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Technical Opportunities for Improving PV Modules and Systems – *The Path to a 50 yr Module*

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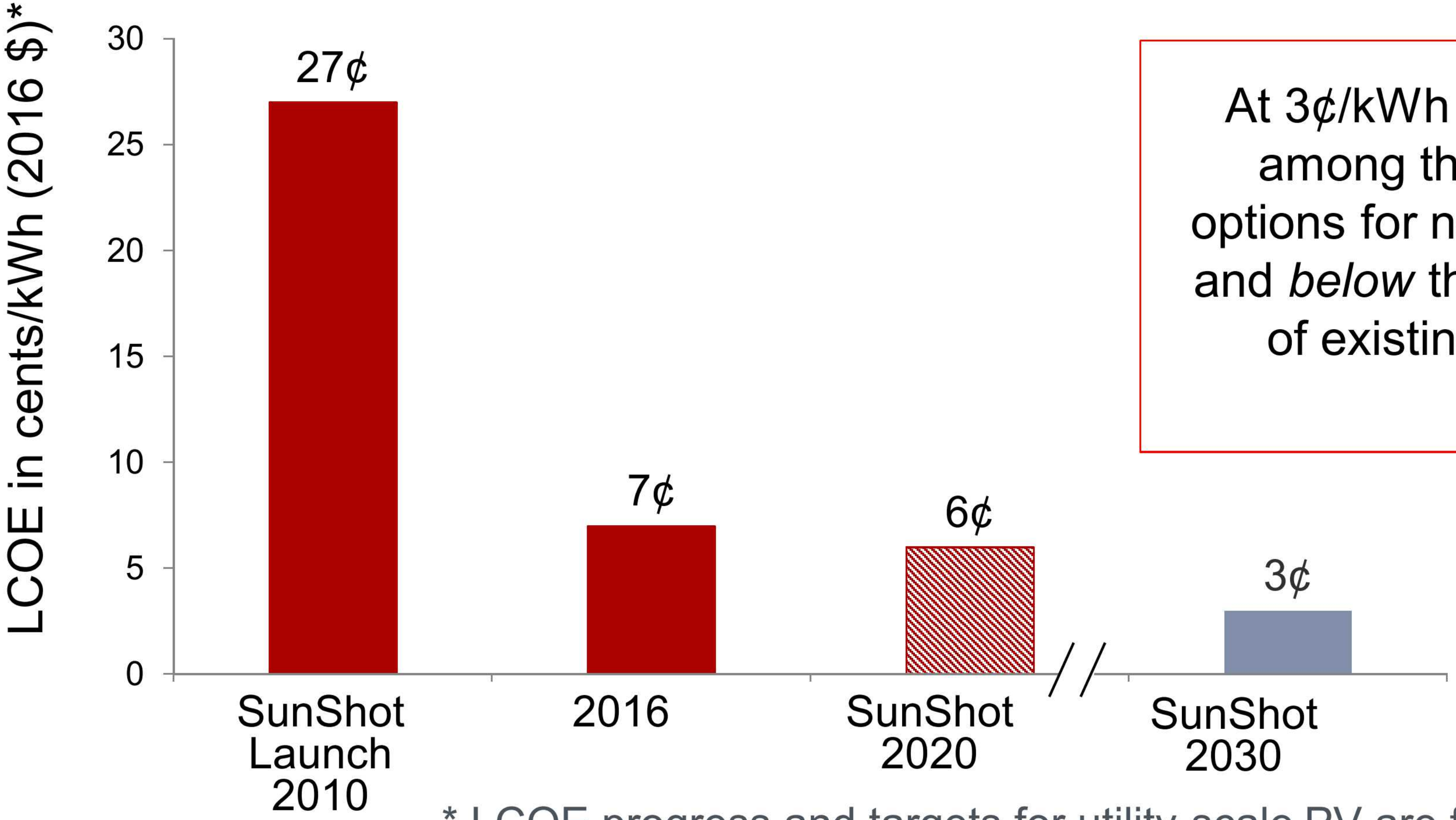
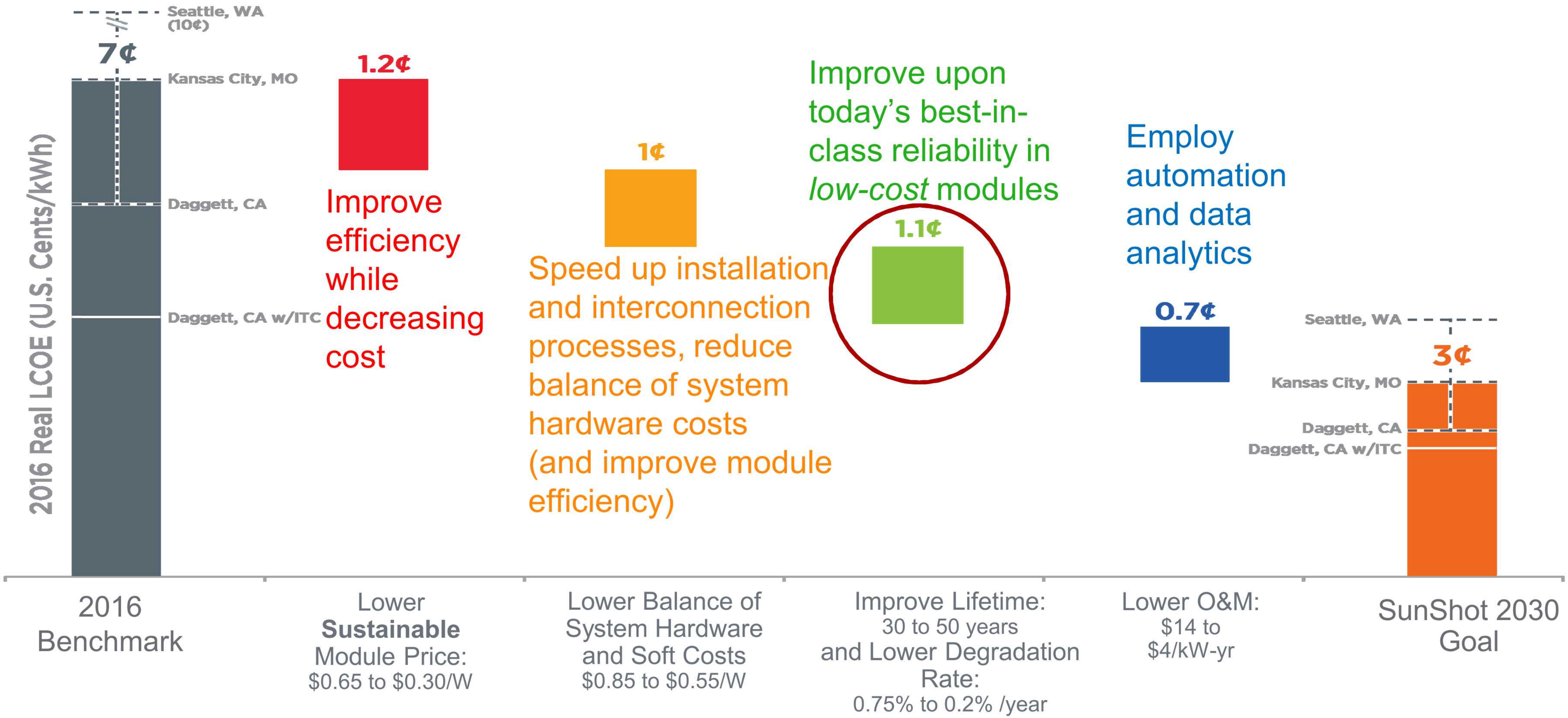
SunShot 2030 LCOE Targets for the US



