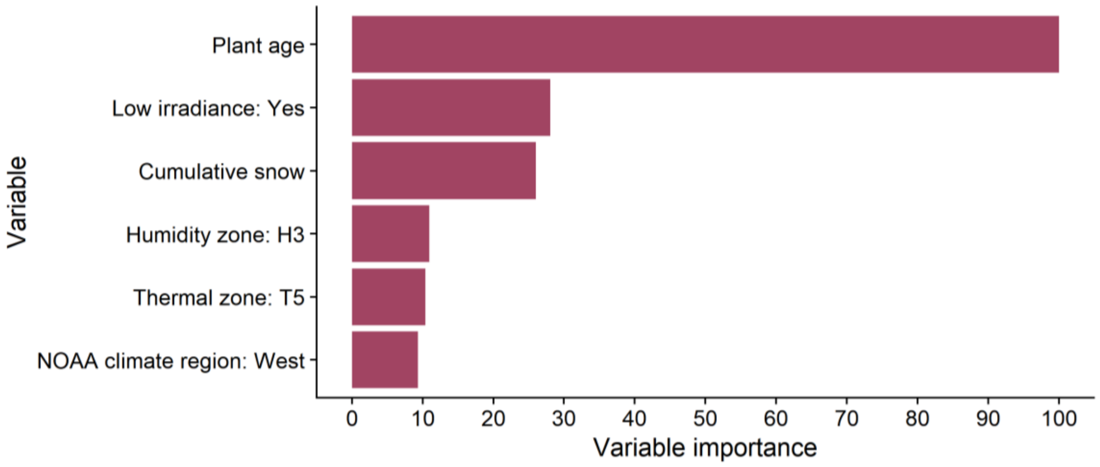


Common drivers of low performance included plant age, irradiance, and weather-specific variables (random forests)

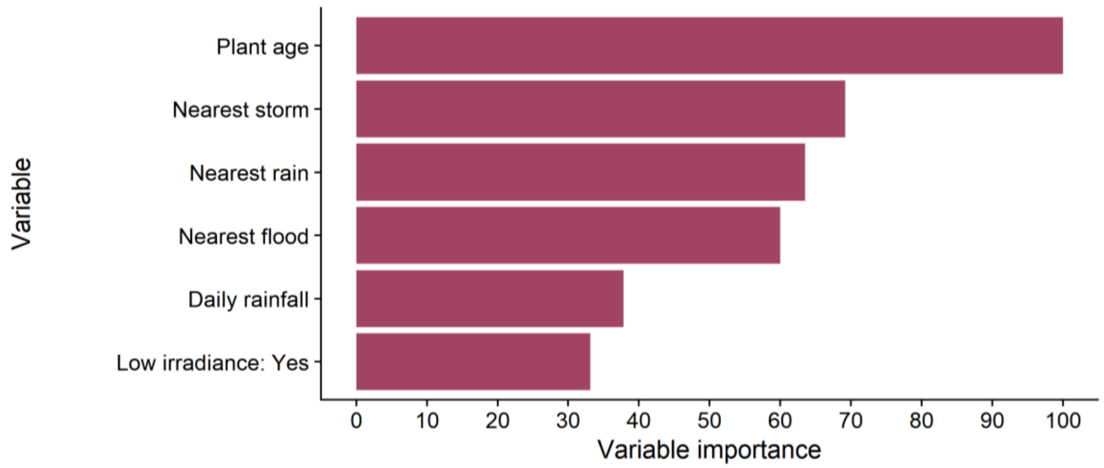
Hurricanes



Snow



Storms



- Plant age dominates across all extreme events for driving low performance
- Weather variables of import varied based on extreme event analyzed
- Details about specific assets and duration of tickets indicate O&M practices and priorities
- Some findings obvious (e.g., low irradiance) while others counter-intuitive (e.g., low wind speeds during hurricanes)

Plant age and O&M influences varied depending on the weather event (LIME)

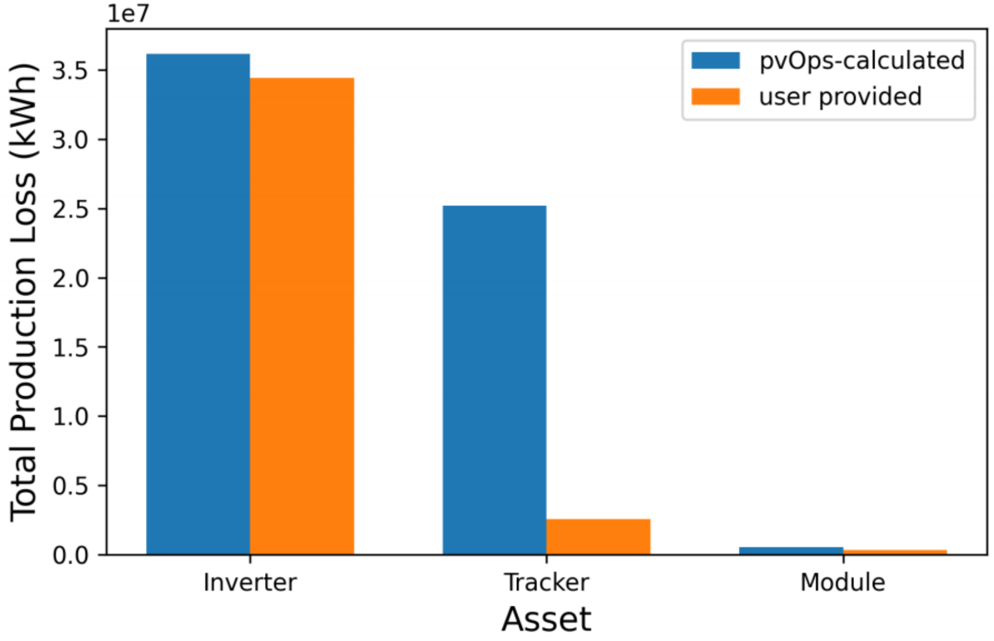
	Hurricanes	Snow	Storm
Plant Age	19-34 months	> 57 months	> 55 months
Geographical Region	Southeast Upper Midwest	Northeast Upper Midwest Northwest Ohio Valley Southeast Southwest	Upper Midwest Southwest
O&M activities	Ticket duration ~ 0 Unknown impacts	None mentioned	Inverter- and facility-level impacts dominate Partial duration of tickets

