NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# The Role of Reliability and Durability in Photovoltaic System Economics

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# Presentation Outline

# Technoeconomic Analysis Activities Within DuraMat

## FY19 Analysis Projects: Three smaller topics for this fiscal year. One multi-year topic.

**Bottom-Up Module O&M and Repowering Economics**

- Identified a priority by SETO and the IAB
- Focus on cracked cells and hot spots this fiscal year
- Coordination and support to several DuraMAT projects

**Coatings for improved energy yield**

- Identified a priority by SETO
- IRR analysis of breakeven coating costs versus improvement in energy yield for sites within the U.S.
- Work with SETO awardees at SLAC, NREL, the University of Minnesota, and WattGlass. Outdoor RTC data collection.

**Bottom-Up Cost Modeling of Module Testing**

- Lends analysis support to core DuraMAT capabilities

**Longer-term multi-year topic:**

- Handbook of module cross-technology reliability and durability testing results and considerations for energy yield assessments. LCOE and IRR relevant evaluation.

## Capability Area & Teaming

**Capability Area(s):** Data, Predictive Simulation, Materials Forensics, Accelerated Test, Field Deployment

**Team:** Mike Woodhouse, Andy Walker, Ran Fu, David Feldman, and Robert Margolis, NREL

## Capability Summary & Impact

Use technoeconomic analysis to inform research prioritization and identify opportunities for impact.

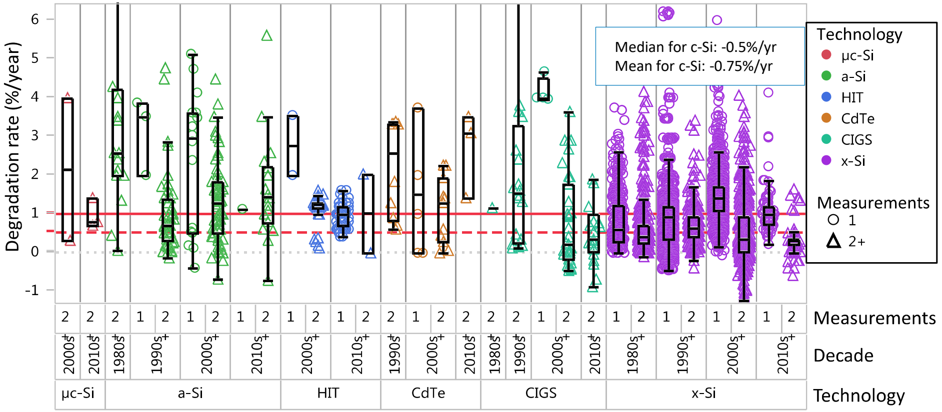
Expected Results

- Provide feedback to researchers about the performance metrics necessary to achieve SETO's goals and to provide value to industry (e.g., energy yield improvements needed to offset any increases in module cost or the value of addressing field failures)
- Connecting researchers to industry
- Facilitate teaming and research prioritization
- Feasibility analysis of materials, designs, and tests
- Identify data needs for application to industry
- Identify opportunities and barriers for new technology commercialization

# Presentation Outline

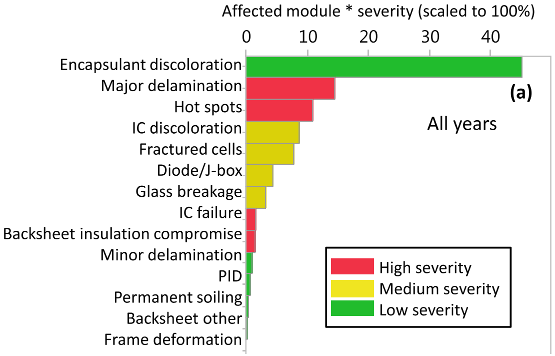
# Starting Questions

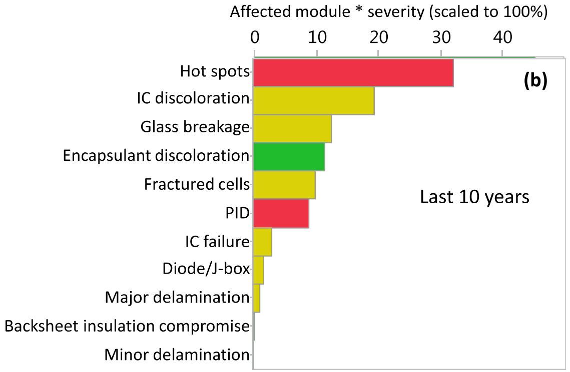
## Degradation rates and failure modes vary across technologies




**The consistent question from projects within DuraMAT: What is the value of solving a particular problem?**

## Major failure modes for c-Si (Mono and Multi)



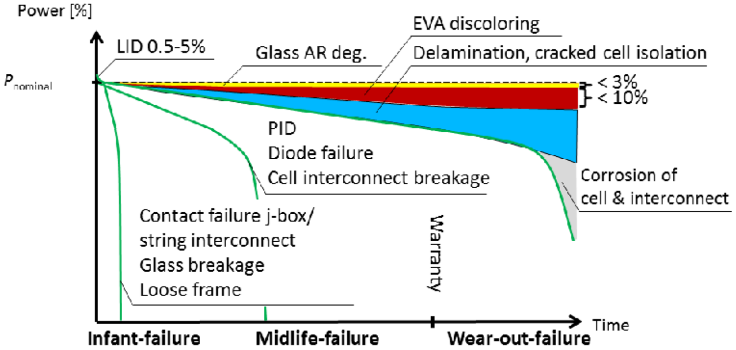
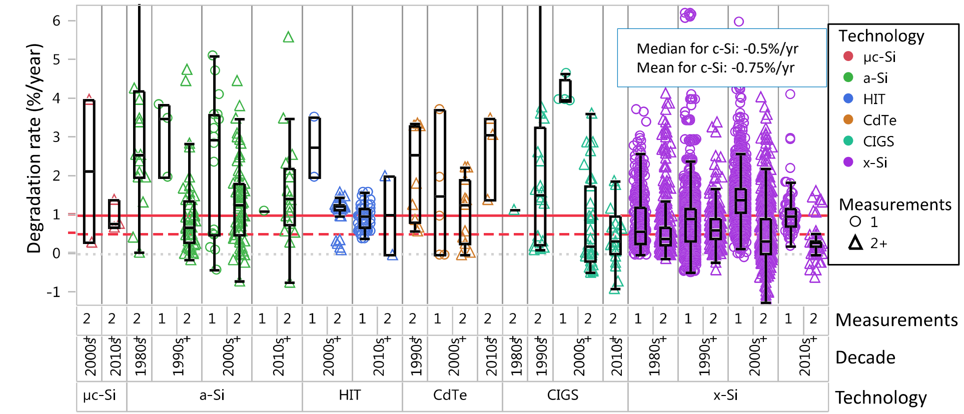



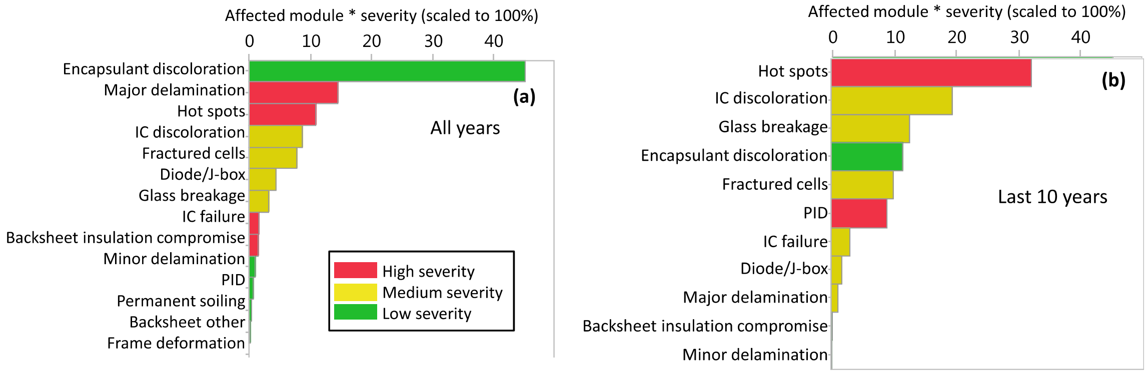

Figure sources. Top: D Jordan, S R Kurtz, K VanSant, and J Newmiller "Compendium of Photovoltaic Degradation Rates", PIP, 2016
Bottom left: D Jordan, T J Silverman, J H Wohlgemuth, S R Kurtz, and K T vanSant "Photovoltaic failure and degradation modes", PIP, 2017. Bottom right: IEA "Review of Failures of Photovoltaic Modules, 2014

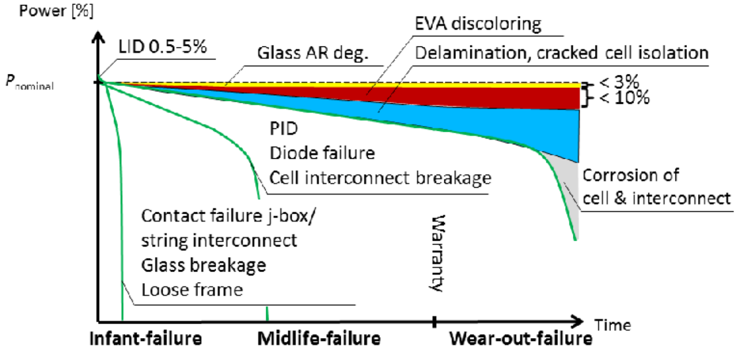
# Starting Questions

## Degradation rates and failure modes vary across technologies




## Major failure modes for c-Si (Mono and Multi)




**Central question for understanding the value of reliability R&D projects: What is the value of solving a particular problem?**

Relevant to PV system economics at a high level:

(1) Solving field failures before they occur can reduce O&M expenses and increase total power production over the performance period. This lowers project LCOE and improves project IRR.

(2) Building more robust systems increases residual value. This lowers project LCOE and improves IRR.

(3) Lower degradation rates means more PPA revenues over the life of the project. This improves IRR.