At 3¢/kWh solar would be among the lowest cost options for new generation—and *below* the variable costs of existing fuel plants.

* LCOE progress and targets for utility-scale PV are for average U.S. climate and without the ITC or state/local incentives. The 2016 number is for a system with one-axis tracking.

A Pathway to 3 Cents per kWh



100 $MW_{(DC)}$ One-Axis Tracking Systems With 1,860 $kWh_{(AC)}/kW_{(DC)}$ First-Year Performance. Includes 5 Year MACRS. Cost of capital is 7% and inflation is 2.5%.

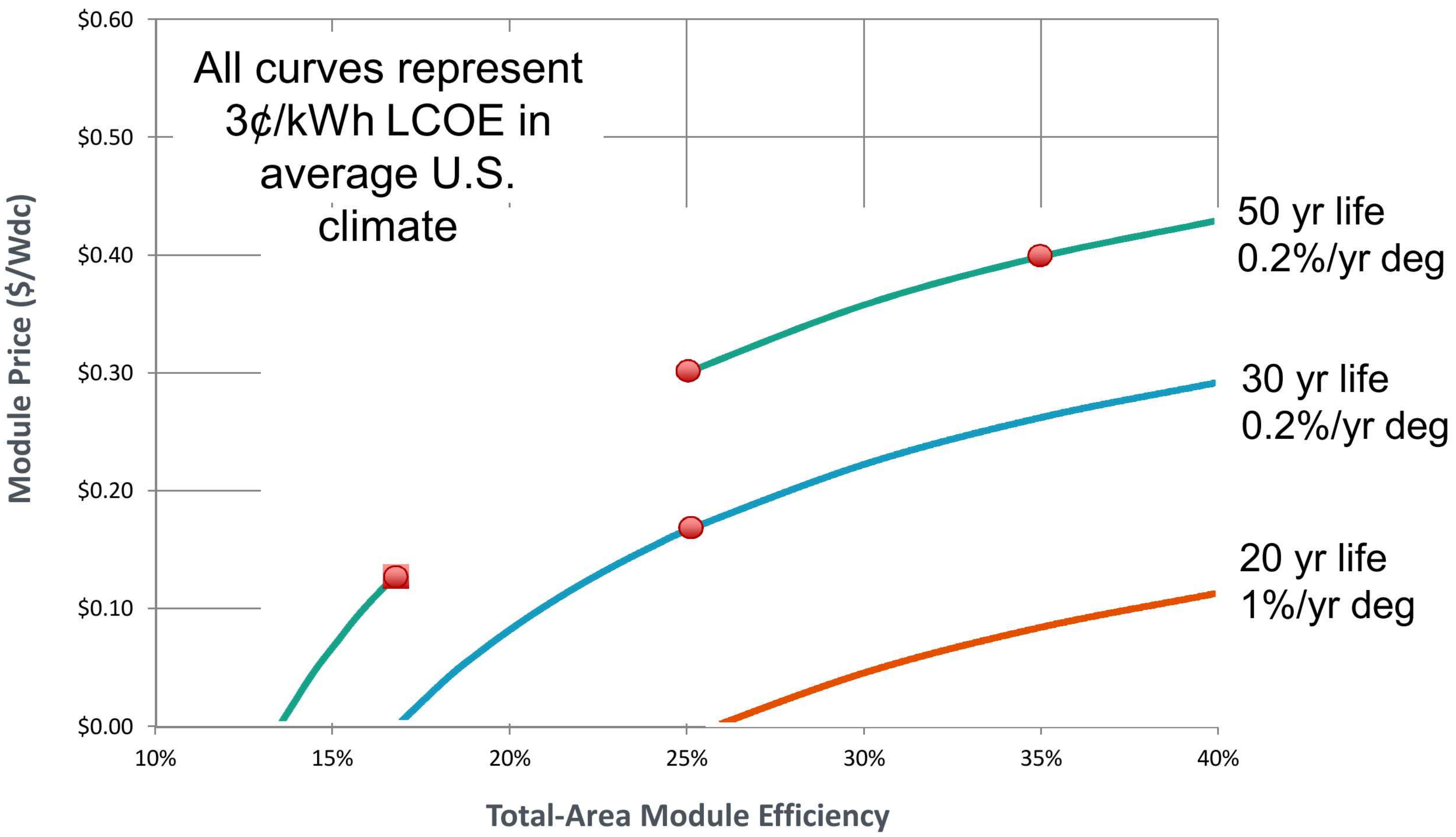
Why are 50-yr Modules so Appealing?

50 yr module provides multiple opportunities to reach SunShot 2030 goals.

- Ultra low cost modules (~$0.12/Wdc), lower efficiency (17%).
- Low cost ($0.30/Wdc), high efficiency (25%)
- Higher cost ($0.40/Wdc), very high efficiency (35%)

Alternatives for 30 and 20 yr lifetimes require such low module prices that it is hard to believe they would ever achieve LCOE goals.

50 yr module reduces future waste streams

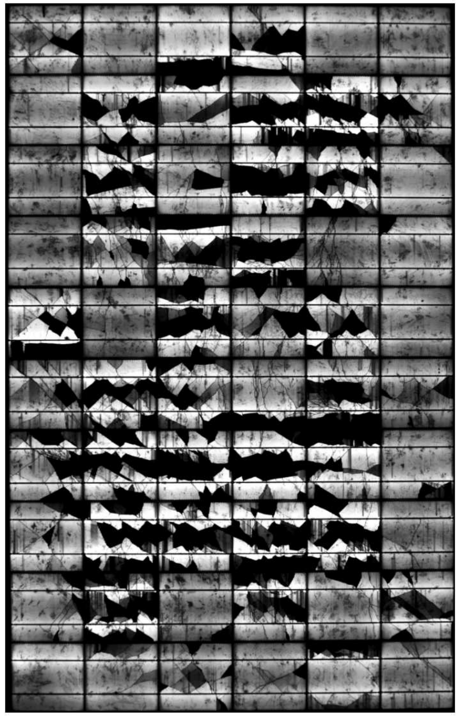


All scenarios assume: 7% cost of capital, 2.5% inflation, $0.85/W system cost, $4/kW-yr O&M, 21% capacity factor

How to Increase Lifetimes and Decrease Degradation Rates?