- Most plants conduct preventative maintenance for hurricanes (including shutting some down; driven by safety concerns)
- Snow tickets didn't emerge in LIME, but were more frequent in May → "seasonal surprises"
- Ground faults/nuisance alarms dominating storm-related impacts
- Medium-sized plants had notable impacts, likely reflecting grid connections via lower voltage distribution circuits, which would make them more susceptible to utility-related outages than larger sites that might be tied into higher-voltage transmission circuits

In summary, integrated assessment of O&M, production, and climate data shows differentiated responses to weather events

- Snow events have largest performance reduction
- Weather + plant features interact to drive low performance
- O&M activities provide insights into local nuances

- Methodological advancements (pvOps: production loss quantifications; baseline energy models)
- Expansion of analysis to other extreme weather events (wildfires) and PV + Storage considerations

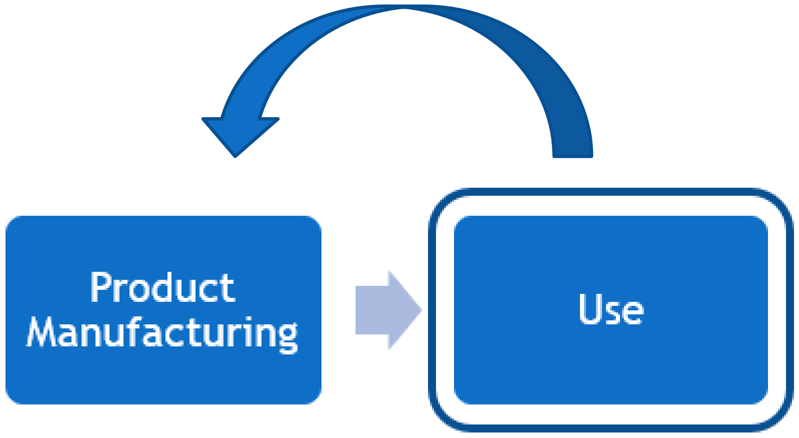


Ongoing Areas of Research

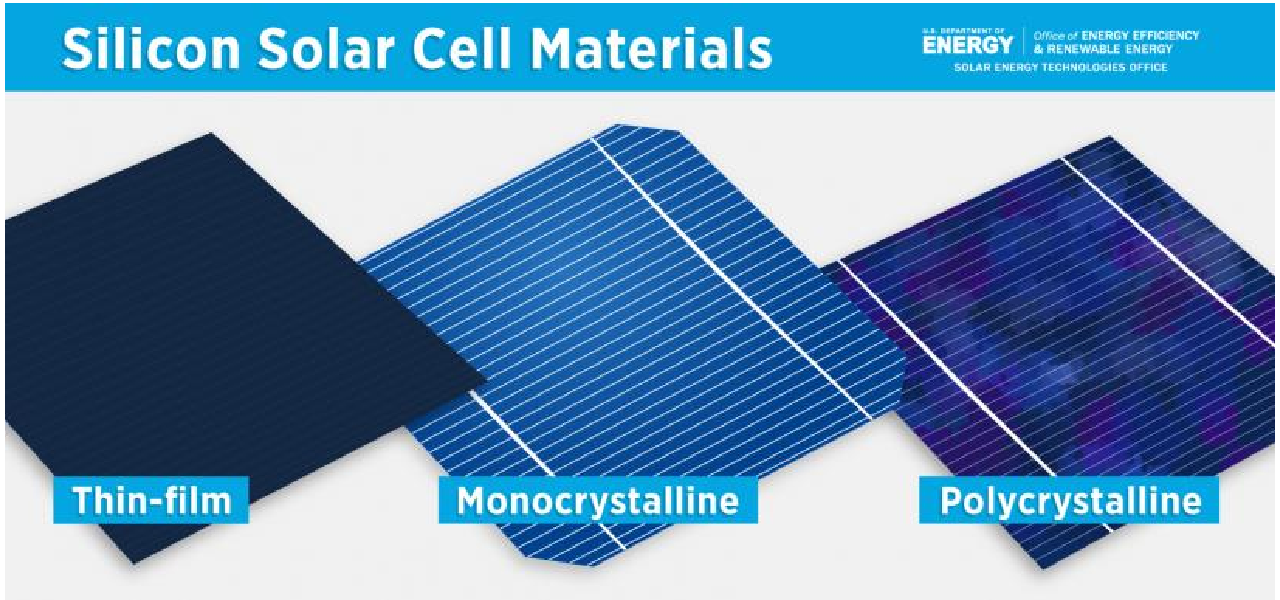
Completing the Feedback Loop: Linking Data, Operations and Maintenance, Manufacturers, and Insurance Markets