**By addressing particular problems, reliability R&D may provide solutions that improve PV project economics**

Figure sources. Top: D Jordan, S R Kurtz, K VanSant, and J Newmiller “Compendium of Photovoltaic Degradation Rates”, PIP, 2016
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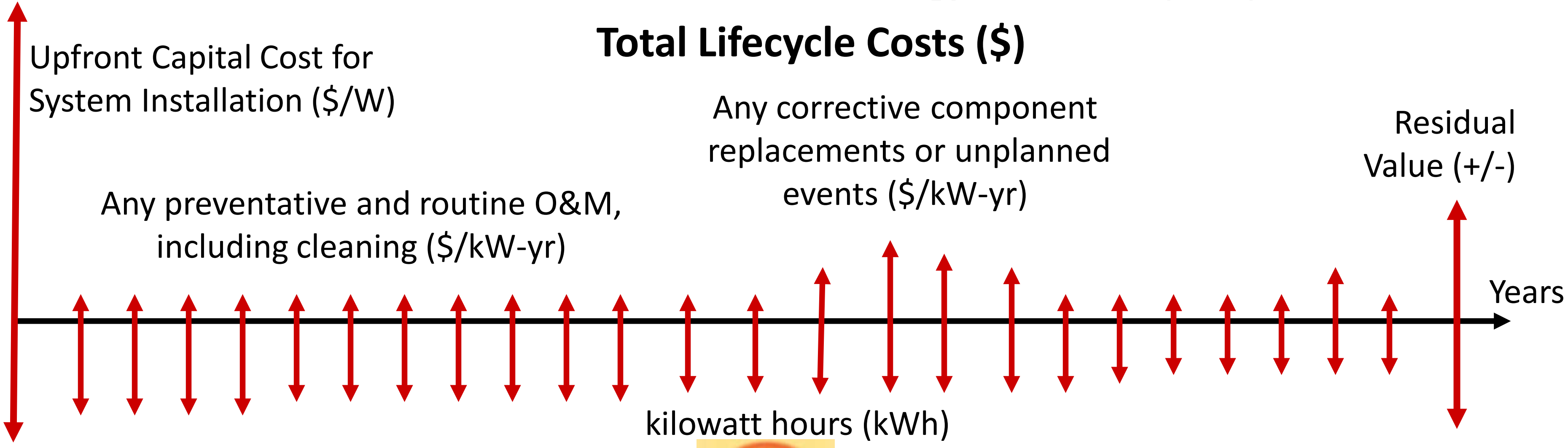
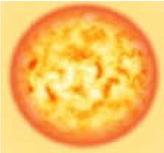
# Introduction to *Pro Forma* Analysis of PV Projects

$$\text{LCOE (\$/kWh)} = \frac{\text{Total Life Cycle Costs (\$)}}{\text{Total Lifetime Energy Production (kWh)}}$$

**Total Lifecycle Costs ($)**



**Benefits Provided by the Sun: Total Lifetime Energy Production (kWh)**

For an overview of the NREL System Advisor Model (SAM) approach to calculating LCOE, please see: Short, W., D.J. Packey, and T. Holt. 1995. *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*. NREL/TP-462-5173. Available online: http://www.nrel.gov/docs/legosti/old/5173.pdf.

# Introduction to *Pro Forma* Analysis of PV Projects

$$\text{LCOE (\$/kWh)} = \frac{\text{Total Life Cycle Cost (\$/W)}}{\text{Total Lifetime Energy Production (kWh/kW)}}$$

**Nameplate Efficiency**

**Module, Inverter, BOS Costs**

**System Architecture**

**Reliability and Durability**

**Financing and Incentives (MACRS and Monetizing the ITC)**

**Recycling Or Repowering?**

$$= \frac{\text{Installation Cost} + \sum_{n=1}^{N} \frac{\text{Annual O\&M Costs}_n}{(1+\text{Discount Rate})^n} - \sum_{n=1}^{N} \frac{\text{Depreciation}_n}{(1+\text{Discount Rate})^n} \text{x(Tax Rate)} - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^n}}{\sum_{n=1}^{N} \frac{\text{Initial kWh/kW}}{(1+\text{Discount Rate})^n} \text{x(1- System Degradation Rate)}^n}$$

Lower degradation rate equals more lifetime kWh

**'Capacity Factor' Term:**
**(System Location, Orientation, Tracking, Bifaciality, Temperature Coefficient, Low light level efficiencies, etc.)**

The underlying discount rate may also be influenced by the PV module and system reliability.

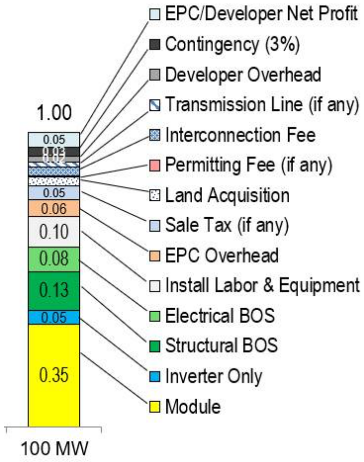
# Bottom-Up Capital Costs Accounting of PV System Installations







| | Poly | Ingot | Wafer | Cell | Module | Module Total | Inverter | Field 1X Tracking* | Total |
|---|---|---|---|---|---|---|---|---|---|
| **U.S. pricing** | $0.05/W | $0.03/W | $0.05/W | $0.09/W | $0.13/W | **$0.35** | **$0.05** | **$0.60** | **$1.0/W** |
| **CapEx ($/kg or $/W, including facilitation)** | Siemens $30-40/kg FBR $35-45/kg | Czochralski $0.08/W Multi $0.04/W | $0.03/W | $0.10/W | $0.07/W | | | | |
| **Minimum Scale** (Annual Production Volume) | 20,000 MT | 5 GW | 5 GW | 2 GW | 500 MW | | | | |




*Includes categories shown but excludes: Construction financing, O&M, monitoring, site security, and sub station transformers (if needed).

**Bottom-up system costs analysis with battery storage is also available.**

For most recent published bottom-up costs analysis, please see:

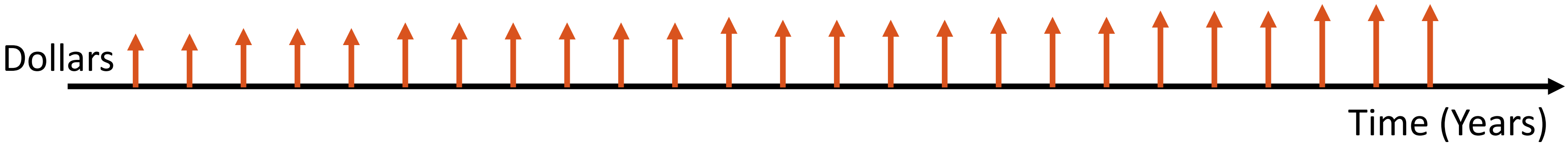

(1) M Woodhouse, B Smith, A Ramdas, and R Margolis "Crystalline Si Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Roadmap", NREL technical report, In Press, 2019

(2) R Fu, D Feldman, and R Margolis "U.S. Solar Photovoltaic Cost Benchmark: Q1 2018", NREL technical report available online: https://www.nrel.gov/docs/fy19osti/72399.pdf

# Bottom-Up O&M Costs Accounting for PV Systems

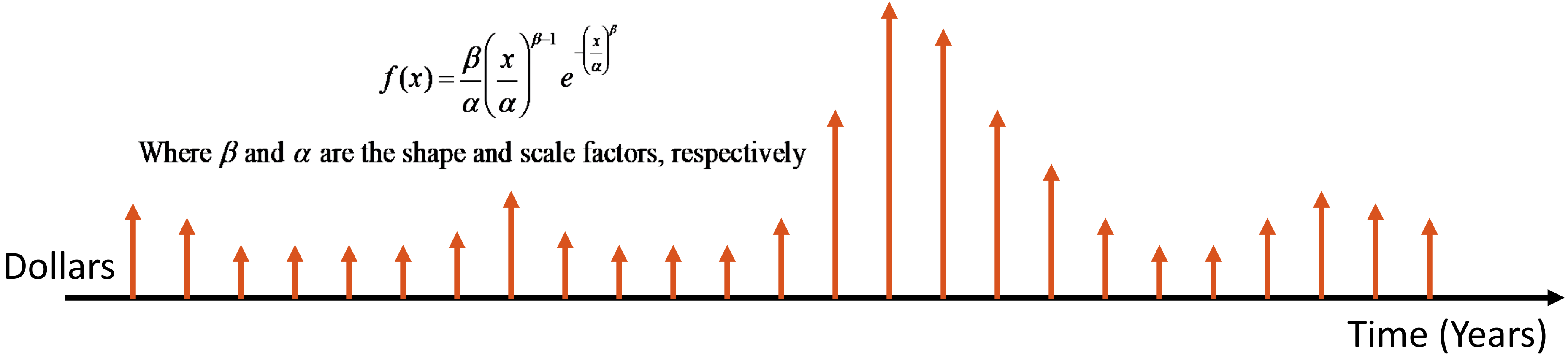
## Preventative Maintenance: Relatively constant cash flow structure

- Module cleaning, system inspection, and planned parts replacement




## Corrective Maintenance: A Weibull distribution cash flow structure

- Unplanned module and inverter replacements




$$f(x)=\frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1}e^{-\left(\frac{x}{\alpha}\right)^{\beta}}$$

Where $\beta$ and $\alpha$ are the shape and scale factors, respectively

# Bottom-Up O&M Costs Accounting for PV Systems

## Preventative Maintenance (Mostly Planned)

- Vegetation management
- Wildlife countermeasures (variable and planned)
- Site maintenance (variable and planned)
- System monitoring, inspection, and security
- Module cleaning
- Tracker lubrication

## Corrective Maintenance (Mostly Unplanned)

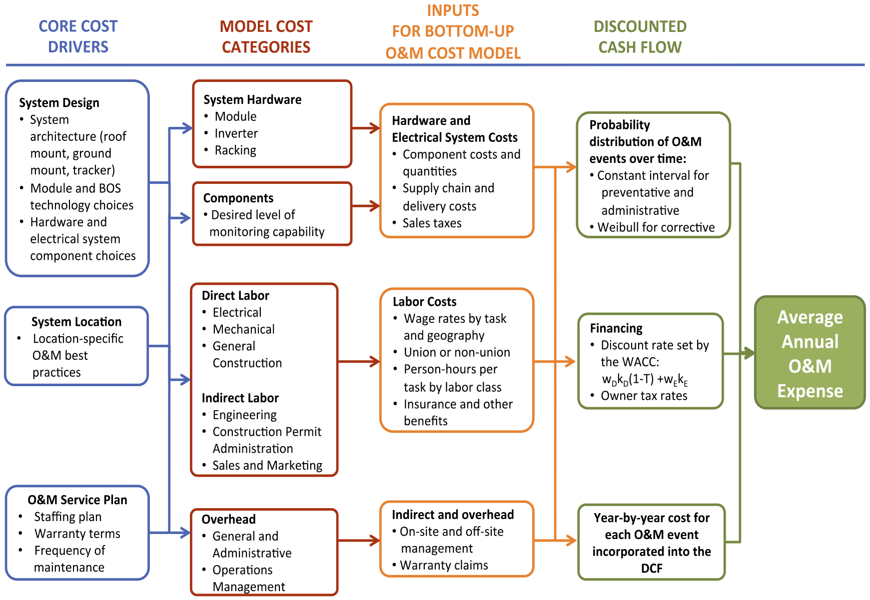
- Reset electrical disconnects and replace electrical components (variable)
- Replace parts or entire units of modules, trackers, and inverters (variable and planned)

