DuraMAT
Durable Module Materials Consortium

Follow-Up from the Photovoltaic Reliability Workshop (PVRW): Cost Modeling Capabilities To Evaluate Trends in PV Technologies

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Monday, May 8, 2023
DuraMAT Webinar

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Presentation Overview

1 Results from PVRW: audience polls (Jarett)

2 Demonstration of Detailed Cost Analysis Models (DCAM) for technology evaluations (Mike)

3 Simplified PV-LCOE calculator for reliability & cost tradeoffs in developing solar technologies (Brittany)

4 Questions and discussion (All)

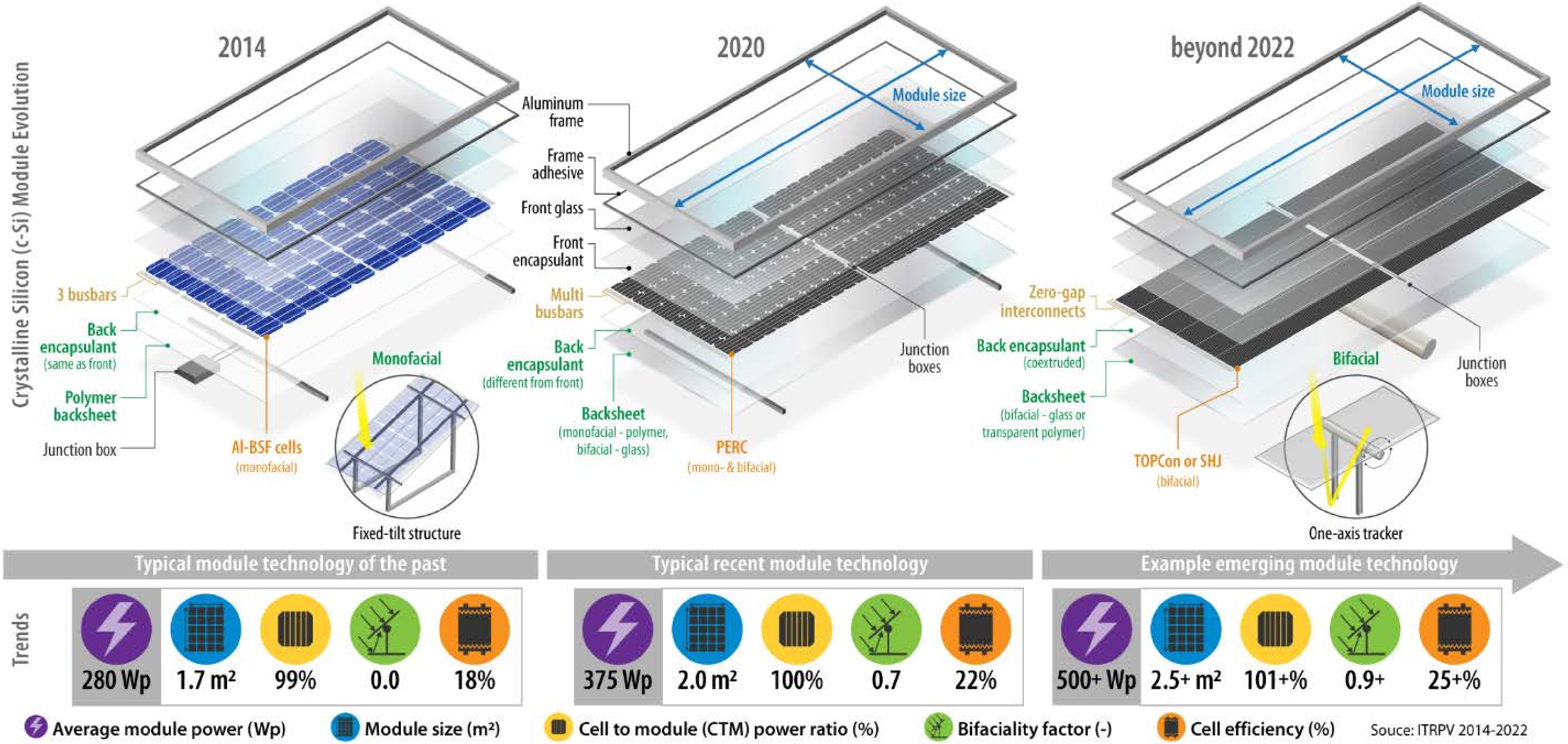
Polling Results

Goals of the DuraMAT Technology Scouting Report

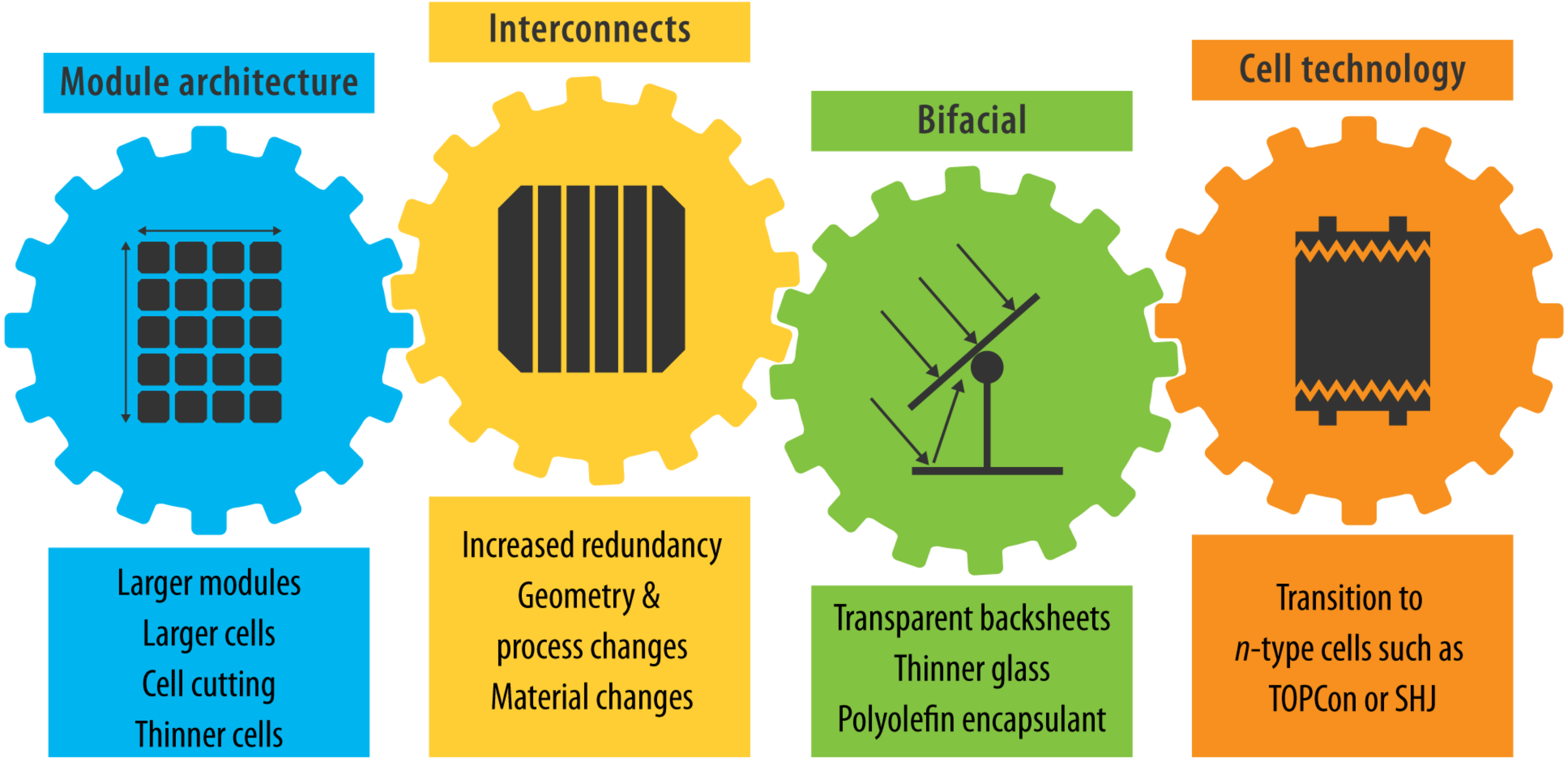
- Track technology changes that could affect PV module reliability
- Assess changes in module reliability risks over time
- Identify the need for new research related to reliability

"PV moves pretty fast. If you don't stop and look around once in a while, you could miss it." *– Inspired by* Ferris Bueller's Day Off