- Understand why modules degrade and fail.
- Choose designs and materials that minimize degradation and failures.

Choices can be climate specific!



Module fielded for 8 years in a **hot dry climate**. Cell cracks are severe. No signs of corrosion.

Module fielded for 8 years in a **tropical climate**. Fewer cell cracks. No signs of corrosion.

Causes of Failure and Degradation

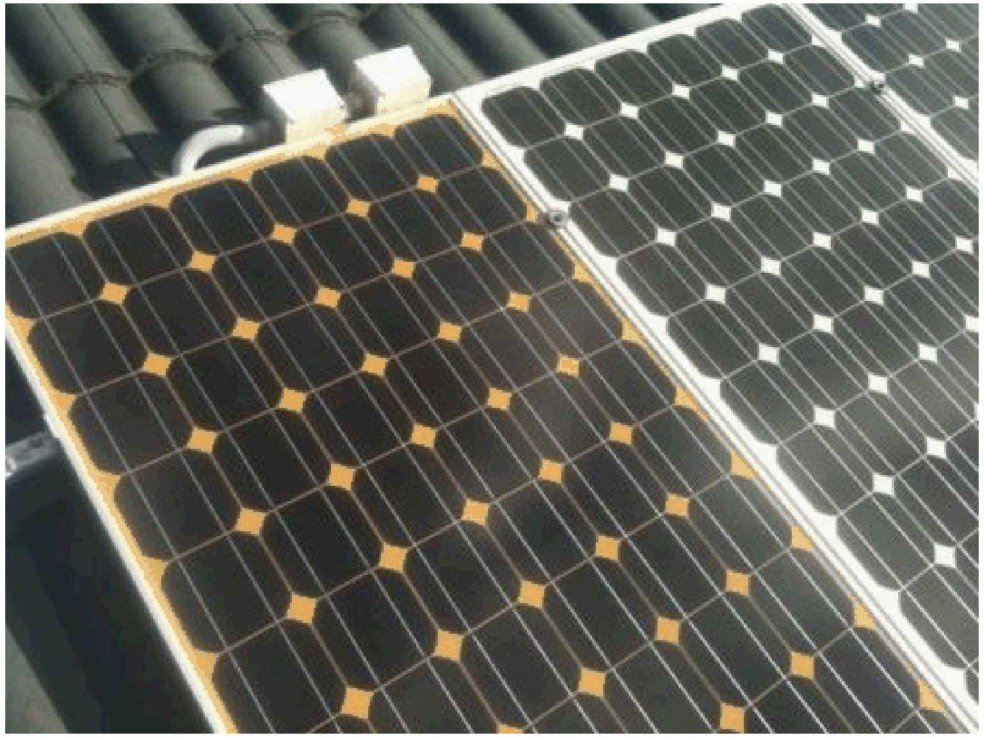
- Damage during shipping or installation
  - E.g., Cracked cells
- Optical degradation of materials
  - UV degradation of encapsulants ("yellowing", "browning")
  - Coatings wearout, scratches in topsheet
- Mechanical stress
  - Wind & snow loading → cracked cells, broken glass, bent frame
  - Thermal cycling, Freeze-Thaw of water
- Chemical transport
  - Water ingress, Acetic acid formation
  - Corrosion
- Failure of accessories
  - J-box, cables, connectors

Prevent damage due to shipping and installation

- Mechanical analysis of stresses from vibration, shock, drop, etc. should be made for various packing solutions.
- Accelerometers installed on pallets – Data used to design package
  - Vertical vs. horizontal stacking
  - Frame vs. frameless
  - Effect of glass thickness
- Proper training and equipment needed for installers
- Field methods for checking that installation is damage free.
  - Field imaging of modules (EL, PL, IR, IV, UVF)

Preventing Optical Degradation

- Polymers degrade when exposed to UV radiation
- Additives are used to absorb UV and thus protect polymer from degradation.
  - Very hard to measure additive concentration.
  - Current method relies on qualification testing (time consuming and does not have full coverage)
- We need better controls and assurances on UV durability of polymers.
- We need to know if/how various formulations affect durability and physical properties.