## Condition-Based Maintenance

- Active monitoring
- Equipment replacement (variable and planned)

## Operations Administration (Planned)

- Payment of O&M
- Administration of project cash flows to bondholders and equity owners
- Accounting and taxes
- Warranty enforcement

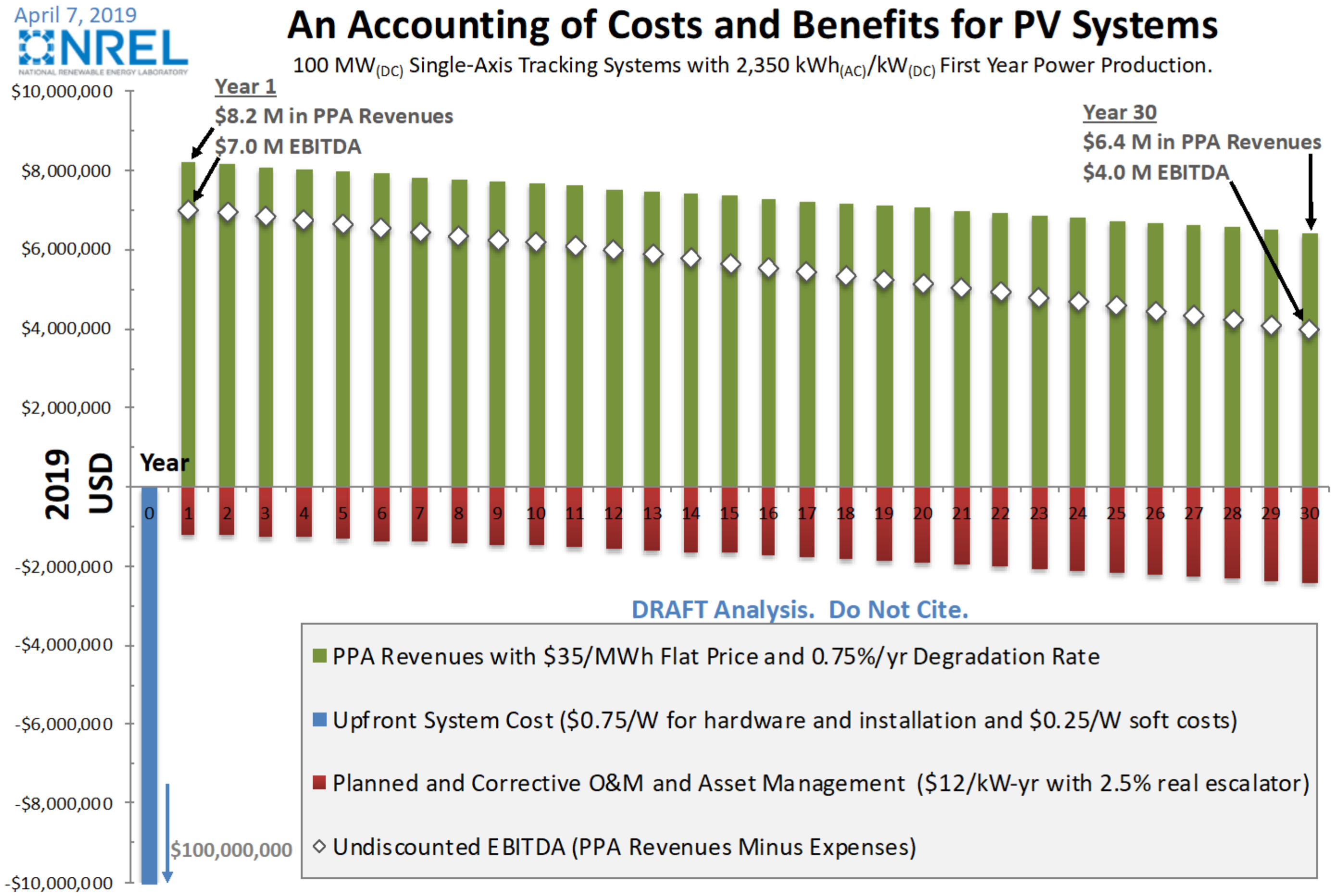


# Bottom-Up O&M Costs Accounting for PV Systems

**NREL and Sandia Cost Model for Average Annual Levelized O&M Expenses by Sector ($/kW-yr)**

| | Residential | Commercial | Fixed-Tilt Utility | One-Axis Tracking |
|---|---|---|---|---|
| **Operations administration (planned)** | $2.6 | $3.6 | $2.8 | $2.8 |
| **Inverter-related actions and component replacement (corrective)** | $18.3 | $5.5 | $3.8 | $3.8 |
| **Module replacement (corrective)** | **$0.8** | **$0.8** | **$0.9** | **$0.9** |
| **Component parts replacement (planned)** | $3.2 | $0.5 | $0.6 | $0.6 |
| **System inspection and monitoring (planned)** | $5.5 | $2.5 | $1.7 | $2.3 |
| **Module cleaning and vegetation management (planned)** | $0.8 | $2.7 | $3.3 | $3.3 |
| **Average O&M expense without escalator ($/kW-yr)** | **$31.2** | **$15.6** | **$13.1** | **$13.7** |

# 100 MW$_{(DC)}$ Single Owner Undiscounted Cash Flows and EBITDA




The mean net capacity factor (CF) for PV projects installed in 2016 and measured in 2017 was 26.8%

- Corresponds to 2,348 kWh$_{(AC)}$/kW$_{(DC)}$
- The range in annual mean CF since 2013 has been 26.5—27.1%
- 78% market share for 1-axis tracking in 2017

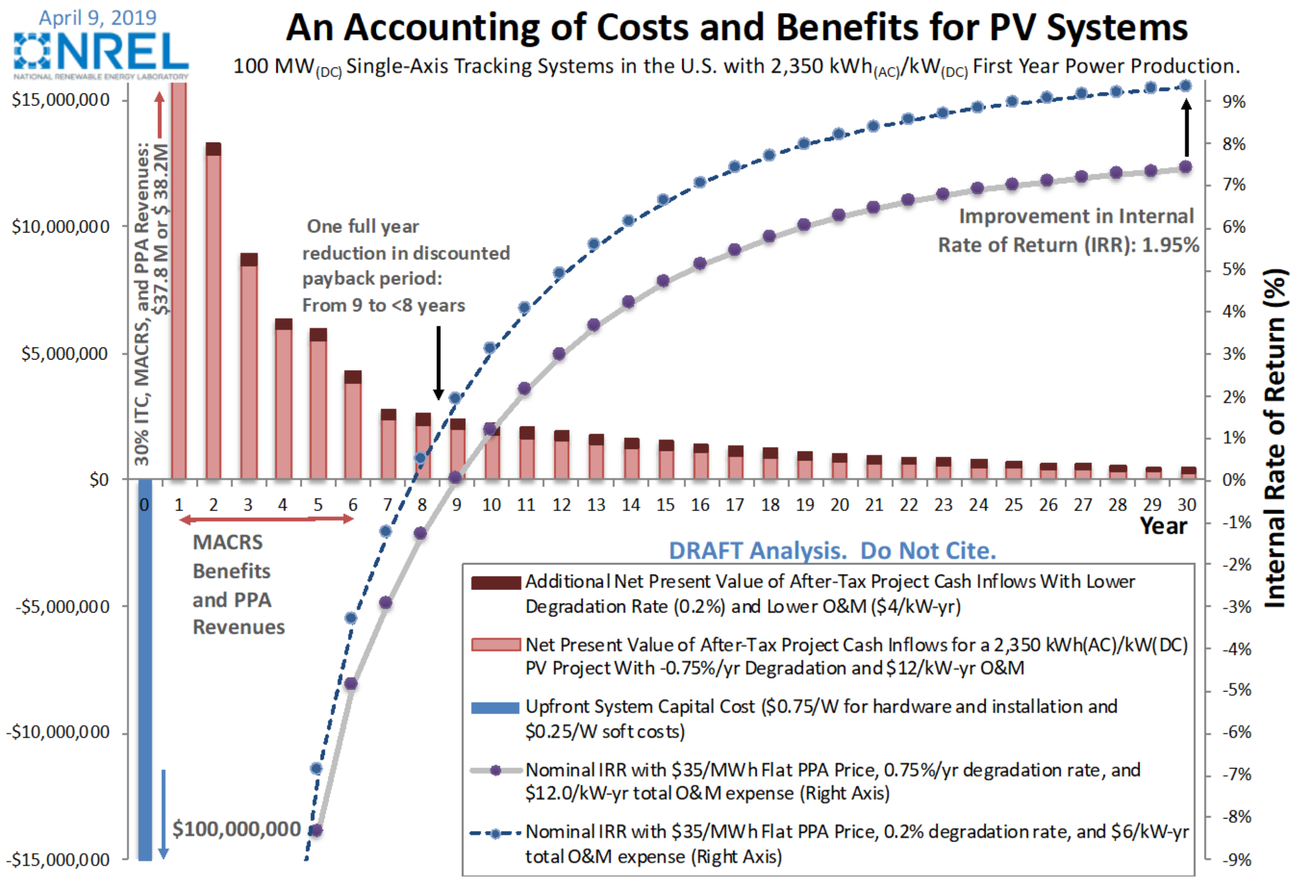
PPA revenues are the product of PPA price times energy yield

- The average levelized price of PPA's signed in 2017 was $41/MWh (Compiled data by Bolinger and Seel (LBNL) of FERC Electric Quarterly Reports)
- Revenues decline over time according to the system degradation rate

Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA):