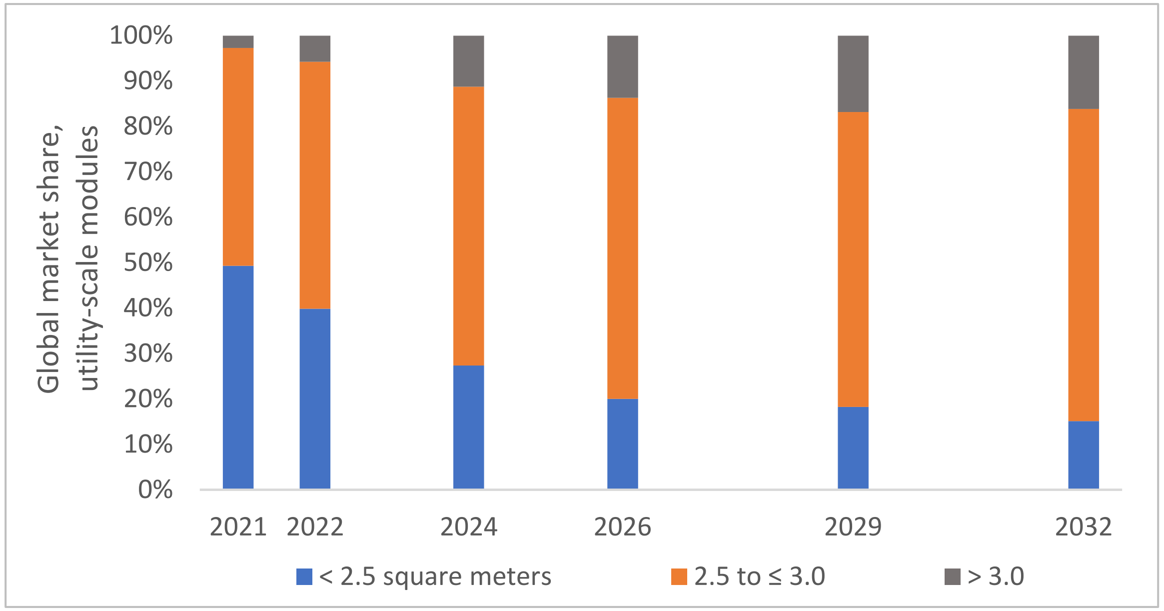
Crystalline-silicon PV module technology changes



Categories of technology change



Example—larger modules



Historical (2021) and projected (2022–2032) ITRPV data on utility-scale module size

Drivers & Benefits

wafer/cell size
- larger cells allow for larger module sizes

increased power output
- larger active area
- improved cell-to-module (CTM) power ratio: $\mathrm{CTM} = \frac{P_{\text{module}}}{P_{\text{cell}} \cdot n_{\text{cell}}}$

Potential Risks

potentially more frequent cell breakage due to
- weather (wind & hail), or shipping, handling, and installation

increased weight
- OSHA handling issues with very large modules; 100-lb modules may be the practical limit
- implications for mounting structure design and cost

increase in electrical current
- electrical BOS (wire size, fusing, bypass diode) must be adapted

new testing equipment necessary to accommodate large modules
- such as dynamic mechanical loading (DML) to assess hail damage and inform insurance coverage

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Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated with Projected Technological Changes

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Number of pages: 34 • Posted: 21 Nov 2022

Jarett Zuboy, Martin Springer, Elizabeth Palmiotti, Joseph Karas, Brittany Smith, Michael Woodhouse and Teresa Barnes

National Renewable Energy Laboratory, National Renewable Energy Laboratory, Sandia National Laboratories, Albuquerque, National Renewable Energy Laboratory, National Renewable Energy Laboratory, National Renewable Energy Laboratory and National Renewable Energy Laboratory

Keywords: Solar, photovoltaic, PV, module, technology, reliability, durability, degradation, interconnection, ...

https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4273054

Audience polling at the 2023 Photovoltaic Reliability Workshop

- What are the biggest challenges to module reliability over the next several years?
- Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?
- What important module technology trends and reliability implications did we miss?

Microsoft PowerPoint stock image

What are the biggest challenges to module reliability over the next several years?

What are the biggest challenges to module reliability over the next several years?

Wordcloud Poll 165 responses 90 participants

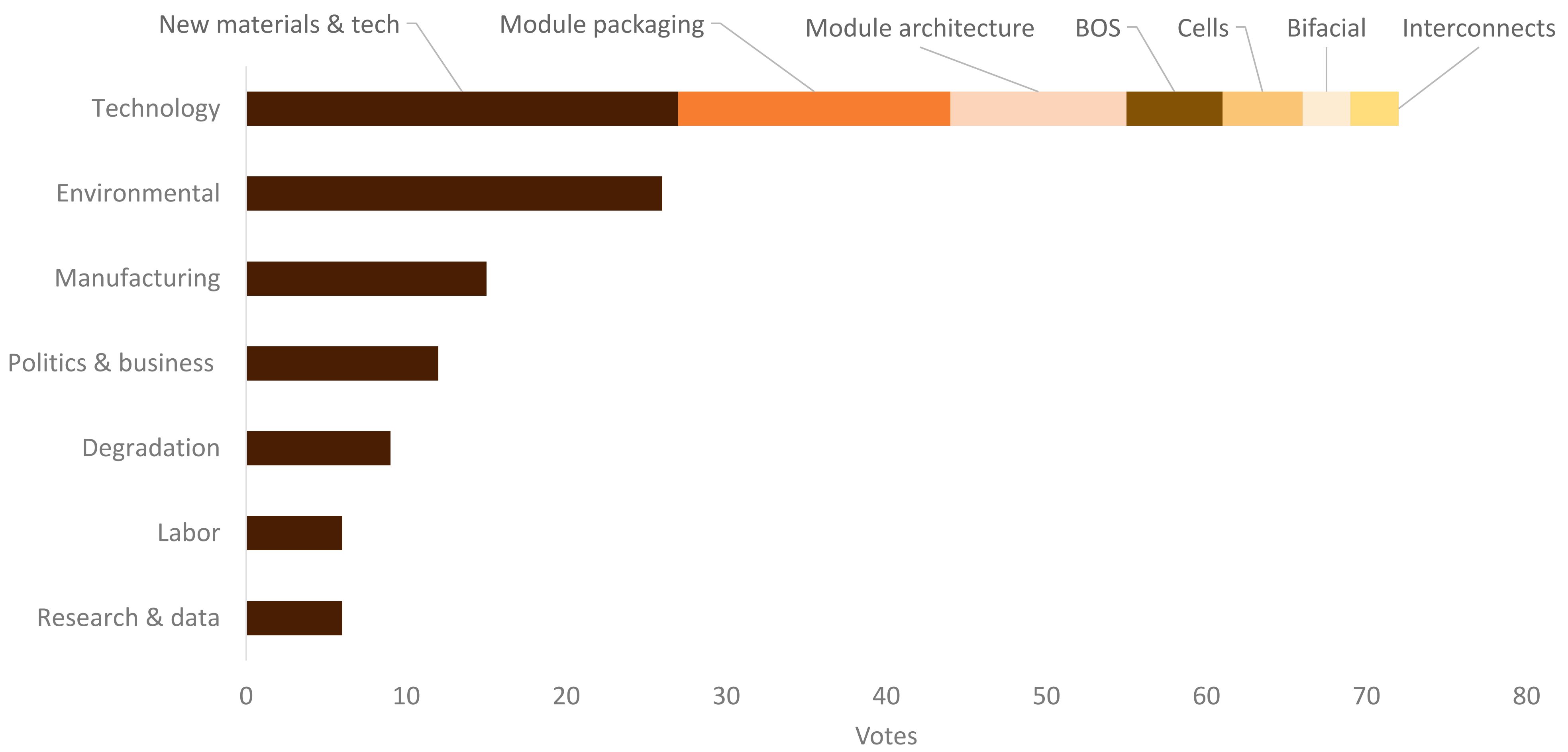
- Derate on Bificial
- extreme weather
- extreme weather events
- module frames
- New materials
- Mfg defects
- Climate change
- Soiling
- handling
- Thin glass
- wind
- Obsolescence
- Hail
- Severe weather
- honesty
- Thinner glass
- Size
- new tech
- big floppy modules
- degradation
- Politics
- Recycling
- Workforce training
- Quality
- perovskite reliability
- large modules
- non glass substrates

What are the biggest challenges to module reliability over the next several years?

Big floppy modules?