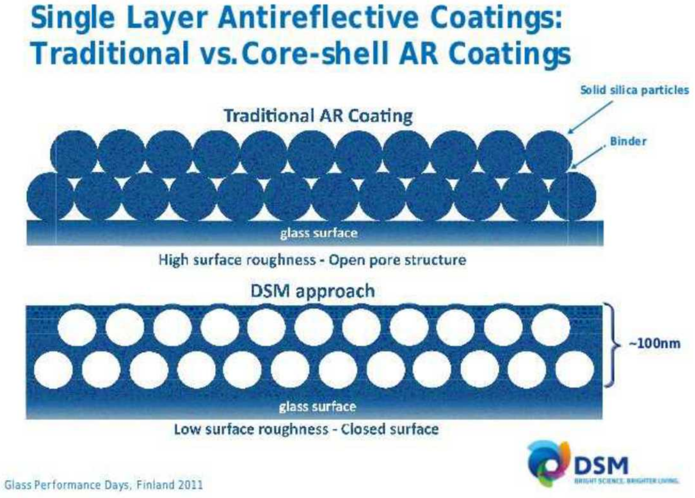


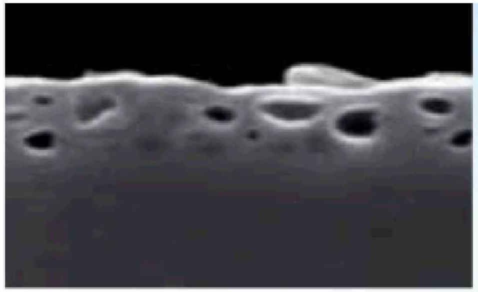
Encapsulant Additive Compounds

- **UV-stabilizers & absorbers –** absorb UV and dissipate as heat
- **Radical scavengers –** antioxidants that remove peroxy, alkoxy, hydroxyl, and alkyl radicals
- **Crosslinking agents –** curing agents that help to form covalent bonds between polymer molecules
- **Adhesion promoters –** coupling agents (typically organosilanes) that help dissimilar materials to bond (e.g. glass, PV cells, encapsulants, backsheets).

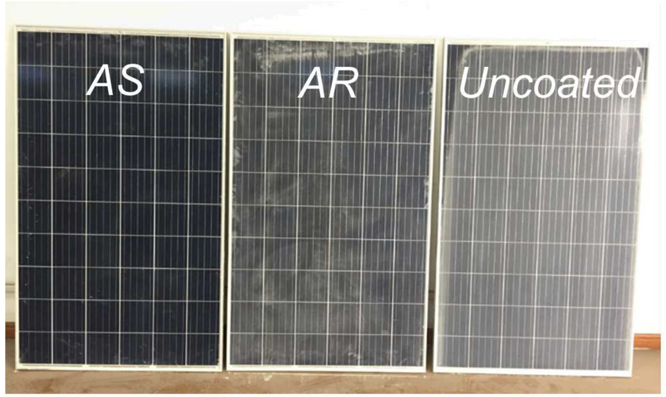
Preventing degradation of Glass coatings

- We need to better understand how different coatings degrade.
- Accelerating ageing studies combined with detailed laboratory characterization is a good first step.
- Uncertain whether common coatings can last for more than a few years in the field.