- Declines over time according to the system degradation rate and O&M expenses

# 100 MW$_{(DC)}$ Single Owner Unlevered After-Tax Project Returns and IRR



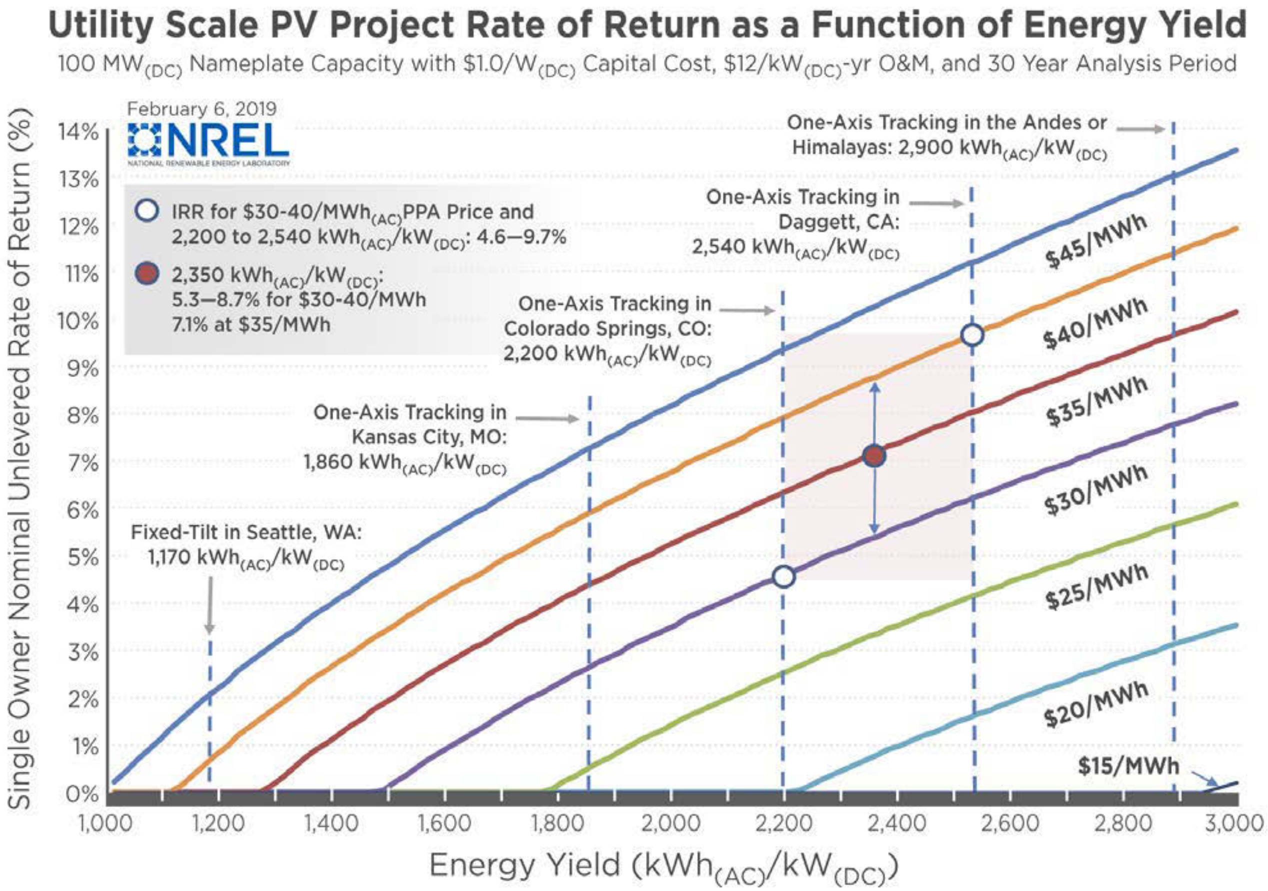

The SunShot reliability goals call upon reducing degradation rates to 0.20%/yr and cutting O&M expenses by two-thirds:

- Improves IRR by 195 bps and takes a full year off the discounted payback period.
- Provides greater system lifetime value:

| **Total Net Present Value (2019 USD)**<br>**7.4% nominal rate of return, \$1.0/W$_{(DC)}$ capital cost, \$35/MWh$_{(AC)}$ flat PPA price, and 2,350 kWh$_{(AC)}$/kW$_{(DC)}$ solar resource.** | |
|---|---|
| PV system with 0.75%/yr degradation rate and \$12/kW$_{(DC)}$ O&M expense | **\$0** |
| **PV systems with SunShot 2030 performance:**<br>0.2%/yr degradation rate<br>\$4/kW$_{(DC)}$ O&M expense | **\$10.6 M**<br>(100 MW$_{(DC)}$)<br>**\$636 M**<br>(2017 U.S. utility-scale PV market: 6 GW$_{(DC)}$) |

Achieving a higher IRR at a given energy yield and PPA price also supports the movement for PV stakeholders to take on even lower PPA prices and lower energy yields!

# The Impact of Energy Yield on PV Project Financial Metrics




Both PV project LCOE and IRR entail *pro forma* discounted cash flow analysis:

– At 1,170 $kWh_{(AC)}/kW_{(DC)}$, only the $40 and $45/MWh projects are profitable (although the rate of return is quite small, at less than 2%)

– At 1,860 $kWh_{(AC)}/kW_{(DC)}$, the $25 - $45/MWh projects are profitable

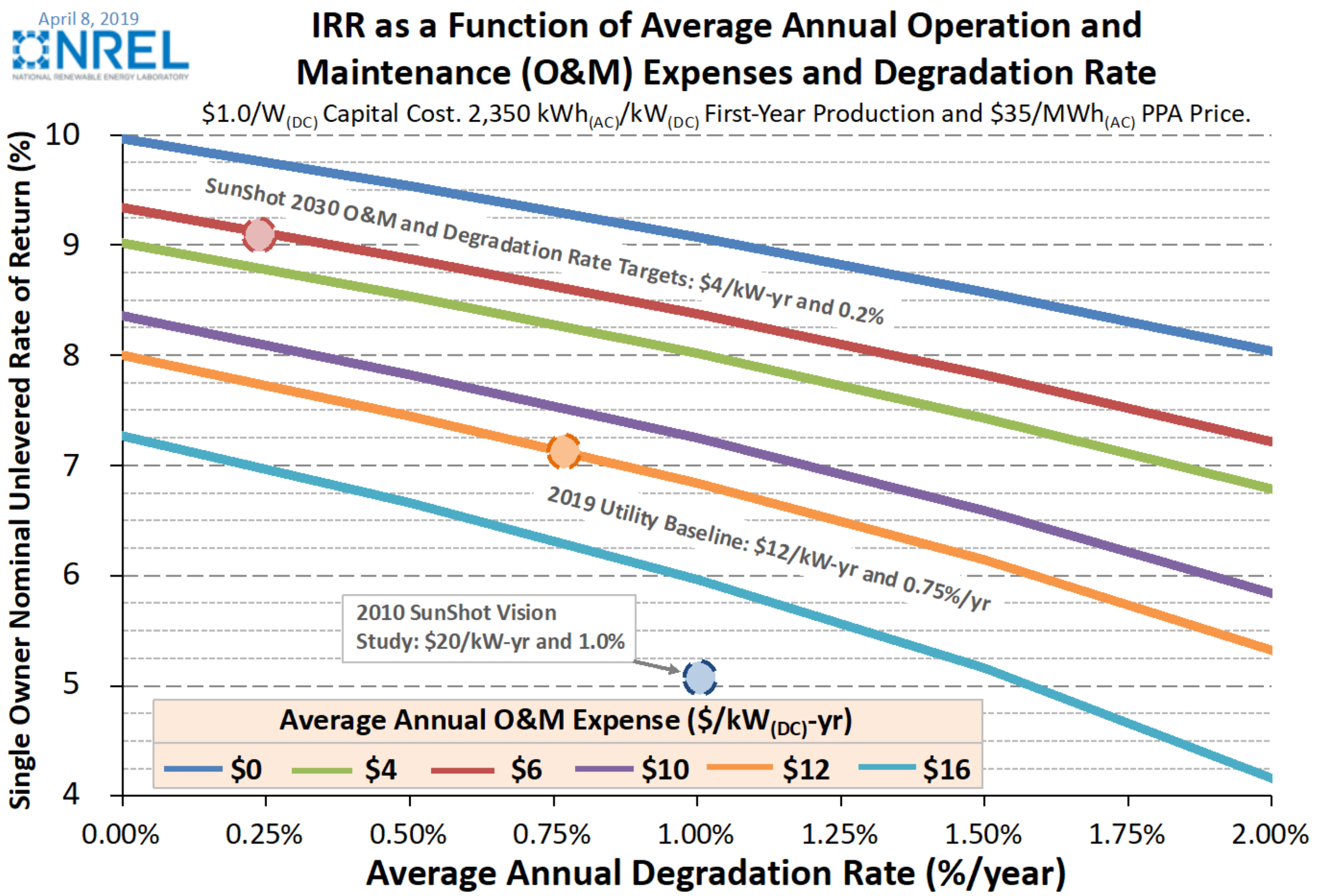
– At 2,200 $kWh_{(AC)}/kW_{(DC)}$, all projects greater than $20/MWh are profitable

– For ≥ 3,000 $kWh_{(AC)}/kW_{(DC)}$, all projects are profitable at the given PPA prices

With a **6% nominal discount rate** assumption:

| Solar resource | Nominal LCOE (Minimum Sustainable PPA price) |
|---|---|
| 1,170 $kWh_{(AC)}/kW_{(DC)}$ | $64/MWh |
| 1,860 $kWh_{(AC)}/kW_{(DC)}$ | $40/MWh |
| 2,200 $kWh_{(AC)}/kW_{(DC)}$ | $34/MWh |
| **2,350 $kWh_{(AC)}/kW_{(DC)}$** | **$32/MWh** |
| 2,540 $kWh_{(AC)}/kW_{(DC)}$ | $30/MWh |
| 2,900 $kWh_{(AC)}/kW_{(DC)}$ | $26/MWh |

# Top Down Impact of O&M on Utility-Scale PV Project IRR




| Opportunity | Impact |
|---|---|
| Reduce O&M expenses from $12/kW-yr to $6/kW-yr at 0.75% degradation | Improve IRR by 113 bps |
| Reduce O&M expenses from $12/kW-yr to $6/kW-yr at 0.20% degradation | Improve IRR by 105 bps |
| Reduce degradation rate from 0.75% to 0.20% at $12/kW-yr | Improve IRR by 63 bps |
| Reduce degradation rate from 0.75% to 0.20% at $6/kW-yr | Improve IRR by 55 bps |
| **Achieve SunShot 2030 reliability goals** | **Improve Project IRR by 195 bps** |