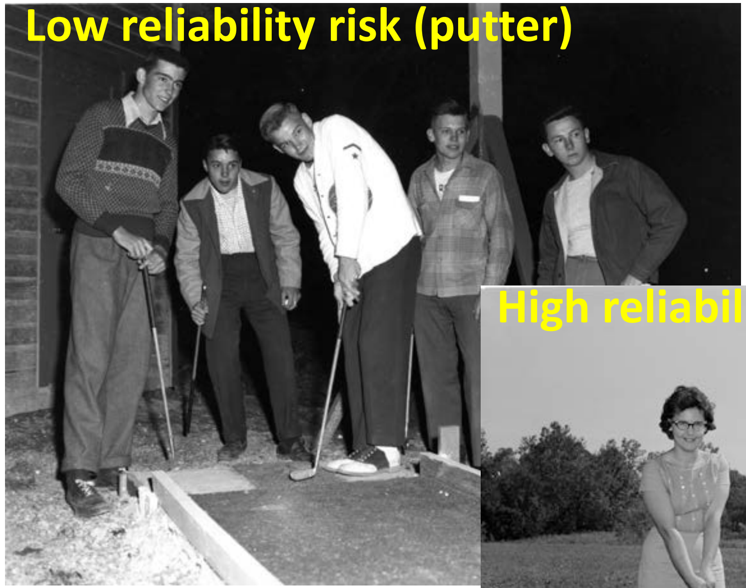
New materials & technology (27)	Environmental (26)	Module packaging (17)	Manufacturing (15)	Politics & business (12)	Module architecture (11)	Degradation (9)
• **New materials & technology (11)** • Obsolescence (6) • Bill of materials (4) • Extending lifetimes (3) • Recycling (3)	• **Extreme weather (10)** • Climate change (6) • Hail (4) • Soiling (3) • Wind (2) • Environmental impacts (1)	• **Glass (incl. thinner & heat-strengthened) (8)** • Encapsulants (4) • Module frames (3) • Backsheets (2)	• **Quality control (8)** • New manufacturers (7)	• Honesty (4) • Politics (4) • Supply chain (2) • Cost pressure (1) • Corporate secrecy (1)	• **Larger modules (10)** • Changes in format (1)	• Cracks (3) • Degradation (3) • Diode failures (1) • Underperformance (1) • UV stability (1)
Balance of system (BOS) (6)	**Labor (6)**	**Research & data (6)**	**Cell technology (5)**	**Bifacial (3)**	**Interconnects (3)**	
• Connectors (2) • High-voltage systems (1) • Integrated applications (1) • Mounting interfaces (1) • Racking (1)	• Handling & installation (4) • Workforce training (2)	• Lack of data (3) • Accelerated testing (1) • Research on thin film (1) • Understanding wear-out (1)	• Perovskites (3) • Non-glass substrates (1) • Tandems (1)	• Degradation of bifacial (2) • Hot spots in bifacial (1)	• Cold solder joints (1) • New interconnects (1) • Open solder (1)	

What are the biggest challenges to module reliability over the next several years?



What are the biggest challenges to module reliability over the next several years?

Honorable mentions: “golf,” “no time machine,” “half-baked modules,” “don't know!”



Photos from U.S. Dept. of Energy (from left): mini golf at Oak Ridge (Flickr Photostream), FEMP 31 1185 (Flickr Photostream), panels with damage (Paul Basore, with permission)

Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?

Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?

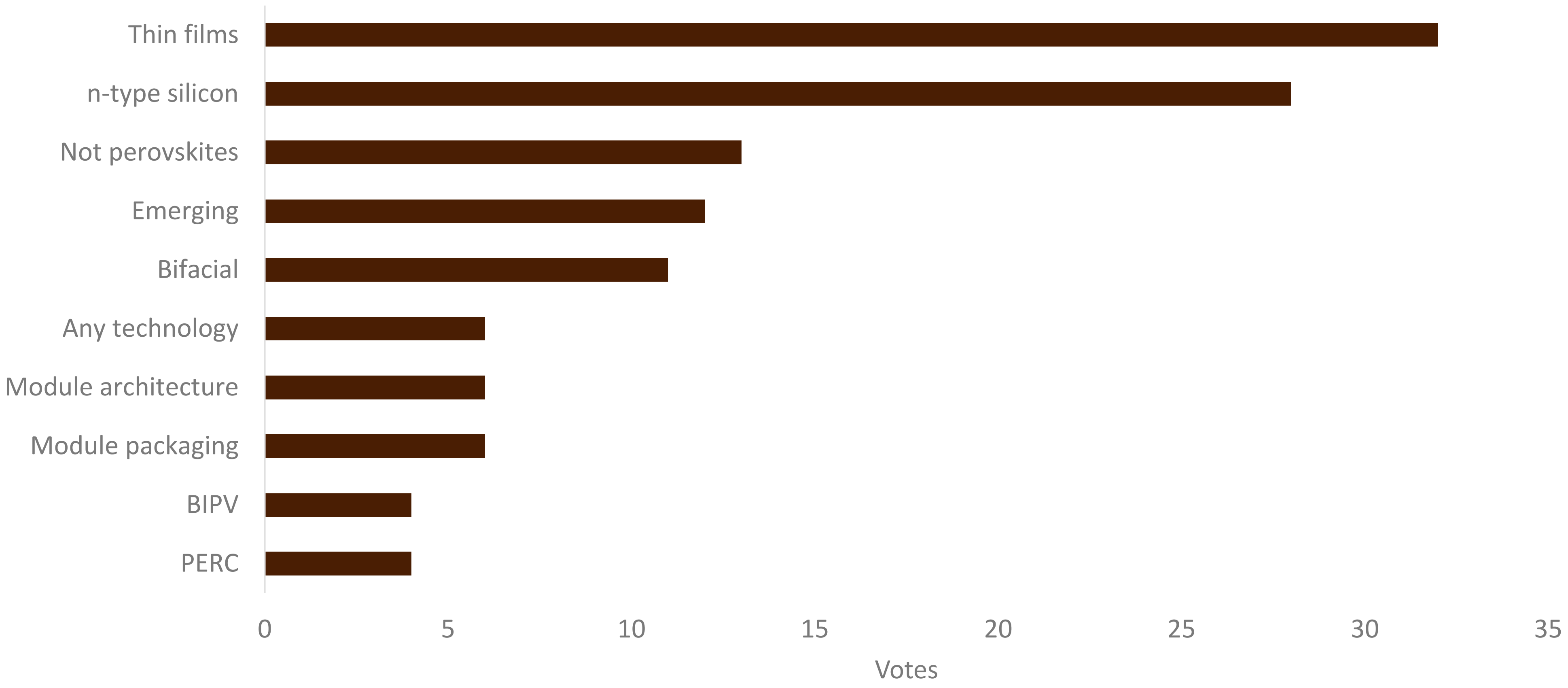
Wordcloud Poll 128 responses 79 participants

Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?

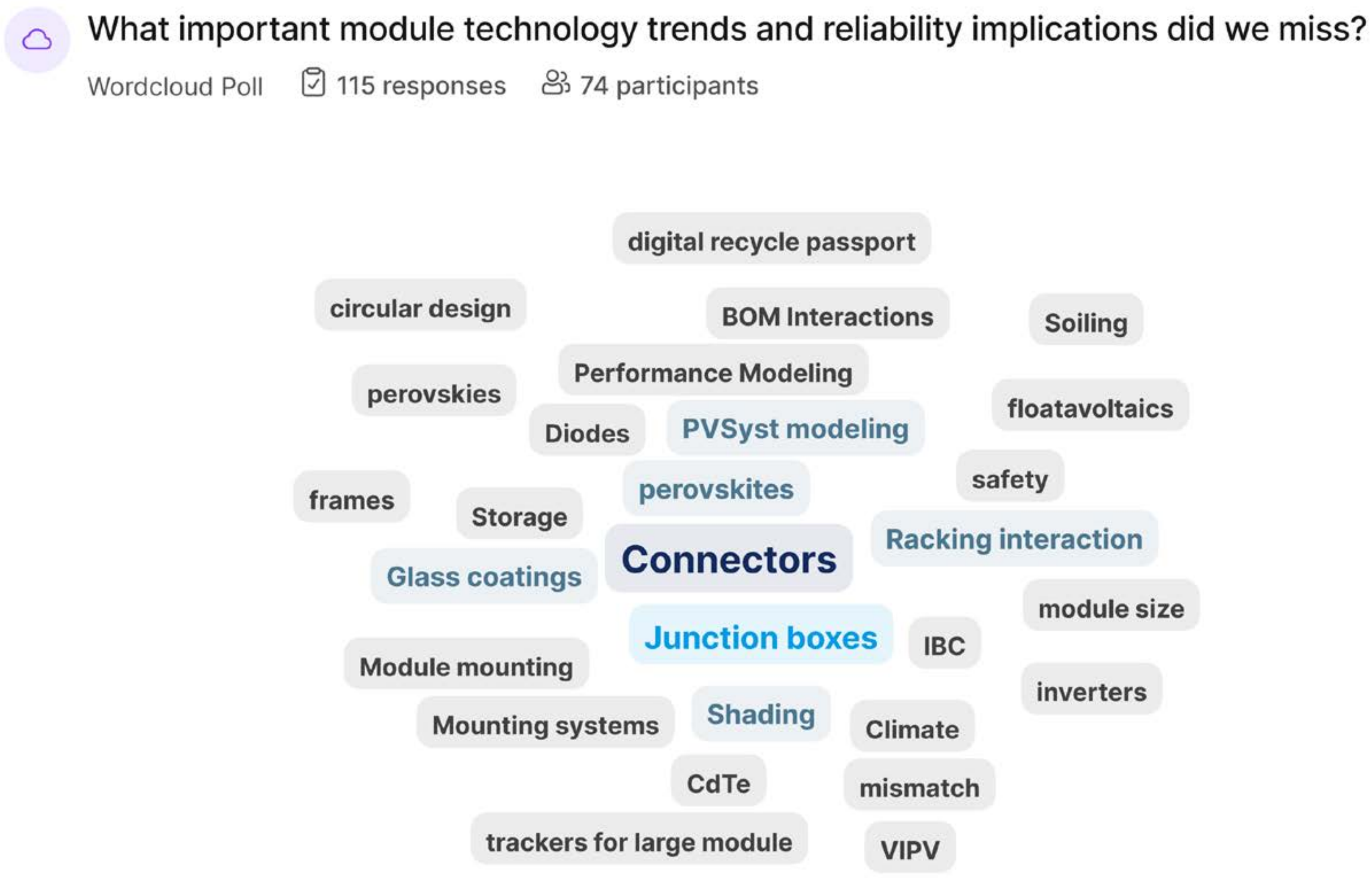
Thin films (32)	**n-type silicon (28)**	**Not perovskites (13)**	**Emerging (12)**	**Bifacial (11)**	**Any technology (6)**	**Module architecture (6)**
• **Cadmium telluride (CdTe) (25)** • Thin films (7)	• **Tunnel oxide passivated contact (TOPCon) (19)** • **Silicon heterojunction (SHJ) (9)**	• **Not perovskites (13)**	• **Perovskites (8)** • Tandems (4)	• Bifacial (5) • Bifacial passivated emitter and rear cell (PERC) (4) • Bifacial TOPCon & CdTe (2)	• Available technologies (4) • All technologies (1) • Silicon (1)	• Larger modules (5) • Custom sizes (1)
Module packaging (6)	**Building-integrated PV (BIPV) (4)**	**PERC (4)**				
• Steel frames (4) • Frameless modules (1) • Untempered glass (1)	• BIPV (4)	• PERC (4)				