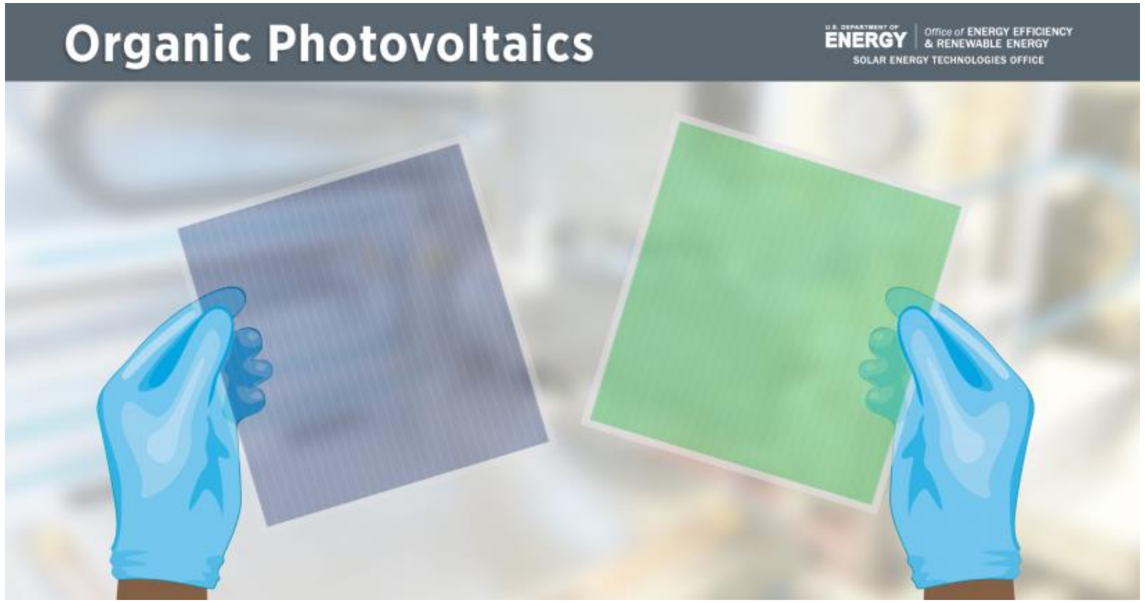
- Recognizes that component manufacturers and plant operators in the PV industry are often motivated financially to focus on initial capital costs, rather than the levelized cost of electricity over the plant's service life.

- Focus on improving solar manufacturing and financing by
  - analyzing data from operations and maintenance logs,
  - identifying top failure modes and
  - supporting solution development and implementation
    - prioritizing hardware solutions to solve them
    - offering insurance discounts for asset owners and manufacturers to promote solution adoptions



Costs Drive Innovation (e.g., PV Cells)





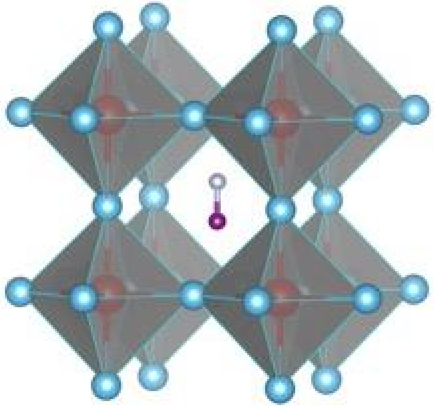
Largest perovskite PV module (China, 2019)

Perovskite-based PV Technologies

What are Perovskites?

- Structure, Composition
- Can be made into solar cells!