# Major Failure Modes for PV Module Technologies

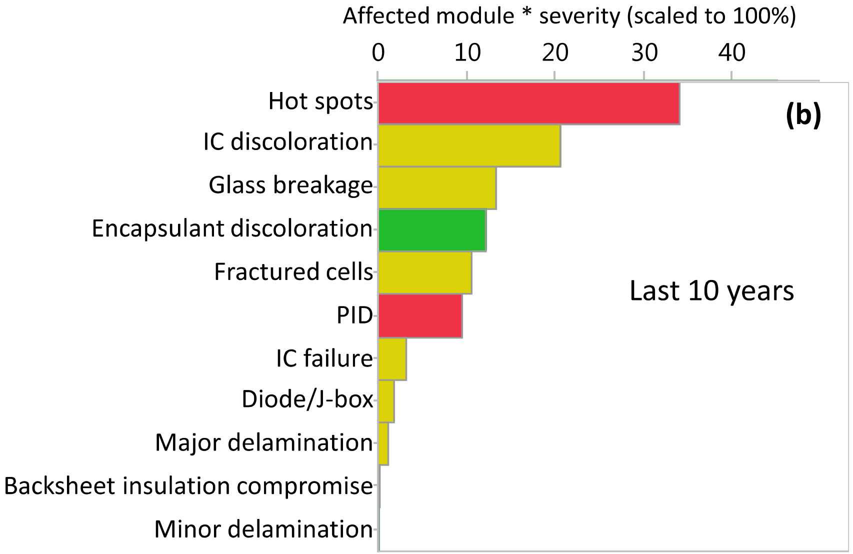
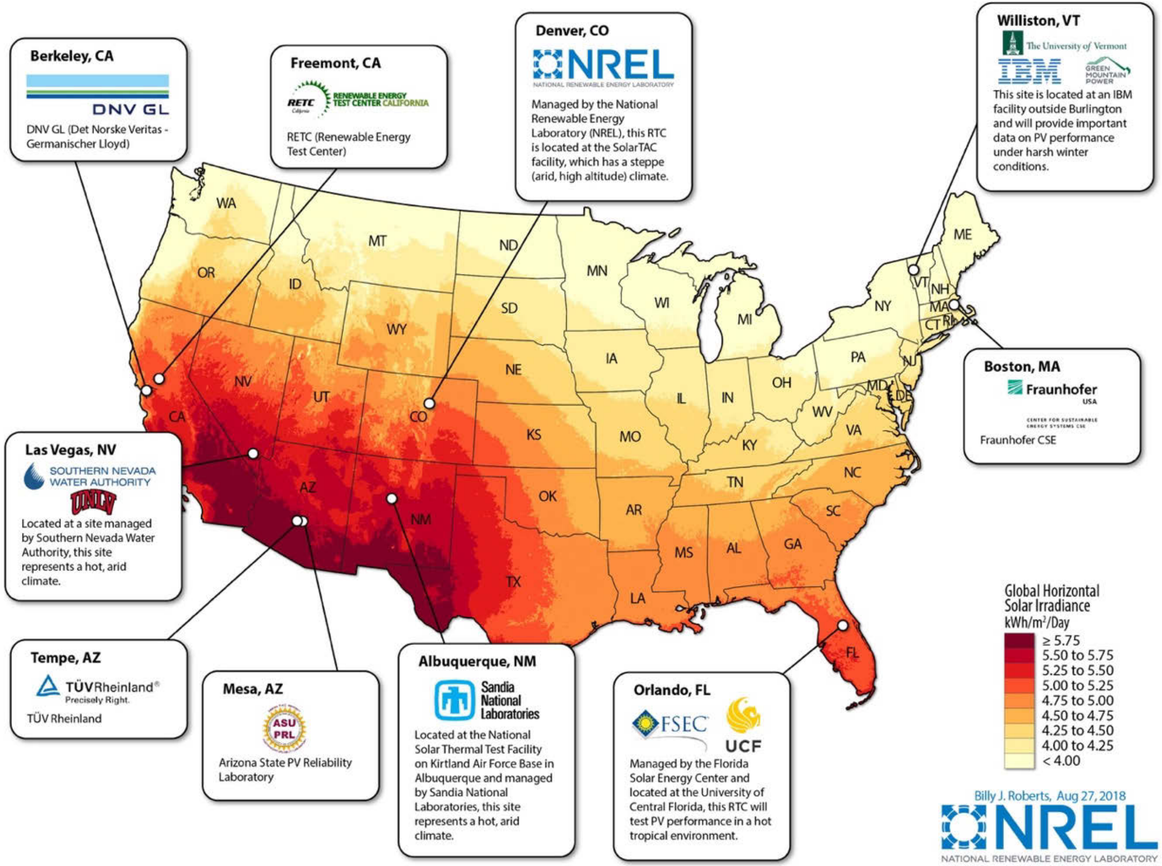



Figure source: D Jordan, T J Silverman, J H Wohlgemuth, S R Kurtz, and K T vanSant "Photovoltaic failure and degradation modes", PIP, 2017.

| Opportunity | Impact Upon 2019 Baseline Utility Scale PV Projects |
|---|---|
| Reduce O&M expenses from \$12/kW-yr to \$11.5/kW-yr at 0.75%/yr degradation | Improve IRR by 10 bps<br>Lower LCOE by \$0.30/MWh$_{(AC)}$<br>(7.4% discount rate) |
| Reduce O&M expenses from \$12/kW-yr to \$11.5/kW-yr at 0.20%/yr degradation | Improve IRR by 9 bps<br>Lower LCOE by \$0.29/MWh$_{(AC)}$<br>(7.4% discount rate) |

# Presentation Outline

# Indoor and Outdoor PV Testing Centers in the United States




Outdoor DOE PV Lifetime and Proving Ground Sites:

- NREL
- Sandia
- Las Vegas, NV
- Orlando, FL
- Williston, VT

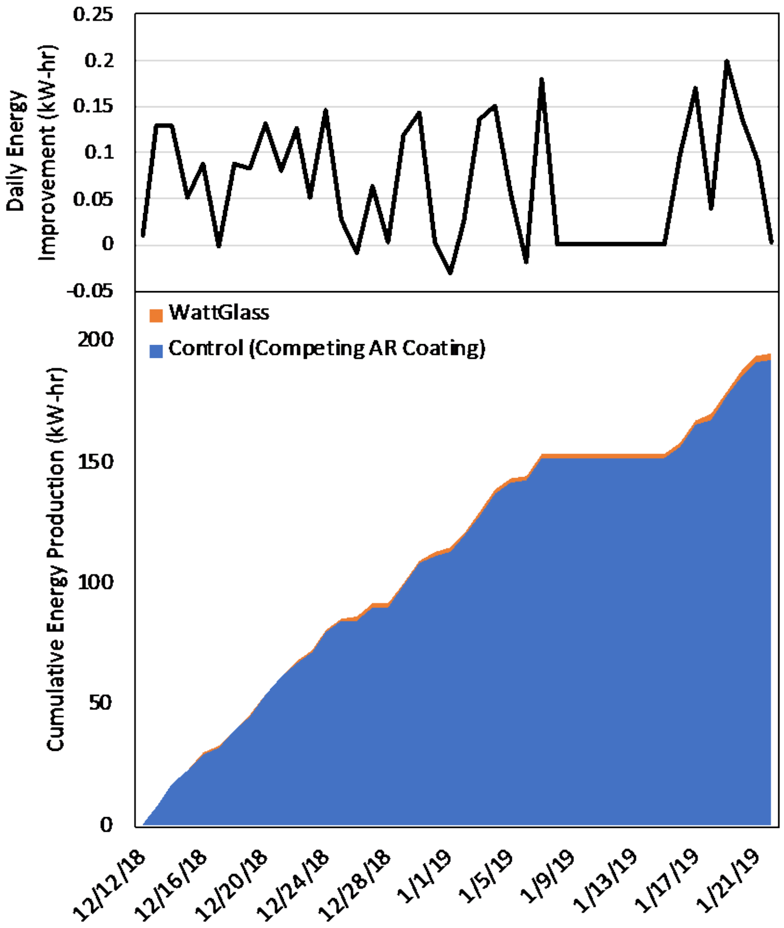
Private Independent Testing Labs (Indoor and Outdoor):

- DNV GL
- RETC
- Fraunhofer CSE
- TUV Rheinland

Indoor University Testing Labs:

- Arizona State

# Improving energy yield with new coatings technologies



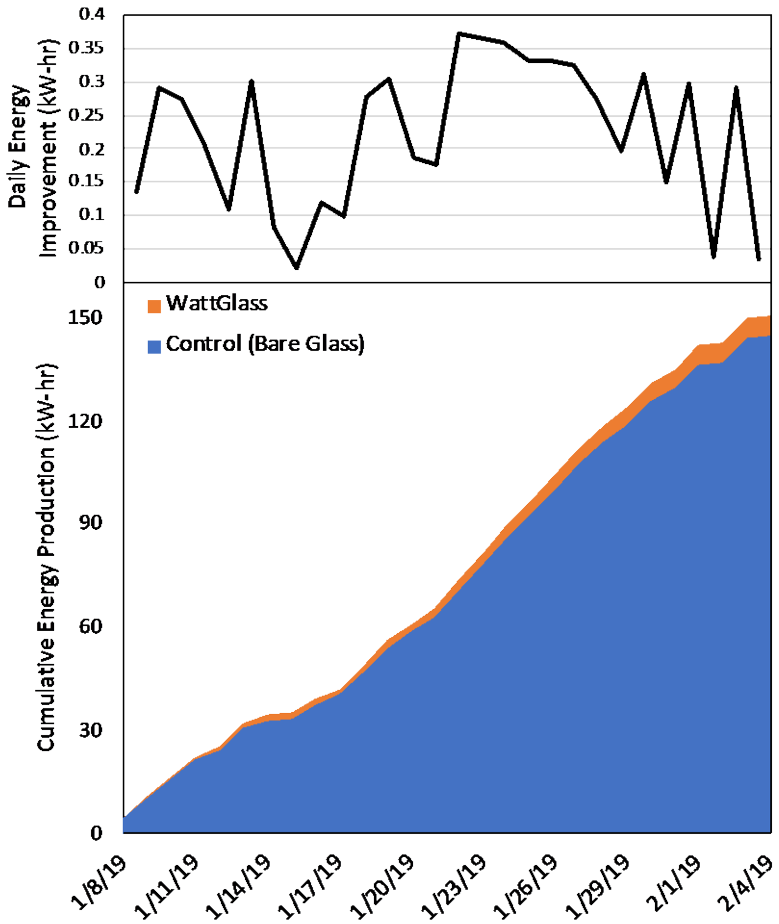

Data from ~3kW of panels installed in Albuquerque, NM

Experimental modules packaged with WattGlass' AR coating
Control modules packaged with a competing AR coating