?

Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?



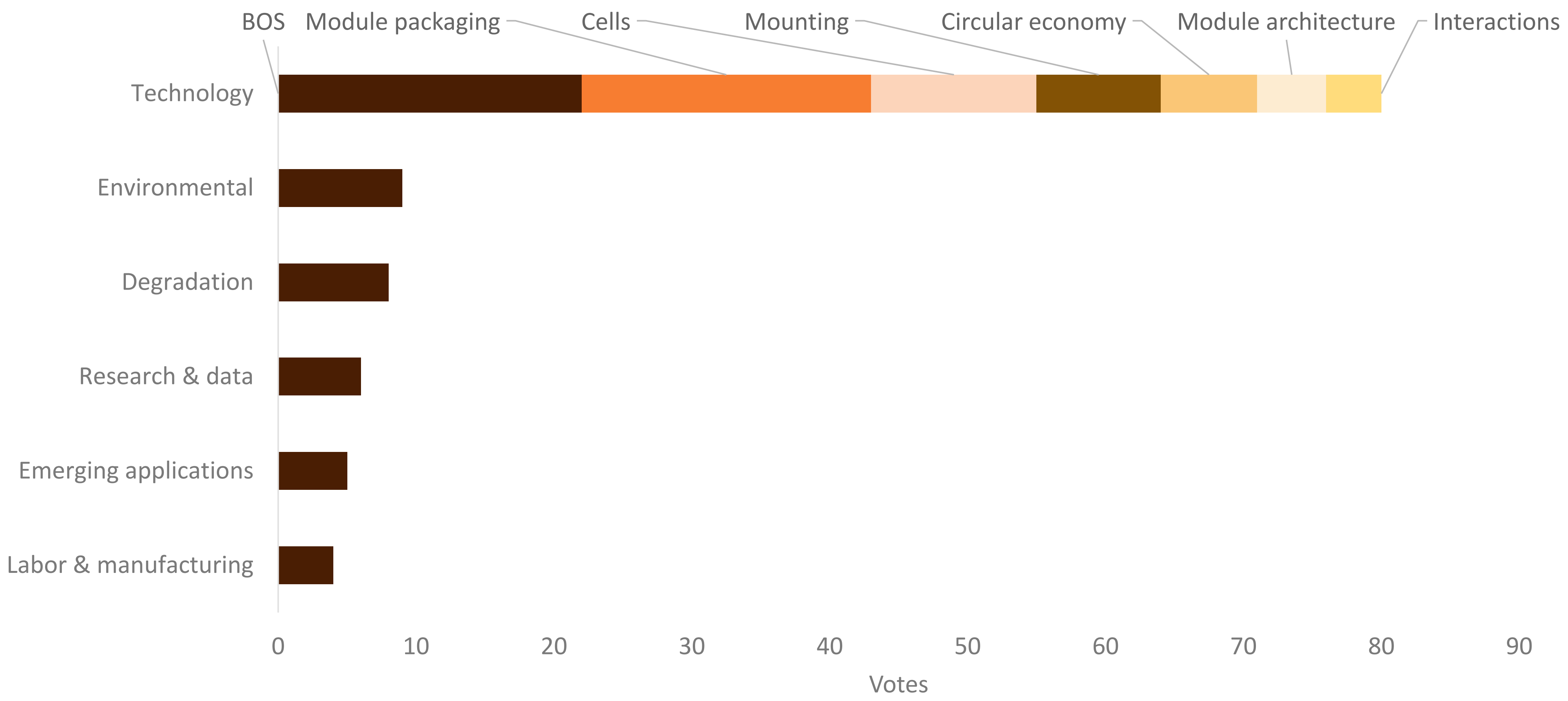
What important module technology trends and reliability implications did we miss?



What important module technology trends and reliability implications did we miss?

Balance of system (22)	Module packaging (21)	Cell technology (12)	Environmental (9)	Mounting (9)	Degradation (8)	Circular economy (7)
• **Connectors (incl. high current) (18)** • Combiner boxes (1) • Electronics (1) • High-voltage systems (1) • Inverters (1)	• **Junction box (8)** • **Frames (incl. thickness, new materials) (4)** • Glass coatings (3) • Diodes (2) • Glass (design, thinning) (2) • Anti-reflective coating (1) • Backsheets (1)	• **Perovskites (5)** • CdTe (3) • Interdigitated back contact (IBC) (2) • Non-glass substrates (1) • Perovskite-Si tandems (1)	• Climate (3) • Extreme weather (1) • Geography (1) • Hail impact (1) • Mechanical loading (1) • Northern climates (1) • Soiling (1)	• **Mounting systems (4)** • Racking interaction (3) • 2-axis tracking (1) • Trackers for large modules (1)	• **Shading (4)** • Hot spots/current mismatch (2) • Corrosion (1) • Leakage current (1)	• **Design for recyclability (4)** • End of life (1) • Recycling (1) • Reducing complexity (1)
Research & data (6)	**Emerging applications (5)**	**Module architecture (5)**	**Interactions (4)**	**Labor & manufacturing (4)**		
• **PVSyst modeling (4)** • Performance modeling (2)	• Storage (2) • Floatovoltaics (1) • Integrated solutions (1) • Vehicle-integrated PV (1)	• Module floppiness (2) • Bumpers for big floppy modules (1) • High-current modules (1) • Module size (1)	• Bill of material (BOM) interactions (3) • Interaction of new technologies (1)	• Installation practices (2) • Safety (1) • Domestic manufacturing (1)		

What important module technology trends and reliability implications did we miss?



Summary—ranked categories across all questions

Biggest challenges
+
Proliferating under IRA
+
Trends we missed

1. Technology (274)
    1. Module packaging
    2. Thin films
    3. BOS
    4. n-type silicon
    5. New materials & technology
    6. Module architecture
    7. Cells
    8. Bifacial
    9. Not perovskites
    10. Emerging
    11. Mounting
    12. Circular economy
    13. Any technology
    14. BIPV
    15. Interactions
    16. PERC
    17. Interconnects

Biggest challenges
+
Trends we missed

2. Environmental (35)
3. Labor & manufacturing (25)
4. Degradation (17)
5. Politics & business (12)
6. Research & data (12)
7. Emerging applications (5)

Summary—top 5 individual responses to each question

Biggest reliability challenges

- New materials & technology (11)
- Extreme weather (10)
- Larger modules* (10)
- Glass, incl. thinner & heat-strengthened (8)
- Quality control (8)

* "Big floppy modules" are categorized under larger modules, but floppiness may encompass other characteristics such as glass thickness.

Proliferating under IRA

- CdTe (25)
- TOPCon (19)
- Not perovskites (13)
- SHJ (9)
- Perovskites (8)
- Thin films* (7)

* Added a 6th place since "not perovskites" is not a technology per se.

Important trends we missed

- Connectors (18)
- Junction boxes (8)
- Perovskites (5)
- Design for recyclability* (4)
- Frames* (4)
- Mounting systems* (4)
- PVSyst modeling* (4)
- Shading* (4)

* Tied for 5th place.