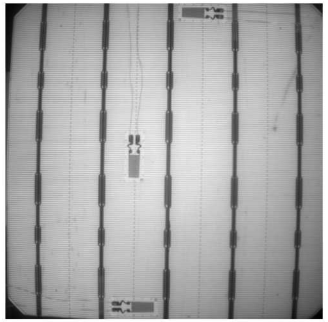
SEM cross-section of KhepriCoat



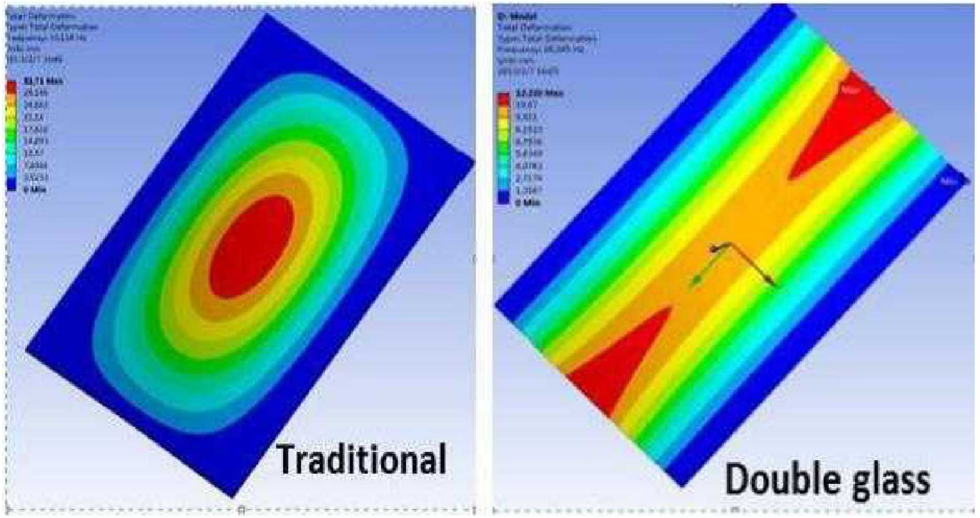
DSM Study in Gobi Desert

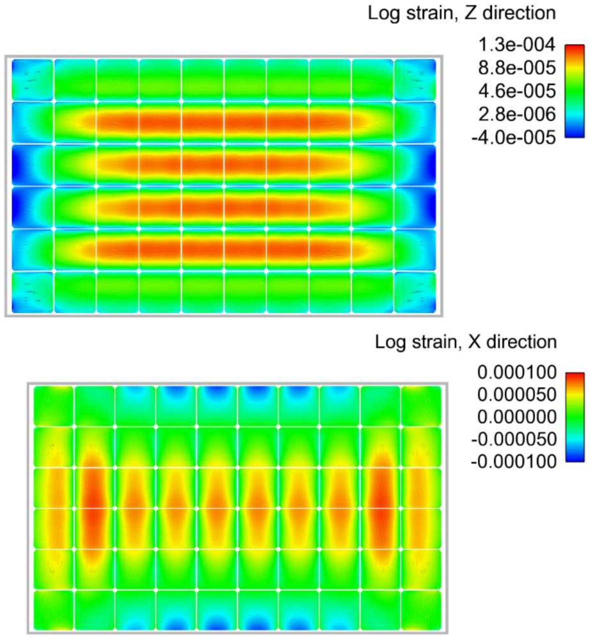
Designing for Mechanical Stresses

- Multiple cell interconnect methods available
- Role of encapsulant physical properties
  - Modulus vs. temperature (glass transition temp)
  - Thickness
- Glass-backsheet vs. glass-glass designs

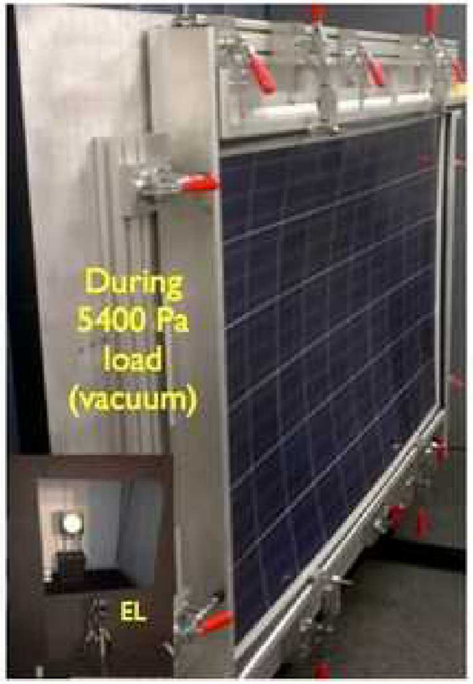


Strain gauges attached to PV cells within laminate





FEA predicted cell strains @ 2400 Pa



Vacuum/air-pressure from rear side

BrightSpot Automation

Module deflected using LoadSpot

Wide Variety of PV Cell Interconnection Approaches

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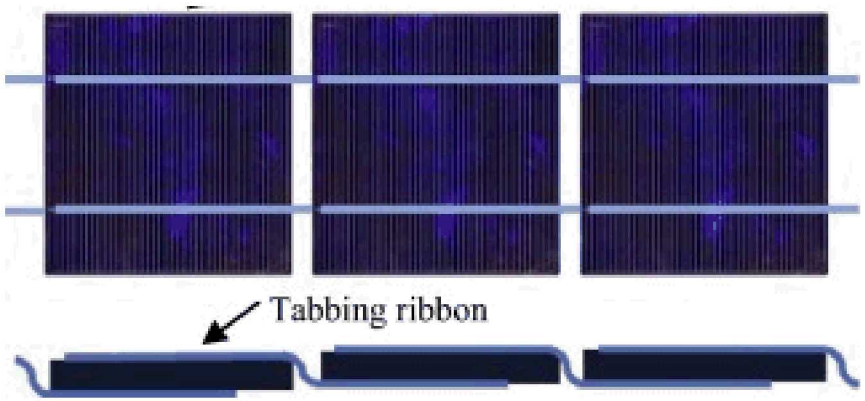
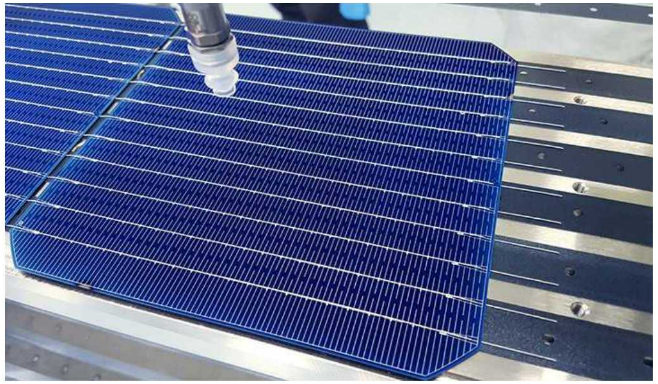
Each method differs in many ways that may affect durability and lifetime