From 12/12/18 – 1/21/19, ~1.4% increase in cumulative energy production

Site maintenance work from 1/8/18 – 1/15/19, so no data in that timeframe

# Improving energy yield with new coatings technologies



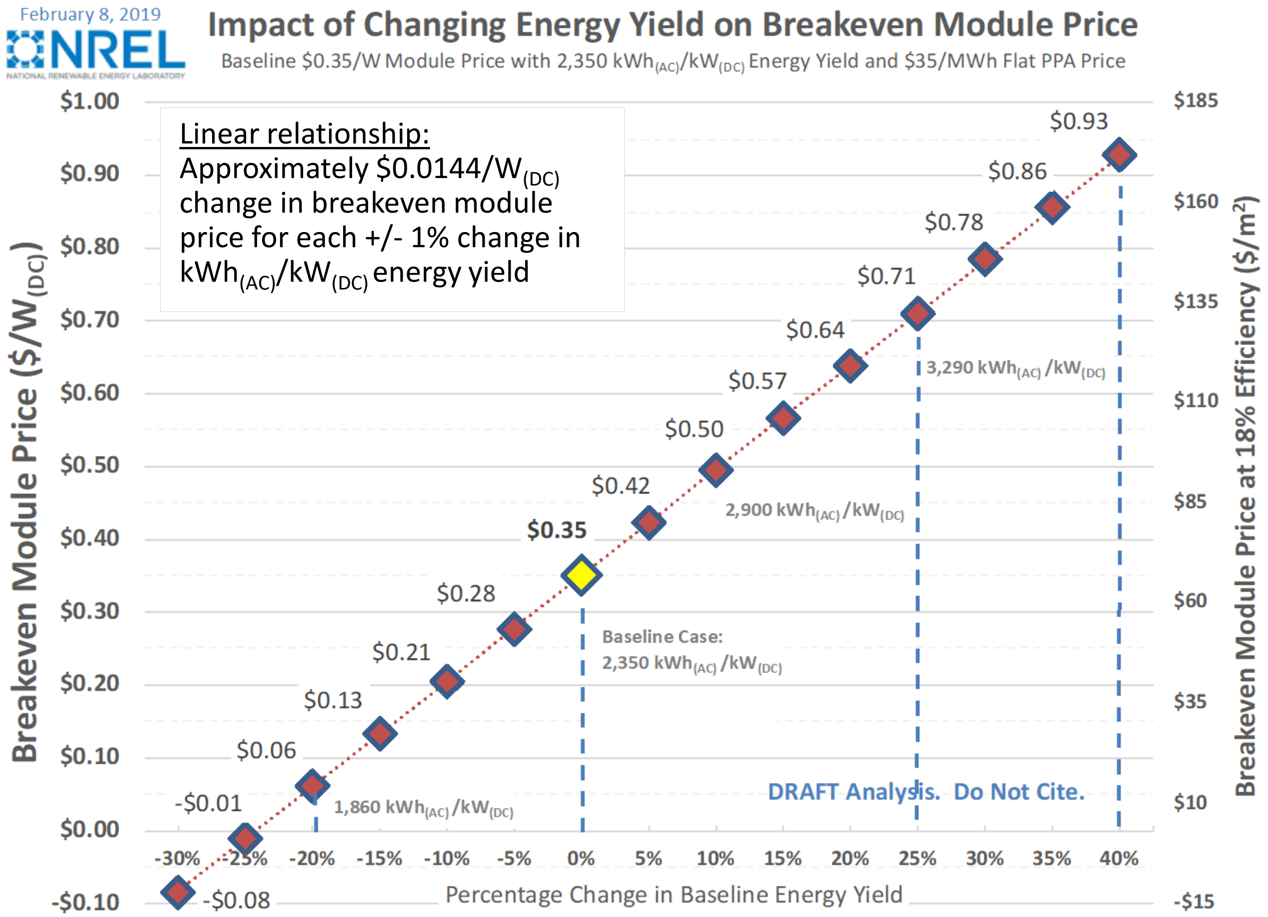

Data from ~3kW of panels installed in Las Vegas, NV

Experimental modules packaged with WattGlass' AR coating

Control modules packaged with bare glass

From 1/8/19 – 2/4/19, ~4.1% increase in cumulative energy production

# The Impact of Energy Yield on Breakeven Module Price




Improvements in energy yield might justify a module price premium.

| Improvement in Energy Yield | Breakeven Price Premium for Self-Consistent IRR (\$/$W_{(DC)}$) | |
|---|---|---|
| 1% | **\$0.0144/W** | |
| | \$2.6/$m^2$ 18% efficiency | \$3.6/$m^2$ 25% efficiency |
| 5% | **\$0.0720/W** | |
| | \$13/$m^2$ 18% efficiency | \$18/$m^2$ 25% efficiency |

Reducing O&M expenses (*e.g.*, reducing module cleaning) might also support a module price premium.

# Presentation Outline

# Methodology and Approach for Bottom-Up Cost Modeling

## MODULE TESTING PROTOCOLS

### IEC-61215

**Potentially Replaced by C-AST**

- Visual Inspection
- Maximum power determination
- Insulation test
- Measurement of temperature coefficients
- Measurement of NMOT
- Performance at STC and NMOT
- Performance at low irradiance
- Outdoor exposure test
- Hot spot endurance test
- UV preconditioning test
- Thermal cycling test
- Humidity free test
- Damp heat test
- Robustness of determinations
- Wet leakage current test
- Static mechanical load test
- Hail test
- Bypass diode testing
- Stabilization/Light induced stabilization

### Other Desired Testing

- PID corrosion/extended PID testing
- Thermal cycling up to 500 cycles for 25 year predictions
- Delamination test
- Snail trail/corrosion/delamination testing
- Light enhanced temperature induced degradation testing
- In situ monitoring of power
- **Combined Accelerated Stress Testing (C-AST)**

## TESTING COST OF OWNERSHIP (COO) INPUTS

### SEMI E-35 Format

- Production and throughput (Uptime and scheduled and unscheduled downtime)
- Equipment prices and relevant depreciation schedules
- Floor space
- Materials and consumables (Lamps)
- Utilities (Electricity, compressed air, cooling water)
- Waste disposal (Waste water and exhaust air)
- Labor: Person-hours per task by labor class (Operators, Supervisors, Engineering, and Maintenance)
- Cost of yield loss

### Location Specific Costs Considerations

- Wage rates by task
- Electricity rates

## GAAP AND IFRS ACCOUNTING STANDARDS

### Variable (cash) costs within the cost of goods sold (COGS)

- Input materials
- Direct labor: Skilled and unskilled wages and benefits
- Electricity
- Maintenance of equipment and facilities

### Fixed (non cash) costs

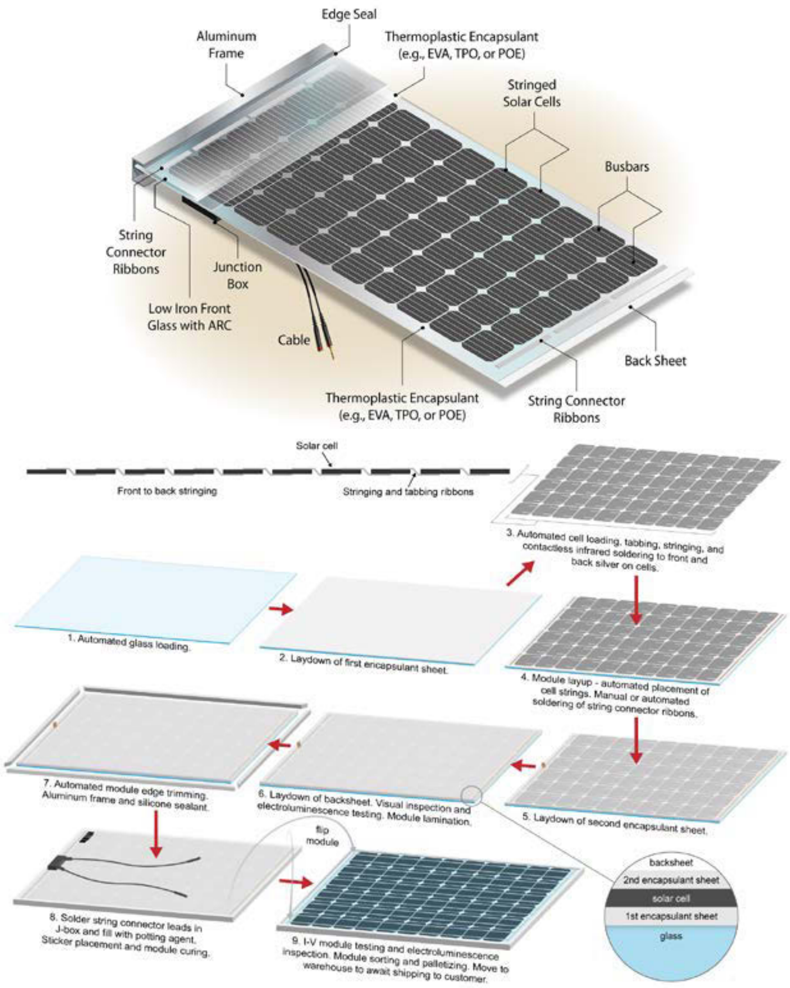
- Equipment
- Building and facilitation

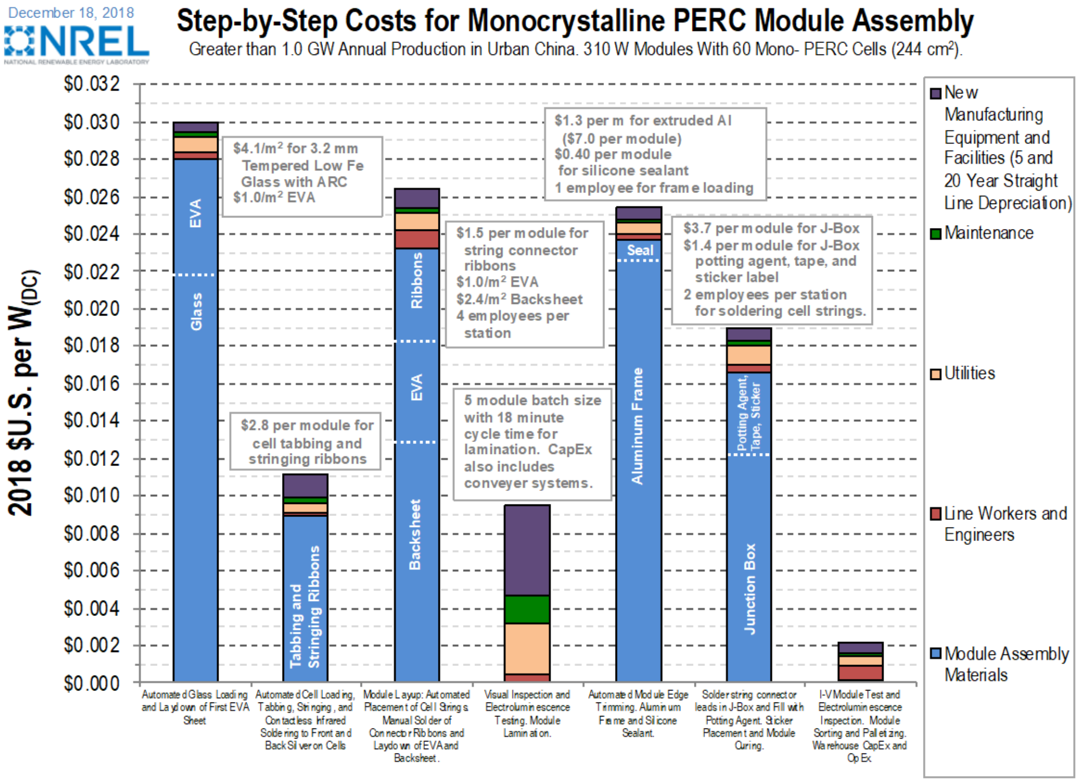
### Research and Development (R&D) and Sales, General, and Administration (S, G, &A)