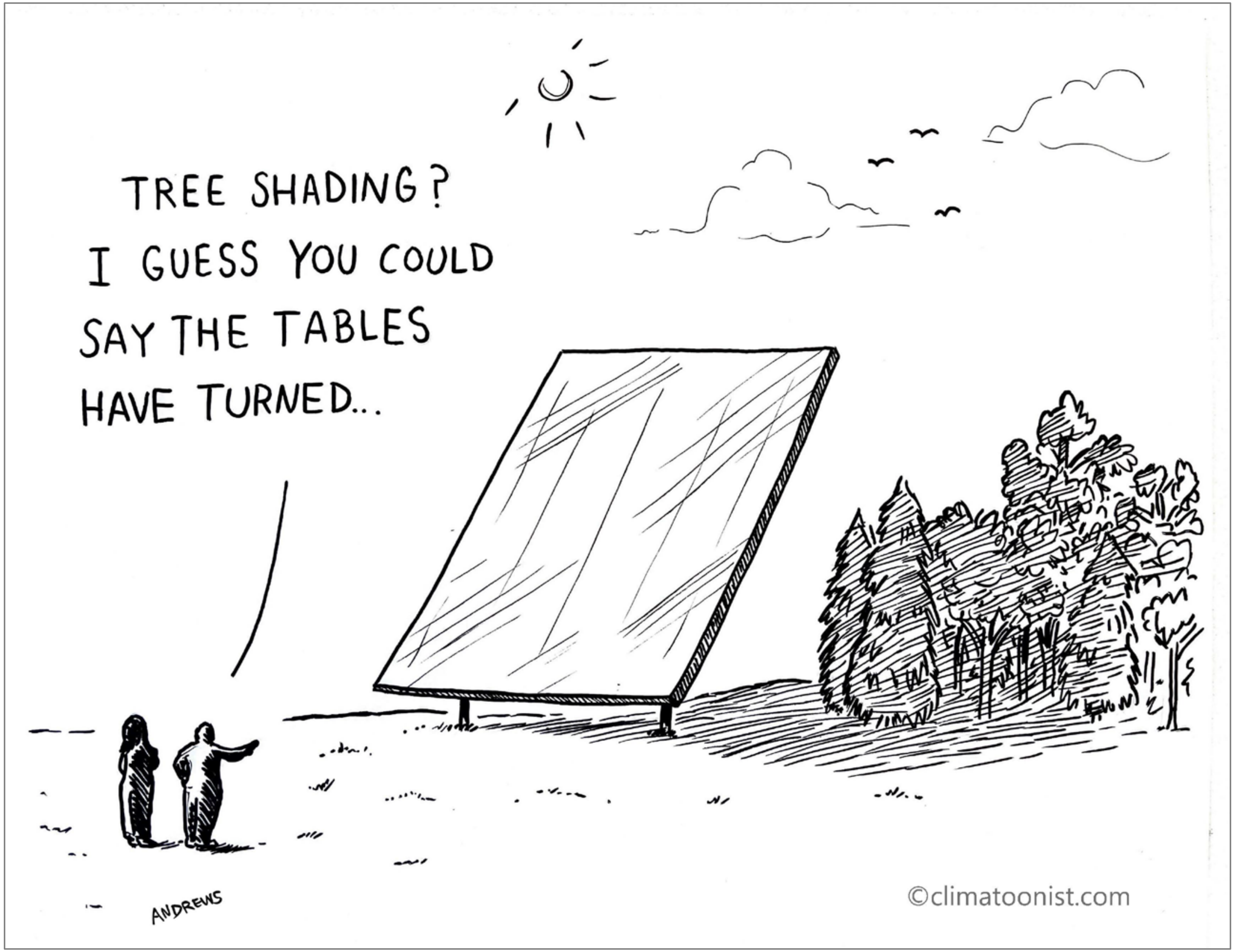
Summary—individual responses on more than one list

- CdTe (28)
- Connectors (20)
- Larger (possibly floppier*) modules (16)
- Perovskites (16)
- Bifacial (14)

- Extreme weather (11)
- Frames (11)
- Glass (11)
- New manufacturers (8)
- Installation (6)
- Tandems (6)
- Hail (5)
- Mounting (5)

- Racking (4)
- Recycling (4)
- Soiling (4)
- Backsheets (3)
- Diodes (3)
- High-voltage systems (2)
- Integrated applications (2)
- Non-glass substrates (2)

* Includes 9 votes for variations of "big floppy modules."



Cartoon from Wes Andrews, Climatoonist, with permission

DCAM Demo

Detailed Cost Analysis Model (DCAM): https://dcam.openei.org/

- Free, public, user-friendly online tool
- Enables bottom-up modeling of PV costs:
  - Manufacturing of ingots, wafers, and cells
  - Assembly of modules
  - Installation of PV systems
- Leverages NREL component and system cost benchmark research
- Can be used to analyze cost impacts of technology choices

Manufacturing Cost Modeling Structure in DCAM

TOTAL COST OF OWNERSHIP (TCO) INPUTS

Inputs For Calculations of Direct Costs
- Tool throughput including downtime
- Equipment price and training
- Facilitation and building
- Materials and consumables
- Utilities (Electricity and Water)
- Waste disposal (Wastewater and exhaust air)
- Labor: Direct operators and supervisors
- Maintenance
- Account of yield loss

Location Specific Costs Considerations
- Local wage rates: Direct operators and supervisors
- Local utility rates: Electricity and water
- Leased or purchased building
- Local considerations for CapEx and materials

GAAP AND IFRS ACCOUNTING STANDARDS

Variable (cash) costs within the cost of goods sold (COGS)
- Input materials
- Direct labor
- Utilities
- Maintenance of equipment and facilities

Fixed (non-cash) costs
- Equipment
- Building and facilitation
- Installation and training

COGS to Delivered MSP
- Research and Development (R&D)
- Sales, General, Administration (S,G, & A)
- Profit across the supply chain
- Taxes, tariffs and import/export duties (Input per destination)
- Sea- and land-based shipping, port entry fees, warehouse, and insurance (Input per destination)

Delivered Minimum Sustainable Price (MSP)

Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf

Manufacturing Cost Modeling Structure in DCAM

1. Direct Cost of Goods Sold

- Materials
- Labor and Utilities
- Maintenance
- Equipment and Facilities

+

2. Overhead and Profit

- Research and Development (R&D)
- Sales, General and administration (S, G, &A)
- Gross and Operating Profit
- Other Revenues and Losses (Not Included)

Factory Gate Minimum Sustainable Price (MSP)

3. Taxes and Trade Duties

- Sales, value-added or other taxes
- Customs or other import duties
- Anti-dumping and countervailing duties (AD/CVD)
- Input per source and destination