- Soldered Busbars have a long history.
  - Stress focused at cell edge
  - Different thermal expansion coefficients → solder bond fatigue.
- Shingling and MWT use ECAs which are relatively new in PV.
  - ECAs can distribute stress but will they last for 50 years?
- MWT is a flat design which minimizes local stress.
  - Not widely adopted

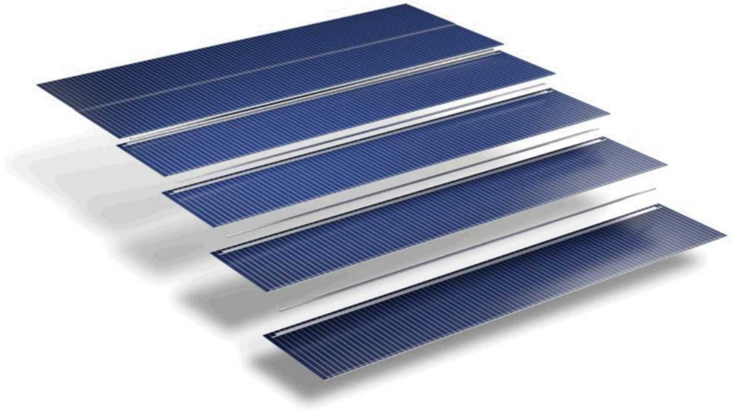
Soldered busbars



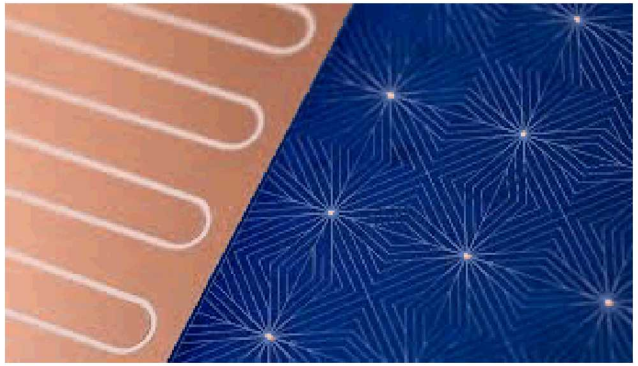
Multiwire



Shingling, Conductive Adhesive (ECA)



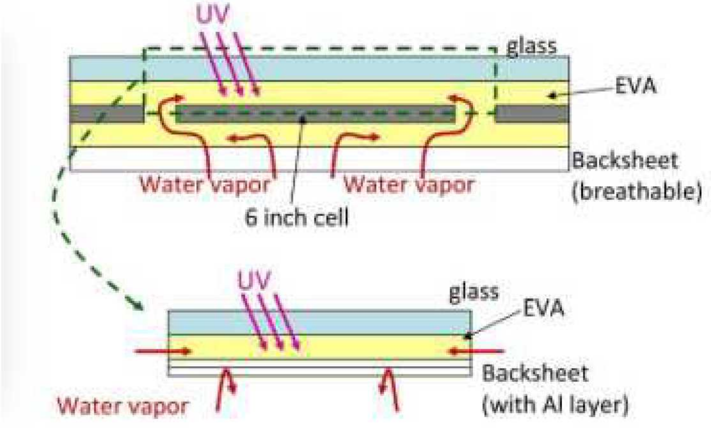
Metal Wrap Through, Conductive backsheet

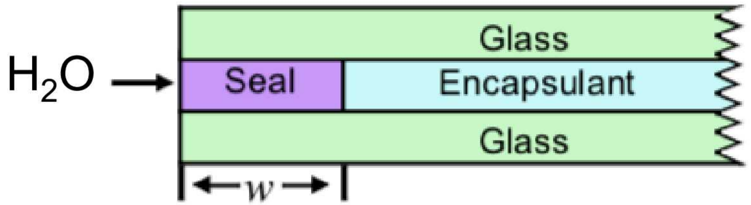


We need more independent studies on how different cell interconnect methods respond to mechanical loading.