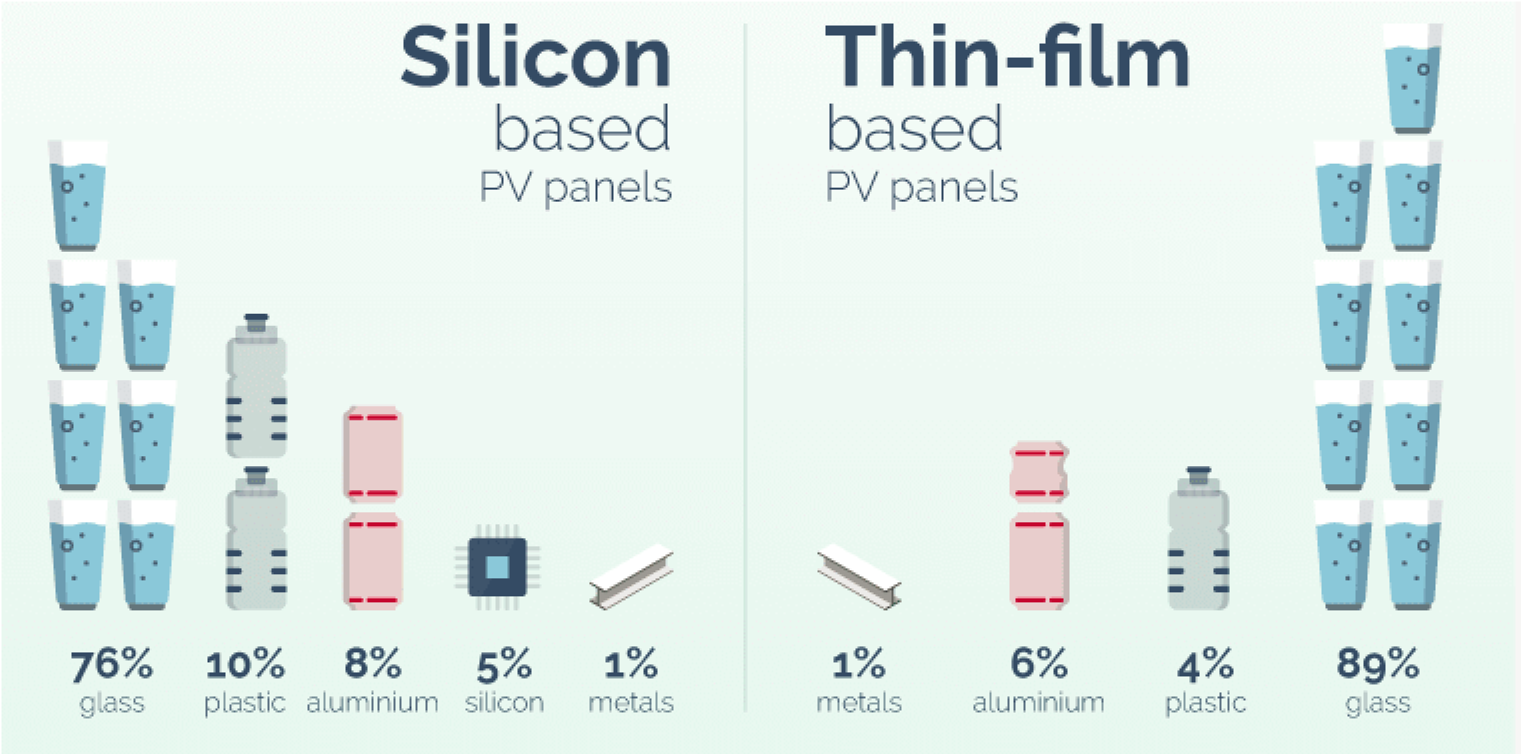
ABX_3



A= Pb, Sn;
X=halides (Cl, Br, I)
B= Organics or metal (Cs)

Source: https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics

End of Life…



Source: GreenMatch.com

Recycling PV panels: Why can't we hit 100%?

In February, non-profit EU solar panel recycling body PV Cycle announced it had collected 5,000 tons of modules in France, of which 94.7% could be recycled. A reader asked us about the remaining 5.3% and here, PV Cycle's communications manager, **Bertrand Lempkowicz**, responds.

AUGUST 26, 2020 CATHERINE ROLLET AND BECKY BEETZ

Solar panel recycling: Turning ticking time bombs into opportunities

With the average lifespan of a solar panel at roughly 20 years, installations from the early 2000s are set to reach end-of-life. Will they end up in landfill or be recycled? The cost of recycling is higher than landfill, and the value of recovered materials is smaller than the original, so there's limited interest in recycling. But given the presence of heavy metals, if waste is managed poorly, we're on track for another recycling crisis.

MAY 27, 2020 MAHDOKHT SHAIBANI, PHD

Agro-PV: A Balancing Act

“The development of fungus on the fruit due to a too wet climate, for example, is a problem that is increasingly frequent. On the hottest day last year, it was 10 degrees cooler under the solar panels; on the wettest day, the plants remained dry. It’s a solution that I really believe in.”