- Organization management
- Human resources
- Accounting staff
- Technology sales, marketing, and promotion to customers
- Future technology research and development

## Total Module Testing Costs

# Process Flow and Costs by Step for Traditional Module Assembly

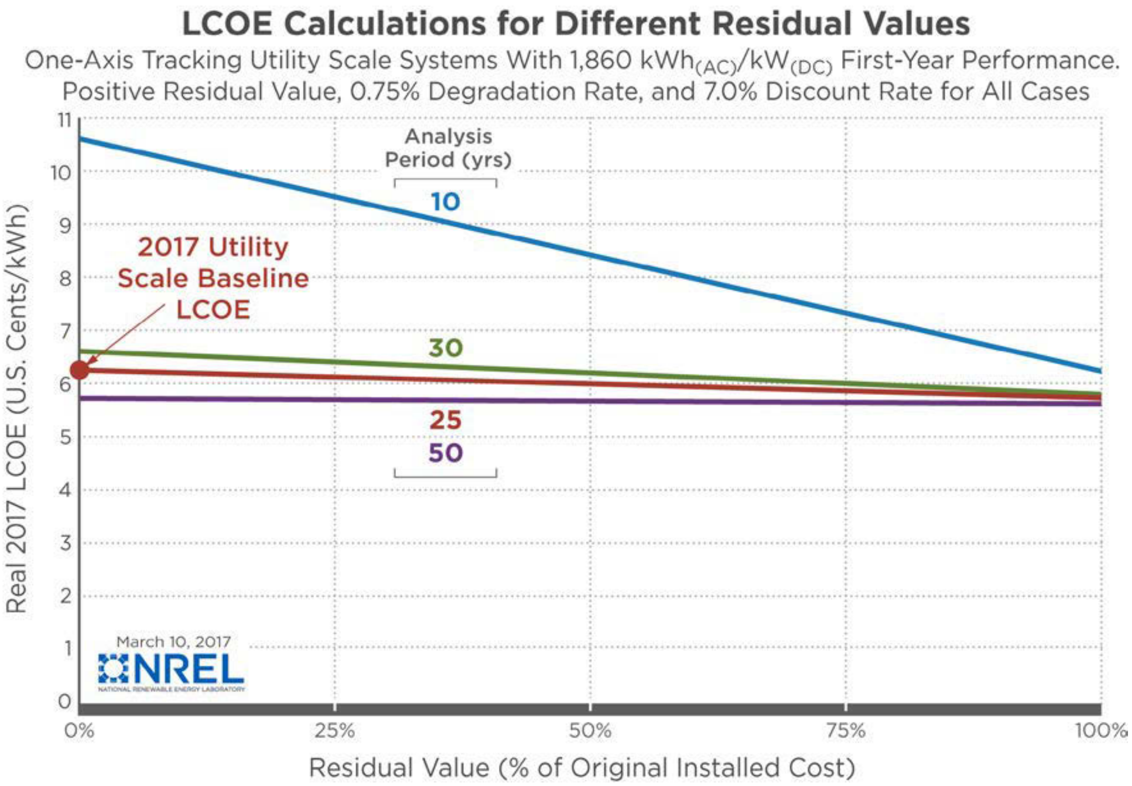



Source of Figures: M Woodhouse, B Smith, A Ramdas, and R Margolis "Economic Factors of Production Affecting Current and Future Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing"

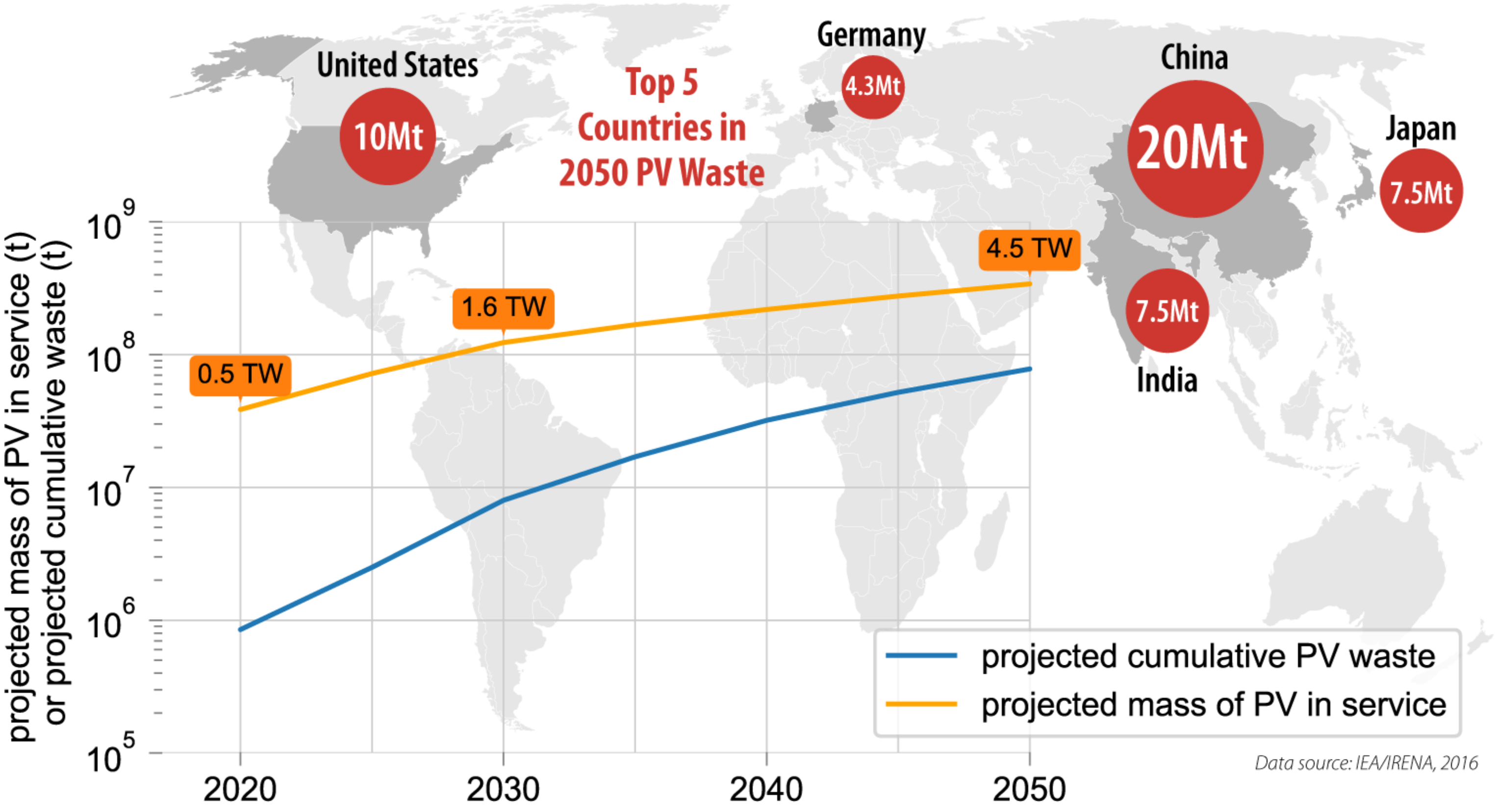
# Presentation Outline

# Top Down Impact of Residual Value on LCOE



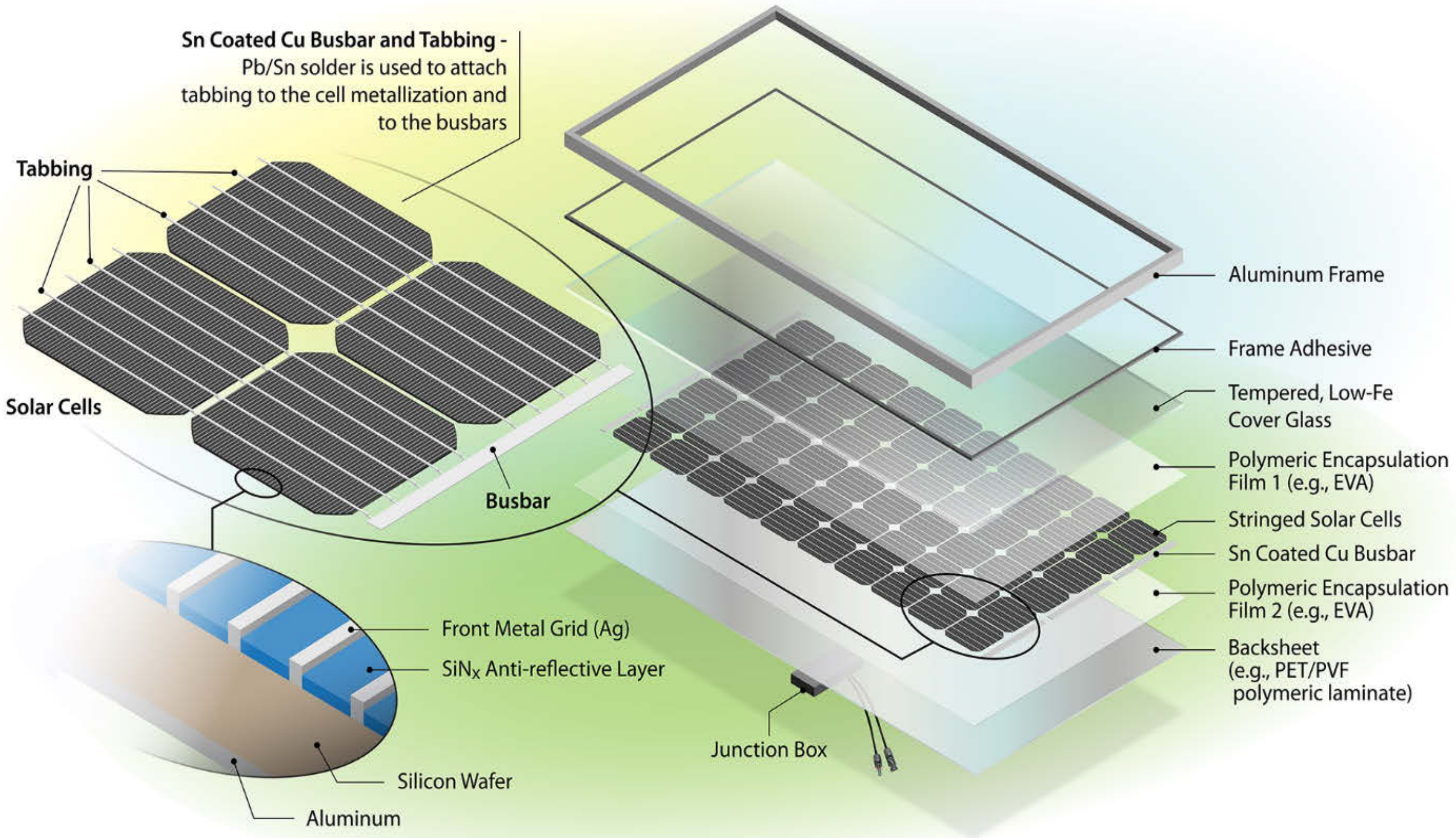

| **Analysis Period (years)** | **10** | **25** | **30** | **50** |
|---|---|---|---|---|
| **Equivalent $/W Value in Initial System Cost** | | | | |
| **Residual value change from 0% to 50% ($/W)** | 0.26 | 0.09 | 0.06 | 0.02 |
| **Residual value change from 0% to 100% ($/W)** | 0.52 | 0.18 | 0.13 | 0.04 |