Managing Chemical Transport within a PV Module

- Two general approaches:
  - 1. Allow some transport in and out of the module.
    - EVA + UV --> Acetic acid
    - Permeable backsheet allows acetic acid to diffuse out
    - Water can diffuse in at night and out during the day when module is hot
  - 2. Severely limit transport of water into module.
    - Glass-glass modules with edge seals (e.g., desiccant filled polyisobutylene)
    - Use encapsulant that does not produce acetic acid (e.g., polyolefin)
- More studies of these two approaches are needed.

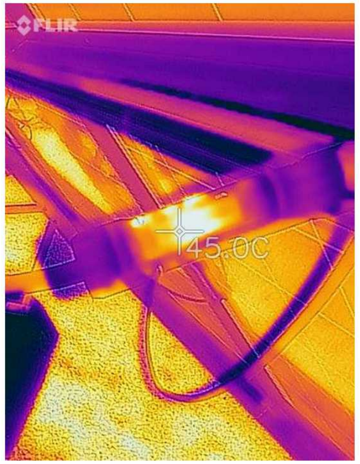




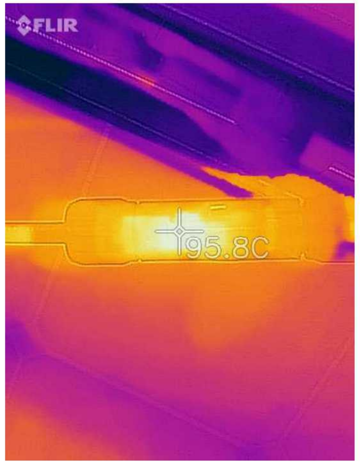
Failure of accessories – J-Box, Connectors, Cables

- Connectors are a common source of failure, but are also field replaceable.
  - *Compatible ≠ Compatible*
- Junction boxes provide housing for bypass diodes or power electronics
  - Pathway for moisture to enter module.
  - Adhesives must be reliable and durable.
- Durability and abrasion resistance of cables (wind)

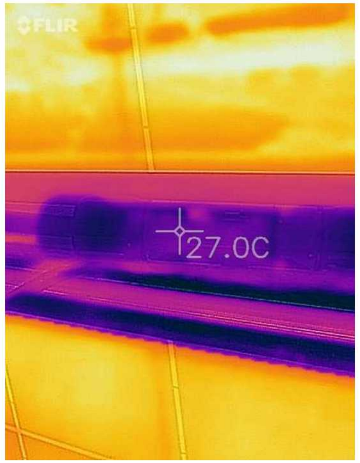
Innovation: Investigations into alternative ways of interconnecting connecting modules, (e.g., wireless power transfer).



Hot Connector (common)



Really Hot Connector (not common)



Cold Connector (common)


Edge-mounted J-Box for glass-glass modules

Summary and Conclusions

- There are significant economic and environmental benefits to extending the lifetime of PV systems.
- There is a wide variety of module designs and materials used in PV modules.
- Each design choice impacts lifetime differently in different climates.
- More laboratory and field studies are needed to optimize module and system designs.
  - Ensure no damage during shipping and installation
  - Choose encapsulants and coatings that will withstand UV exposure, wind, dust, snow, etc.
  - Design to minimize mechanical and thermomechanical strains
  - More investigations comparing cell interconnection strategies are needed.
  - Glass-backsheet or glass-glass?) – Can water transport be tolerated in a 50 yr module?
  - Connectors, cables, and J-box are weak parts of the module. Alternatives?
- How to maintain or reduce costs while designing for longer lifetimes?

Thank you!

Upcoming Events

- 2020 PV Reliability Workshop, Lakewood, CO USA (February 25-27, 2020)
  - PV Materials, Modules, and Systems Reliability
- SiliconPV2020 & BifiPV 2020 Workshop, Hangzhou, China (March 30-April 3, 2020)
- 14th PV Performance Modeling Workshop in Salt Lake City, UT USA (May 19-20, 2020)
  - PV Measurement, Modeling, Monitoring and Integration
- IEEE PVSC, Calgary, Canada (June 14-19, 2020)
- bifiPV Workshop 2020 in Walnut Creek, California, USA (July 2020)
  - Bifacial cells, modules, systems, modeling, and characterization