- Rini Kusters, Fruit Farm Owner

Source: PV-Tech

Aqua-PV

Industrial water ponds

Quarry/mine lakes

Irrigation reservoirs

Retention ponds

Desalinization reservoirs

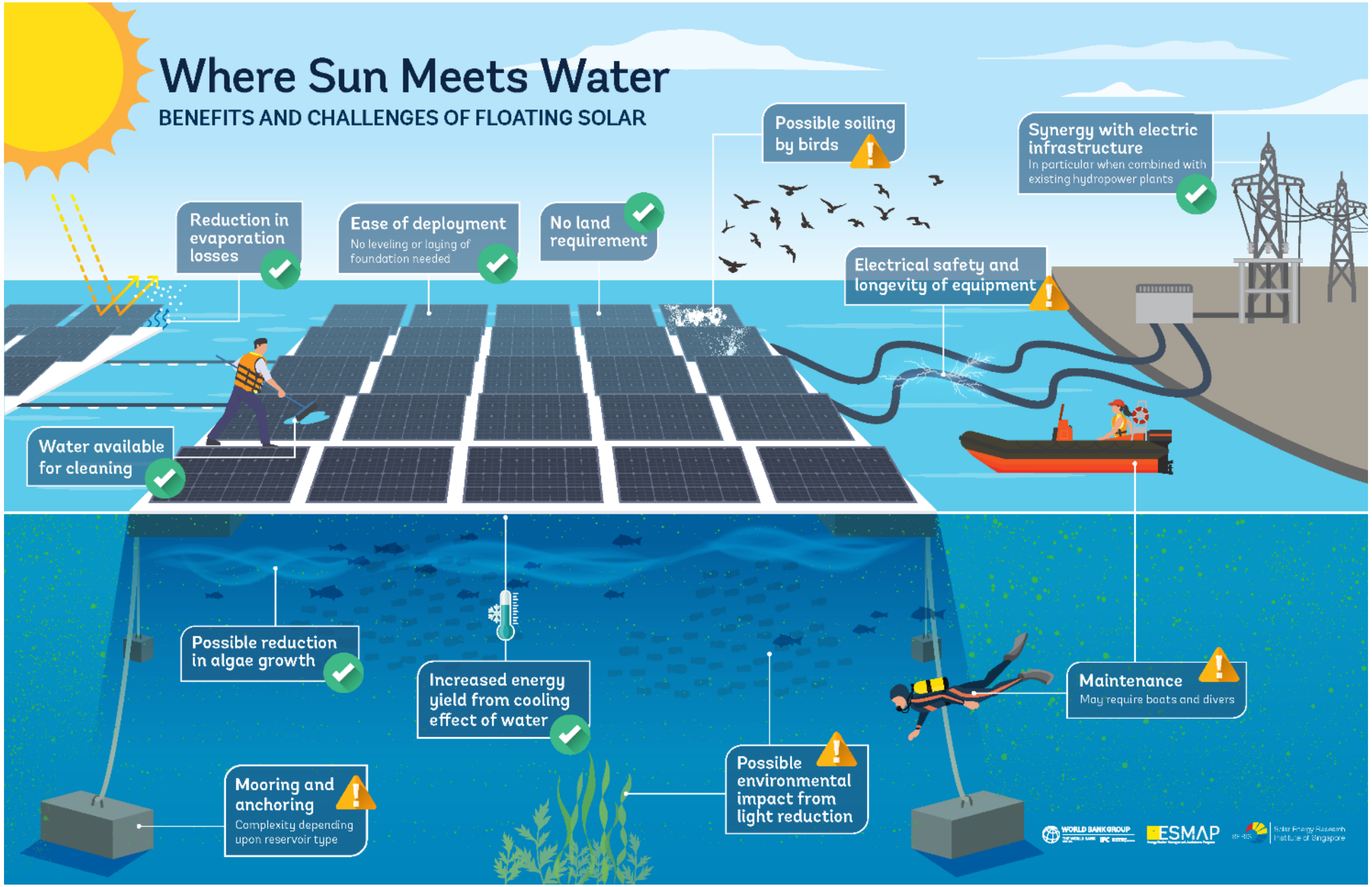
Water treatment sites

Drinking water surfaces

Dams/Canals

Aquaculture Farms

…

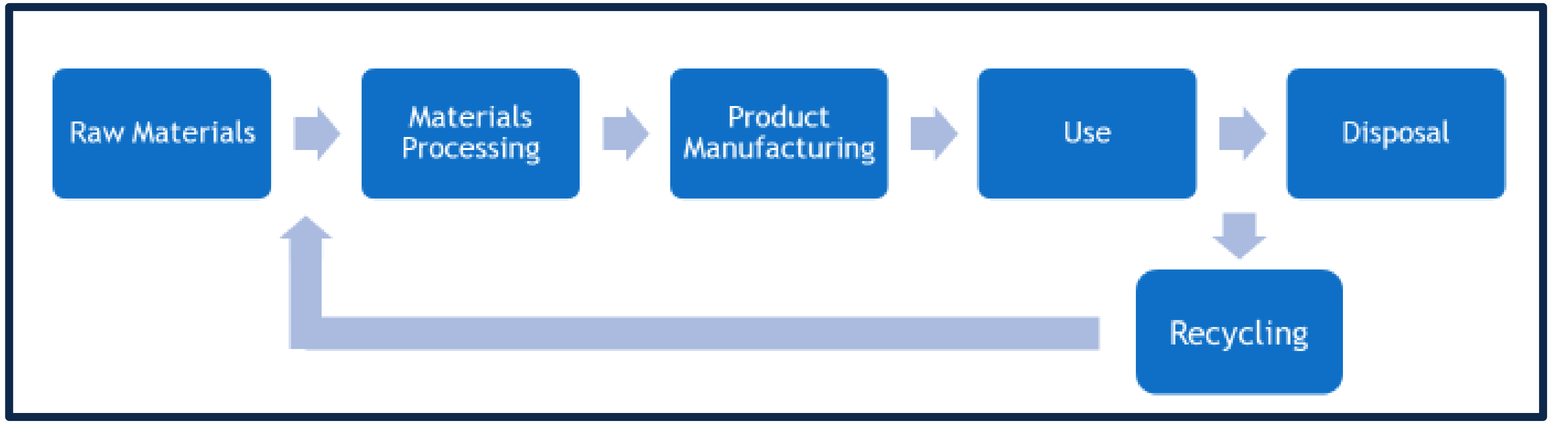


Source: ZPENERGY

What does justice mean in the context of sustainable energy?

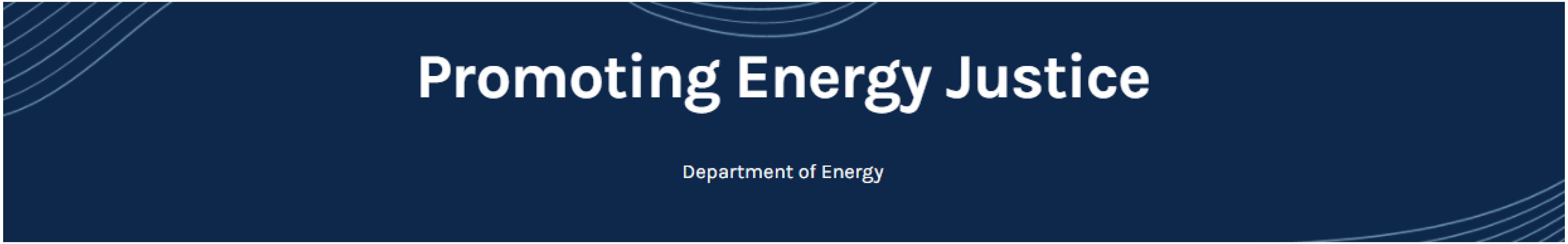
Write down examples of justice being done well or poorly.