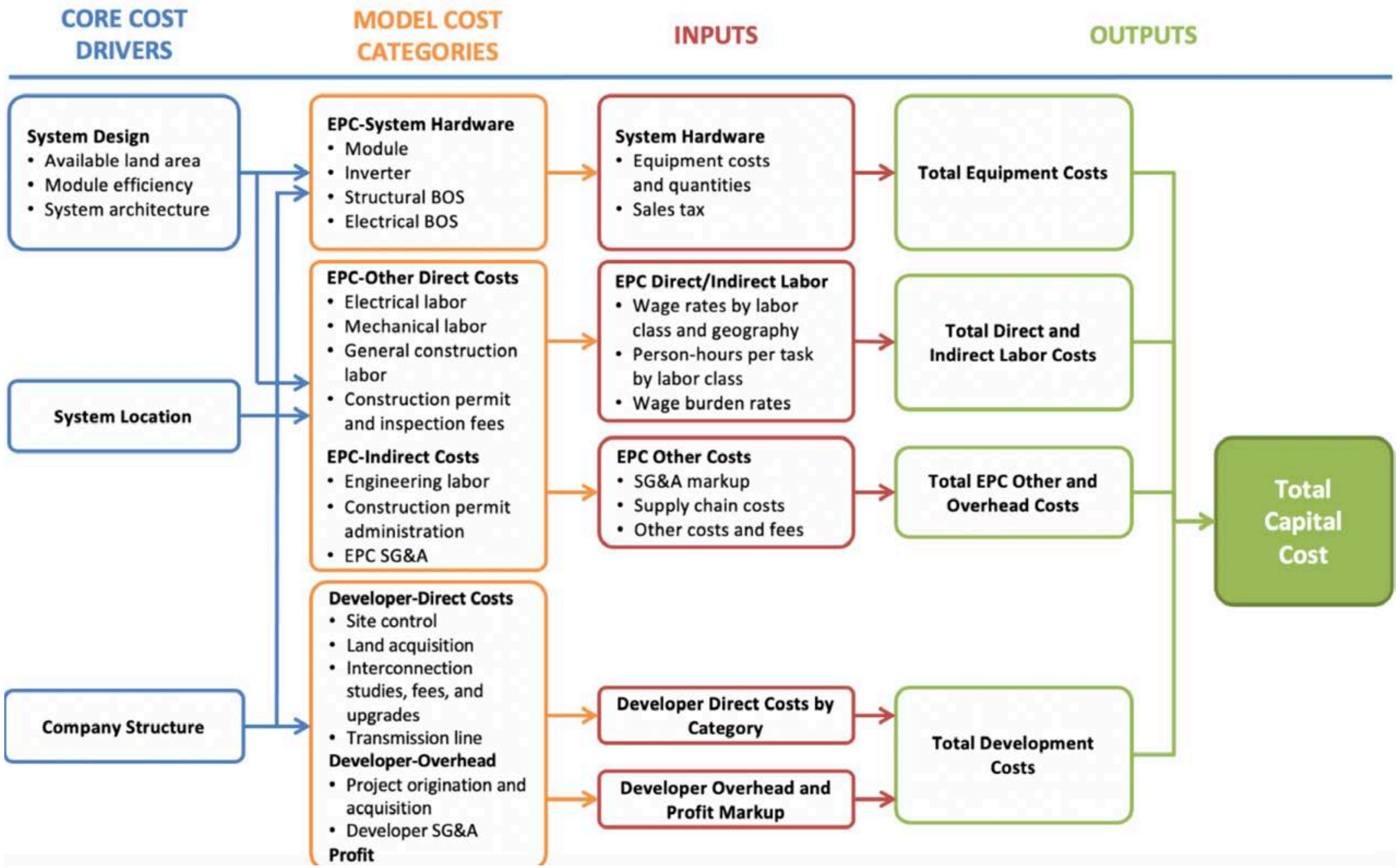
+

4. Shipping and Delivery

- Sea shipping: Modules per container and shipping container costs
- Land shipping: Miles from port to destination and cost per mile/kilometer
- Insurance, entry bond, shipping fees
- Warehouse
- Input per source and destination

Delivered Minimum Sustainable Price (MSP)

System Cost Modeling Structure in DCAM



Detailed Cost Analysis Model (DCAM): Demonstration

Utility + PV / **Q1-2022 Utility PV Benchmark** Public Updated: **January 23 2023**

Copy project Upload JSON Download Options

Save Calculate Notes

Search Inputs Advanced Inputs Output

INPUTS

System Description + add note

Year	2022	
Project Location	United States	
Axis Type	One-Axis	
Project Size	5	MWDC
System VDC	1500	VDC
Transmission Line	2.7	miles
Nominal to Real USD Factor	0.952	

Modules + add note

Module Efficiency	20.3	%
Module Width	40.32	inches
Module Length	76.68	inches
Module Power	405	W
Module Weight	47.84	lbs
Module Price	0.33	$/W

OUTPUT

Utility-PV MSP Results ($/Wdc)

MSP - Minimum Sustainable Price

Project Size (MWDC)	5
Axis Type	One-Axis
EPC/Developer Net Profit	0.0893
Contingency	0.0292
Developer Overhead	0.111
Transmission Line	0
Permitting Fee	0.0419
Interconnection Fee	0.0217
Sales Tax	0.0419
EPC Overhead	0.0898
Installation Labor & Equipment	0.133
Electrical BOS	0.143
Structural BOS	0.151
Inverter	0.0397
Module	0.314
Total Utility + PV System Cost	1.21

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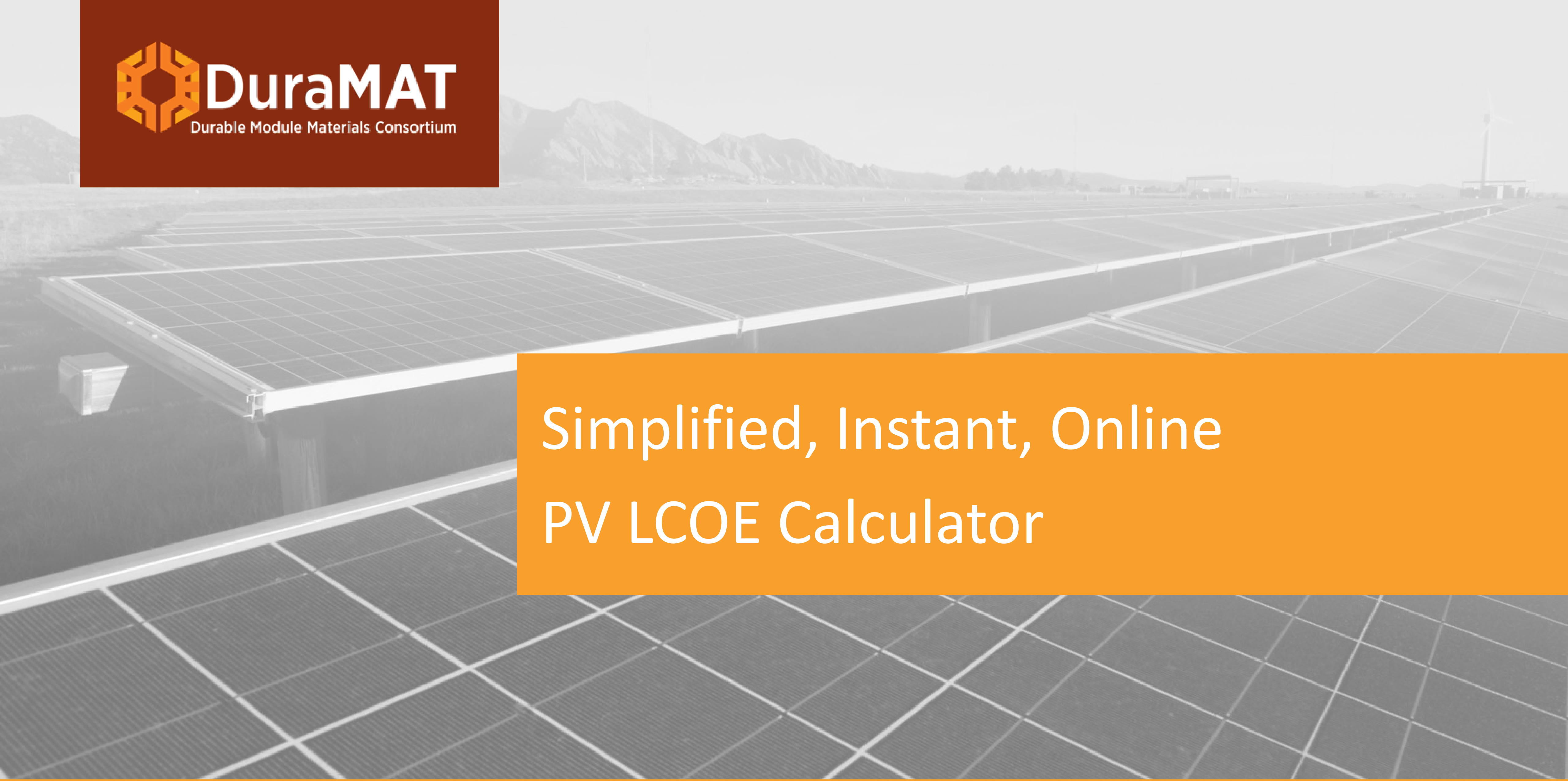
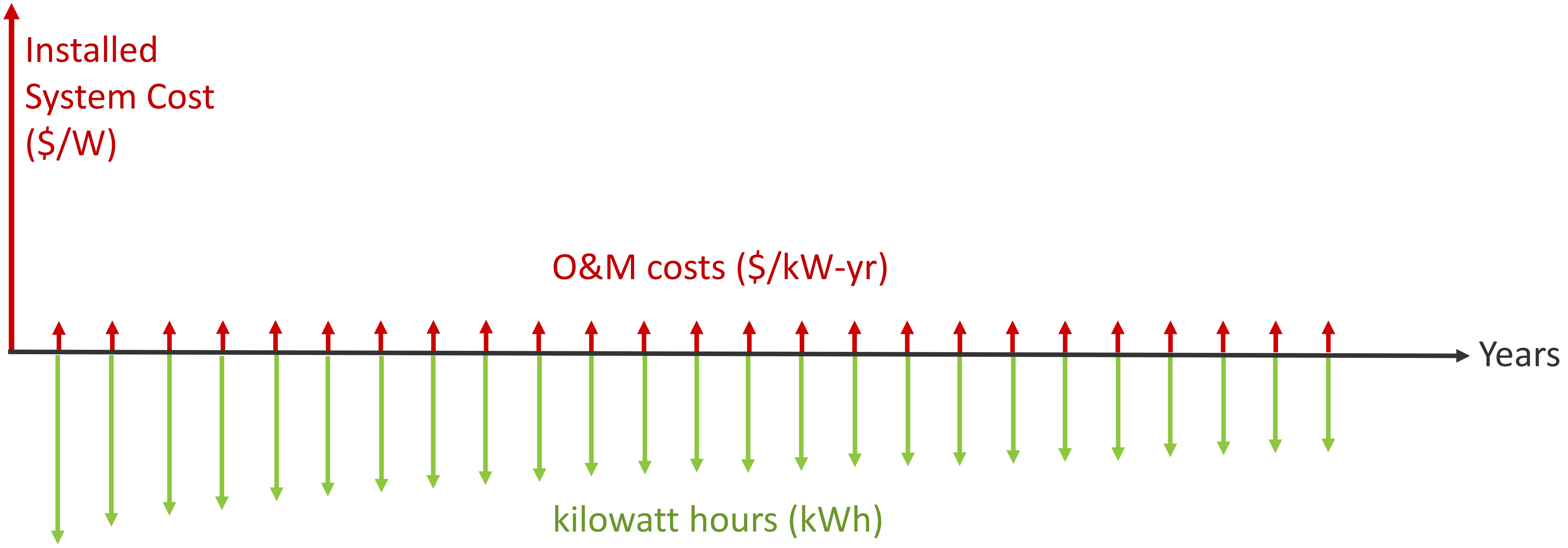