# The Scale of Responsibility for PV Module Waste Streams



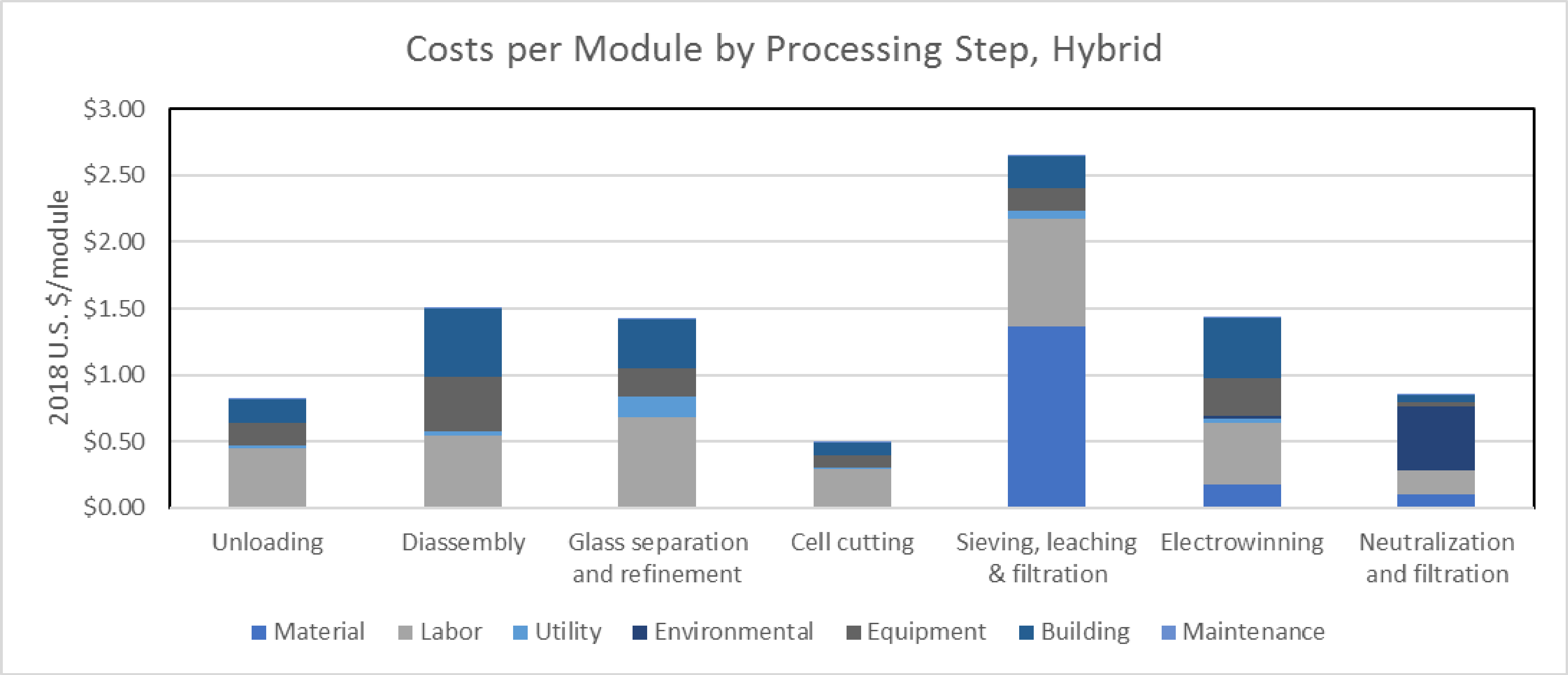

Source of figure: G Heath, T Silverman, H Cui, T Remo, M Kempe, M Deceglie, D Ravikumar, P Sinha, T Barnes, and A Wade "Recycling R&D to Bring PV Modules into the Circular Economy", In preparation for submission to *Nature Energy*

# PV Module Recycling



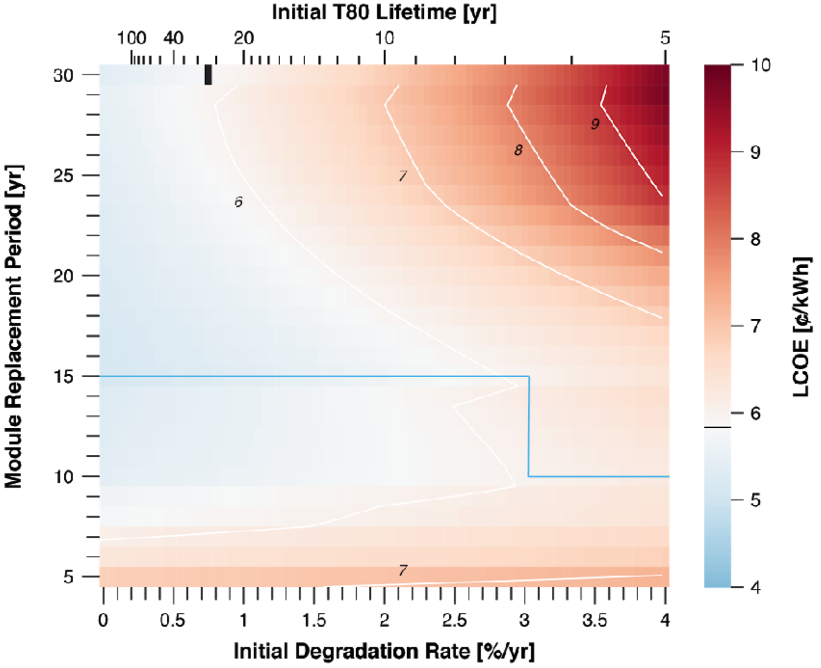

Source of figure: G Heath, T Silverman, H Cui, T Remo, M Kempe, M Deceglie, D Ravikumar, P Sinha, T Barnes, and A Wade "Recycling R&D to Bring PV Modules into the Circular Economy", In preparation for submission to *Nature Energy*

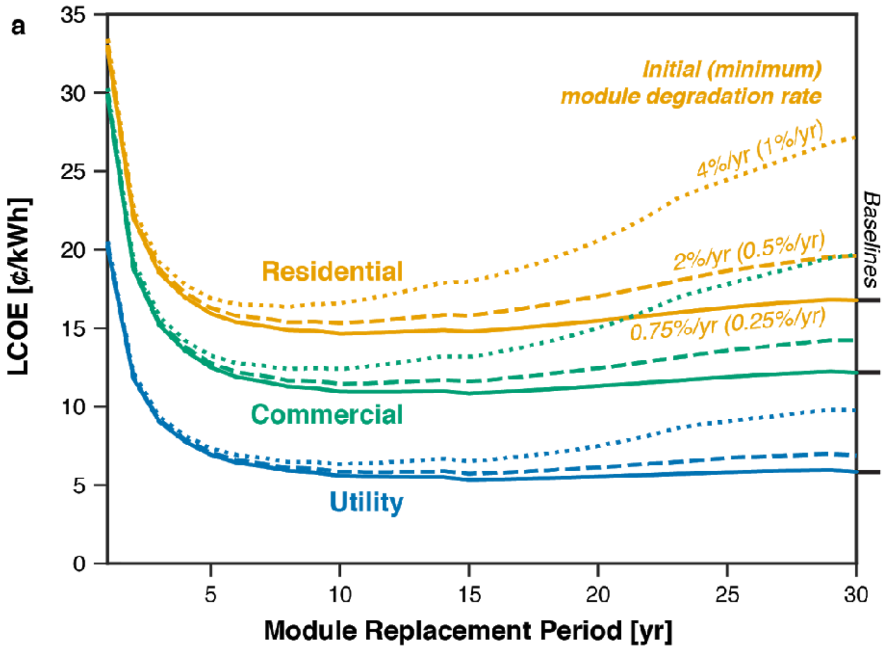
# Developing PV Module Recycling Roadmap


Source of figure: G Heath, T Silverman, H Cui, T Remo, M Kempe, M Deceglie, D Ravikumar, P Sinha, T Barnes, and A Wade "Silicon for PV Recycling Roadmap", In preparation

# Repowering Economics




- LCOE as a function of module replacement period and degradation rates
- Source of figure: “J Jean, M Woodhouse, and V Bulovic, “Lower the cost of solar energy with periodic module replacemnts”, submitted to *Nature Energy*

# Presentation Outline

# Conclusions and Proposed Next Steps

- We have identified some critical gaps in understanding that would be helpful for PV project financial models. These include specific correlations between the causes of field failure and their overall impact upon system degradation and O&M expenses.

  **Next Steps**: To work with DuraMAT awardees to gather state-of-the-art knowledge relevant to these questions. It is also hoped the DataHub might provide such data in the future.

- We have identified further work that is needed in the areas of bottom-up O&M and module manufacturing and testing cost modeling. For O&M, we need to somehow correlate field failure data (or at least performance modeling) to project cash flow expectations during each year of the analysis period. In bottom-up module cost modeling, within the near-term we need to examine the cost premiums for depositing new coatings on glass and for better manufacturing process control procedures that reduce hot spots and cracked cells.

  **Next Steps**: To work with DuraMAT awardees to gather state-of-the-art knowledge relevant to these questions, and to provide any analysis that might be helpful to quantify the overall value proposition of specific research projects.

# Thank You

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