Community Impacts



Oversights can occur at all aspects of the life cycle

Conversations to limit negative impact are occurring across all energy programs



Solar Career Map

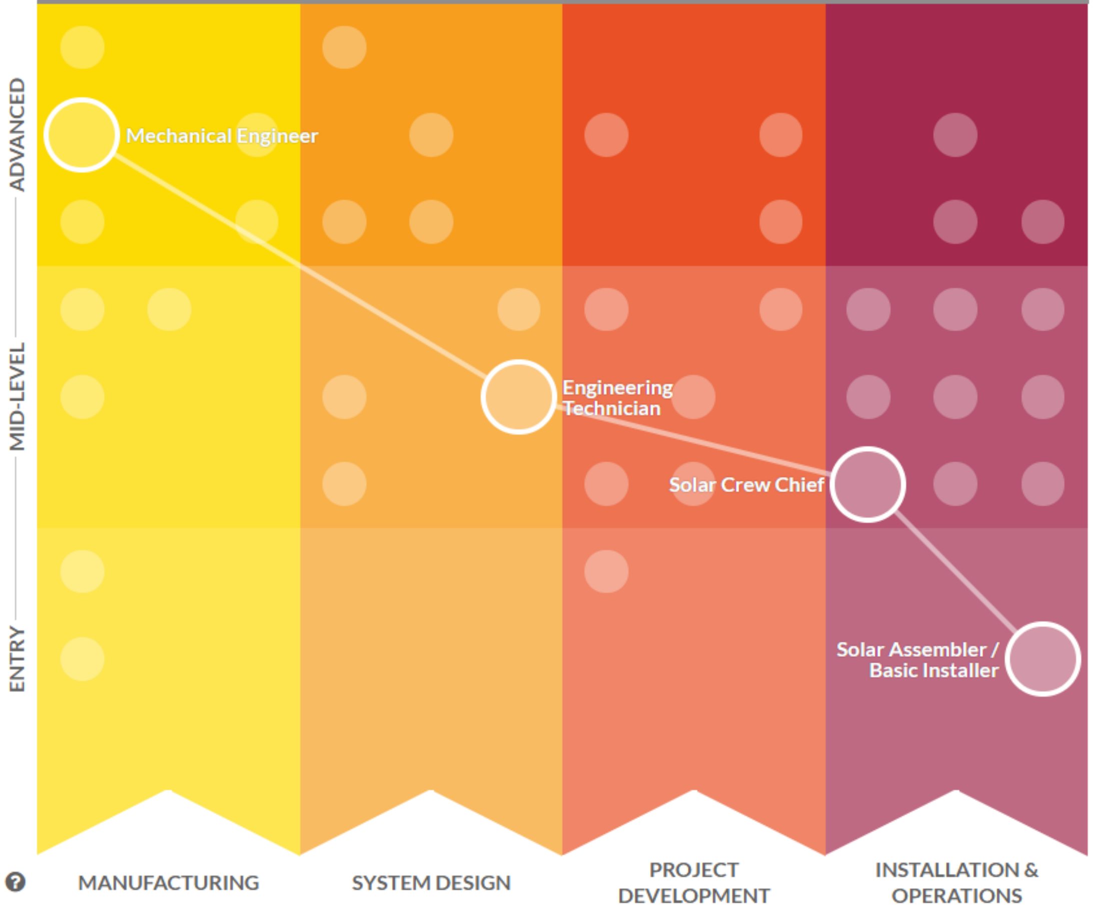
JOBS — Where's my job?

- MANUFACTURING +
- SYSTEM DESIGN +
- PROJECT DEVELOPMENT +
- INSTALLATION & OPERATIONS +

ADVANCEMENT ROUTES | MULTI-SECTOR ROUTES | VETERAN JOBS

There are many ways to pursue evolving interests or new opportunities in solar. These wide-ranging sample career routes are intended to suggest affinity and possibility; each would entail significant intermediate sequences of work and learning. Click a path on the right to explore other solar itineraries.

- Development ▶ Operations
- Operations ▶ Manufacturing
- Development ▶ Design
- Operations ▶ Development



MANUFACTURING

- Materials Scientist
- Environmental Engineer
- Mechanical Engineer
- Electrical Engineer
- Industrial Engineer
- Process Control Technician
- Quality Assurance Specialist
- Instrumentation and Electronics Technician
- Advanced Manufacturing Technician
- Computer Numerical Control (CNC) Operator

PROJECT DEVELOPMENT

- Lawyer with Solar Expertise
- Solar Project Developer
- Solar Utility Procurement Specialist
- Electrical Inspector with Solar Expertise
- Code Official with Solar Expertise
- Building Inspector with Solar Expertise
- Solar Marketing Specialist
- Solar Sales Representative
- Solar Site Assessor

INSTALLATION & OPERATIONS

- Solar Instructor
- Solar Installation Contractor
- Solar Fleet Manager
- Electrician with Solar Expertise
- Solar PV Technician (commercial/utility)
- Solar Project Manager
- Solar Service Technician (residential)
- Solar PV Installer
- HVAC Technician with Solar Expertise
- Plumber with Solar Expertise
- Roofer with Solar Expertise
- Solar Crew Chief
- Solar Assembler / Basic Installer