Simplified, Instant, Online PV LCOE Calculator

U.S. DEPARTMENT OF ENERGY | DuraMAT | NREL | Sandia National Laboratories | BERKELEY LAB

Levelized Cost of Energy (LCOE)

$$\text{LCOE (\$/kWh)} = \frac{\text{Total Costs over Service Life (\$)}}{\text{Total Energy Produced over Service Life (kWh)}}$$



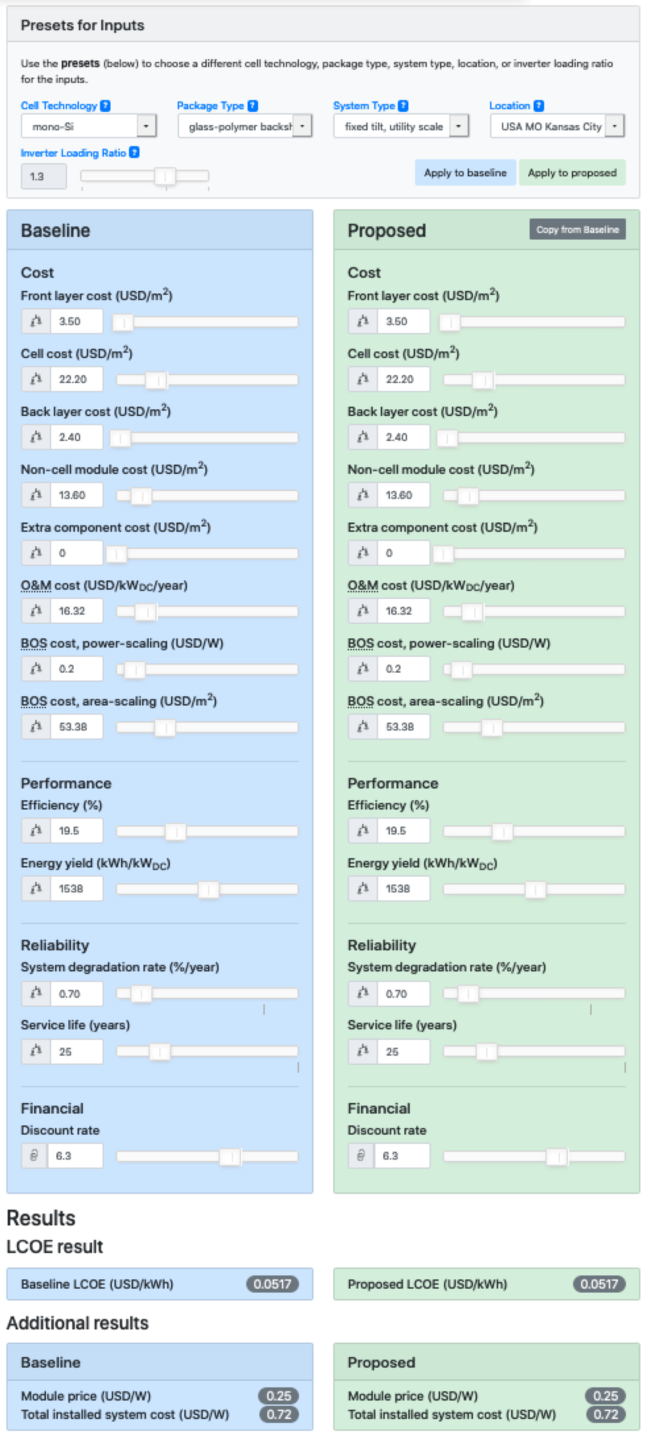
Simplified PV-LCOE Calculator: pvlcoe.nrel.gov

- PV technology-specific
- Editable preset fields, targeting research applications
- Instant comparison of proposed changes to a baseline system

System Advisor Model (SAM): sam.nrel.gov

+ Different financial models
+ Detailed options for module and system designs
+ Can model solar + storage

– May be more challenging for new users to navigate
– Difficult to quickly evaluate research directions without introducing confounding factors



Simplified PV-LCOE Calculator

Calculator access:

- pvlcoe.nrel.gov
- nrel.github.io/PVLCOE/
- github.com/NREL/PVLCOE
- datahub.duramat.org/dataset/lcoe-calculator-tool

Full Tutorial:

www.nrel.gov/docs/fy22osti/80842.pdf

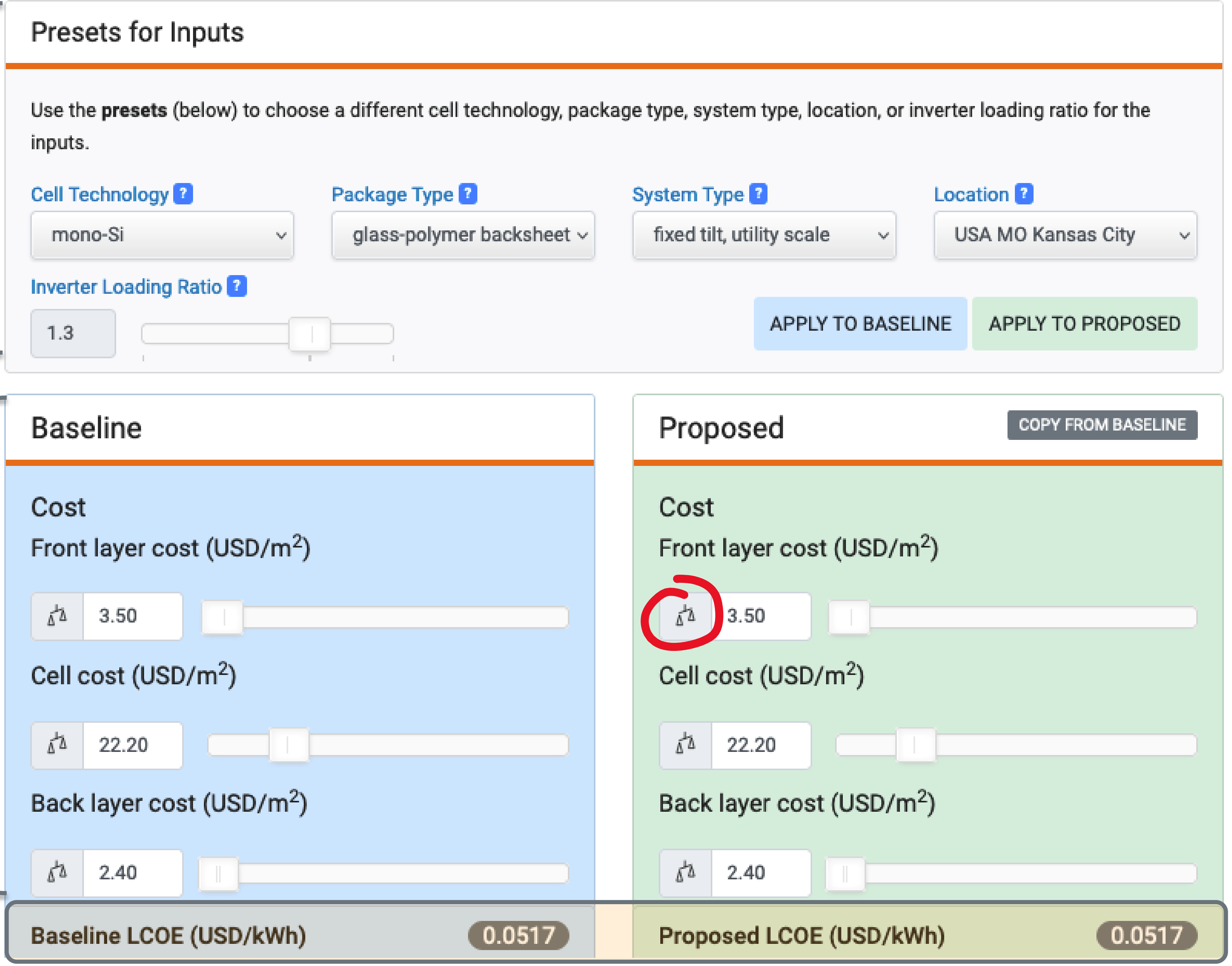
Calculator architects:

Tim Silverman
Mike Deceglie
Sophie Andrews
Kelsey Horowitz

Step 1: Select from a set of system options

Step 2: Default input values pre-populate, based on selections
(additional fields visible on website)

Step 3: Results generated include LCOE, module price & system cost (not shown)



Example: What cost for improved clamps would still be competitive?