SYSTEM DESIGN

- Software Engineer
- Solar Energy Systems Designer
- Power Systems Engineer
- Structural Engineer
- Utility Interconnection Engineer
- Residential PV System Designer
- Engineering Technician
- IT Specialist

http://irecsolarcareermap.org/

Photovoltaics Department

- Increase the reliability and resilience of PV systems:
  - Balance of Systems and Soft Costs
  - Materials & Fabrication
  - Field Experimentation
  - PV Performance and Modeling
  - Regional Test Centers
  - Open source software development

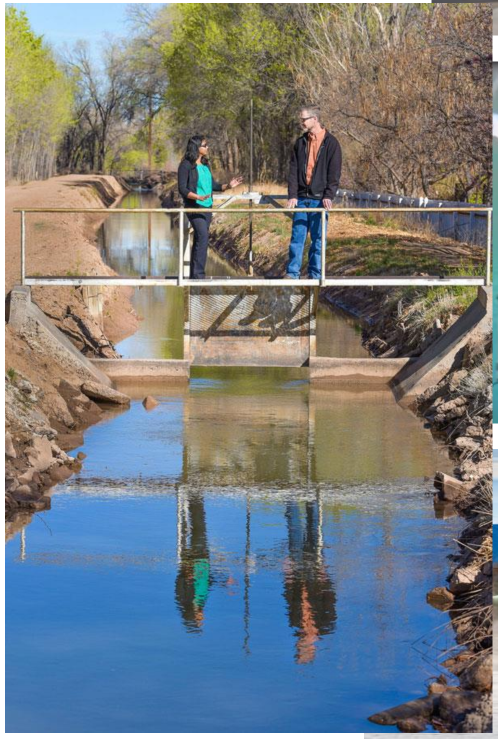
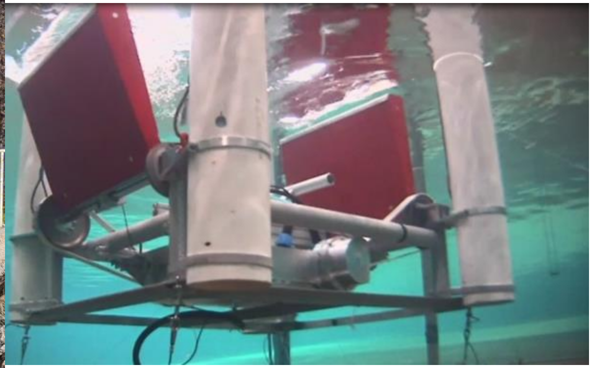
Learn more at http://pv.sandia.gov

Energy and Water Systems Integration

- Increase the security and resilience of the nation's energy and water systems.

  - Energy-food-water modeling and analysis
  - Data analytics for renewable energy
  - Climate impact to energy systems
  - Coupled human behavior and engineered systems
  - Grid modernization
  - Water security
  - Infrastructure resilience
  - Building energy efficiency
  - Open source software development

Learn more at http://water.sandia.gov


Sandia National Laboratories

- Research at Sandia covers 5 major program portfolios
- Over 14,000 employees with offices in NM and CA
- Energy and Geosciences Center
  - Utilize and balance energy from all sources, improve the cradle-to-grave management of each energy source, and improve environmental stewardship.
- Renewable Energy Technologies Group
  - Reduces the cost, improves the resilience and reliability, and decreases the regulatory burden of wind, solar, and marine energy systems and investigates the intersection of water-energy-agriculture.

Wind Energy | Water Power | Concentrating Solar | PV Materials & Technologies | Energy & Water Sys Integration

Student Opportunities

High school through post-doc positions

Summer and year-round schedules

Multi-disciplinary teams
- Engineering, math, operations research, data science, economics, sociology, computer science

Basic and applied research

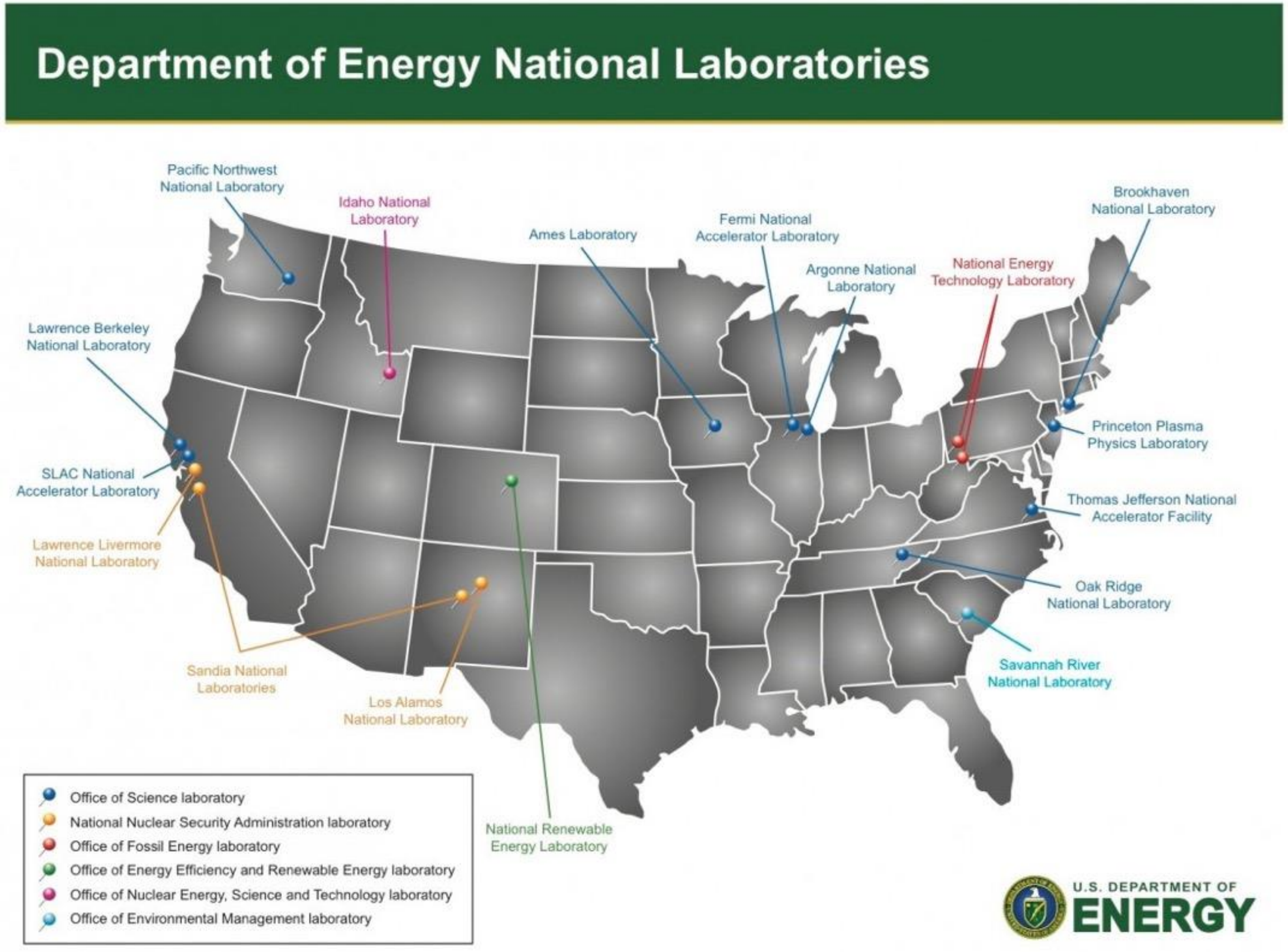
Campus recruiting

We recruit at the some of the best colleges and universities, looking for talented individuals to join our diverse workforce.

https://www.sandia.gov/careers/students_postdocs/index.html

US National Laboratories – Career opportunities

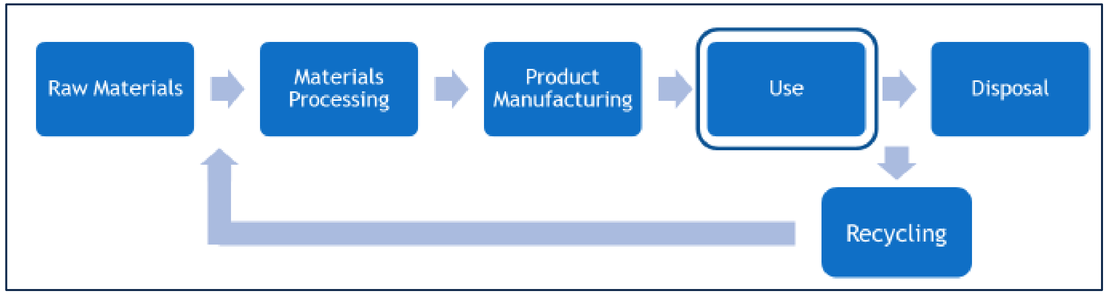
- FFRDC: Federally funded R&D Centers
  - Public-private partnerships to conduct R&D for the US government
  - Special funding opportunities
  - Cannot compete with private industry
- Expensive and high-risk R&D projects
- Large scale demonstrations

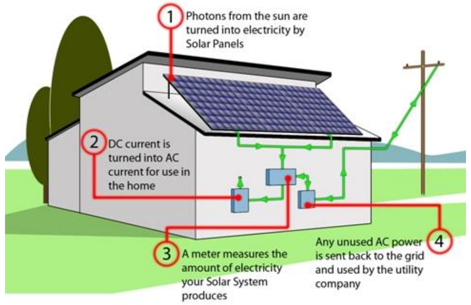


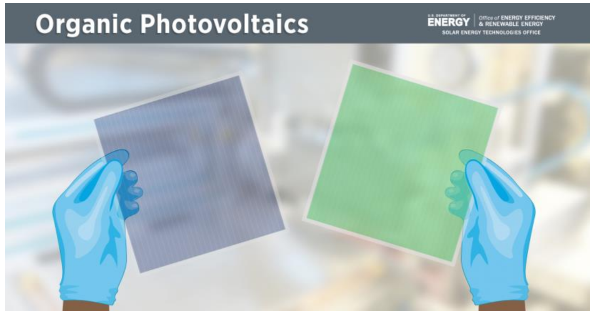
Author your Own Story

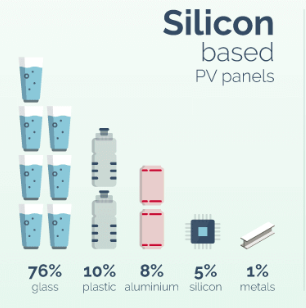
- There is no single "right" way to tackle the problem
  - Energy issues will require civil, environmental, chemical, industrial, systems, … engineers
  - It will also need data scientists, developers, managers, policymakers, economists, humanists, …

➢What role will you play?!









Thank you for your time!

tgunda@sandia.gov