If someone designed clamps that were more secure, or easier to use, this could potentially:

- Require less installation labor
- Reduce O&M expenses (maintenance, replacements, insurance)
- Reduce degradation rate
- Increase service life
- Or all the above?

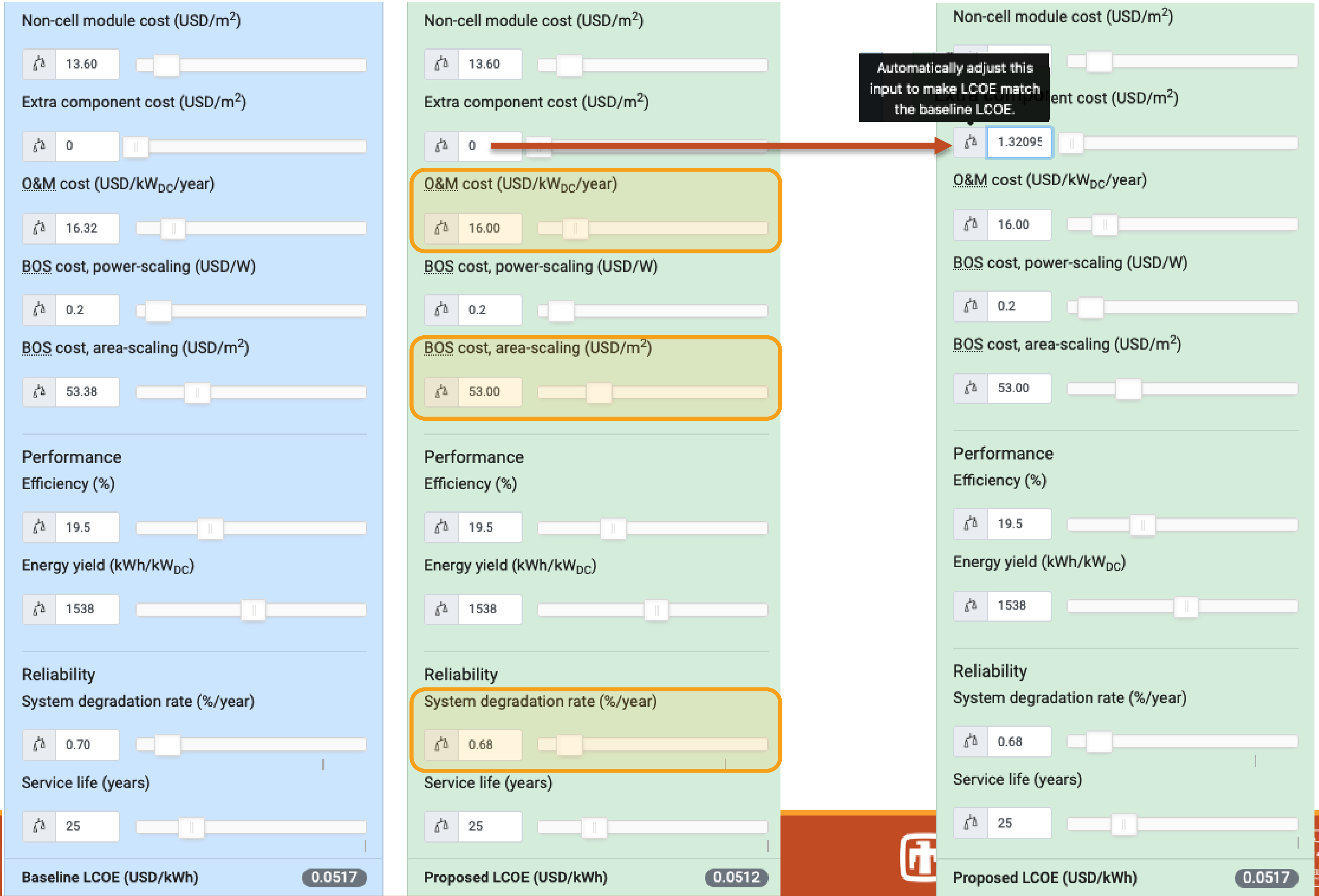
For an equal LCOE, how much more could the new clamps cost?

Step 1: Preset menu selection (leaving at defaults in this example)
Step 2: Propose cost/maintenance/performance improvements

If the clamps enable slight reductions in:

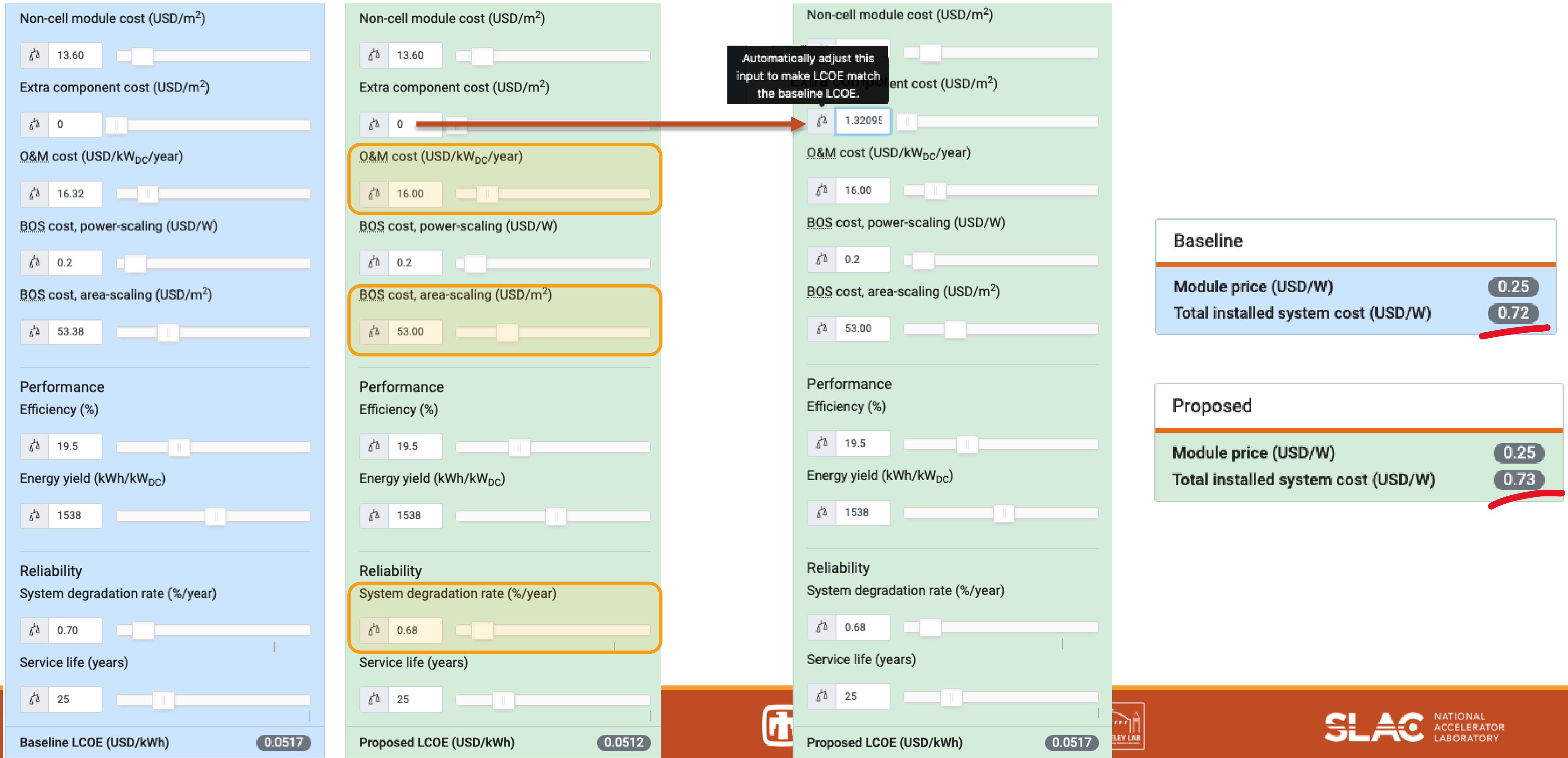
- O&M costs
- install labor
- degradation rate

Step 3: Compare results



The system can tolerate an extra $1.32/m^2 for the same LCOE

Step 3: Compare results



Questions / Discussion

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