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On the Costs and Value of Enhanced PV Module Testing Protocols

Michael Woodhouse[(1)], Tristan Erion-Lorico[(2)], and Peter Hacke[(1)]

(1) NREL Strategic Energy Analysis Center (SEAC)
(2) PV Evolution Labs (PVEL)
(3) NREL Reliability Engineering Group

Presentation Outline

1. **Introduction (Teresa Barnes, DuraMAT Director, 5 minutes)**
2. Module Underperformance Case Study (Tristan, 15 minutes)
3. Economic Impacts to a Portfolio of PV Projects (Mike, 15 minutes)
4. Overview of C-AST (Peter, 5 minutes)
5. Bottom-Up Cost Modeling of C-AST (Mike, 10 minutes)
6. Conclusions, Next Steps, and Questions (Mike, 10 minutes)

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MAKE DATA MATTER.

MODULE UNDERPERFORMANCE

A CASE STUDY IN WHAT CAN GO WRONG

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PVEL is the Independent Lab for the Downstream Solar Market

Global

300+ downstream partners worldwide with 30+GW of annual buying power

Comprehensive

Testing for every aspect of a PV project from procurement to O&M

Experienced

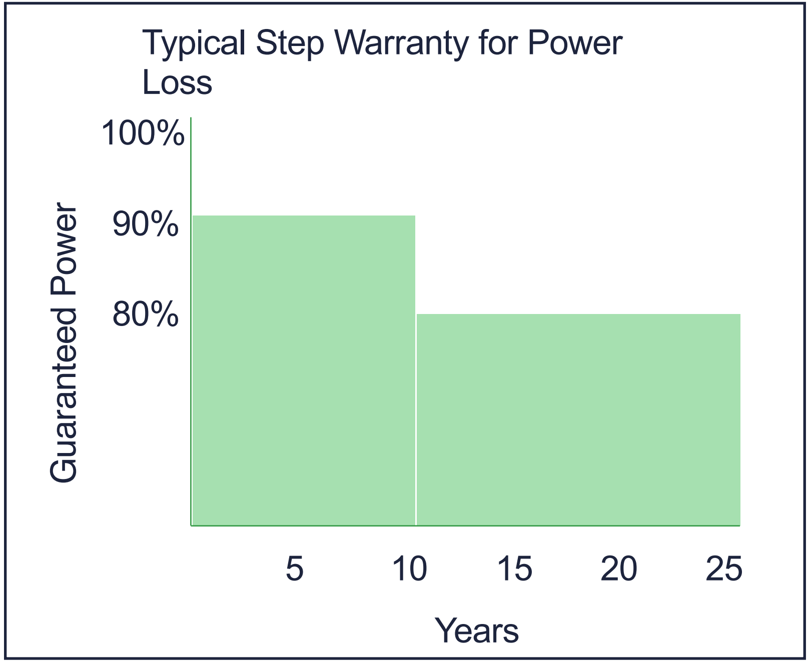
Pioneered bankability testing for PV products nearly a decade ago

Market-driven

Continuously refining test programs to meet partner needs

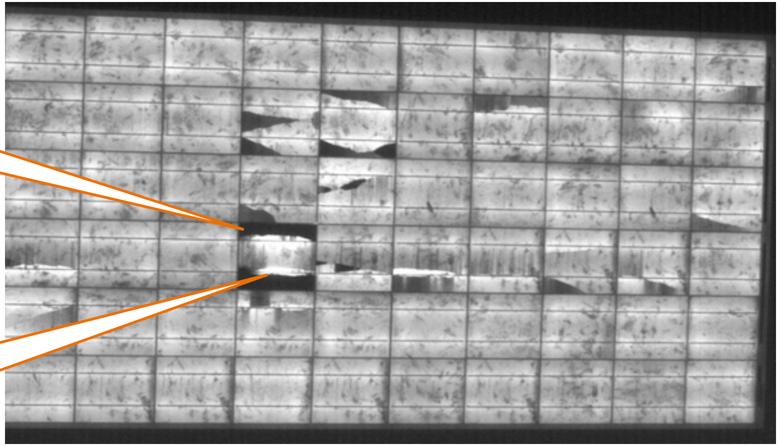
Building a 10 MW Project in California

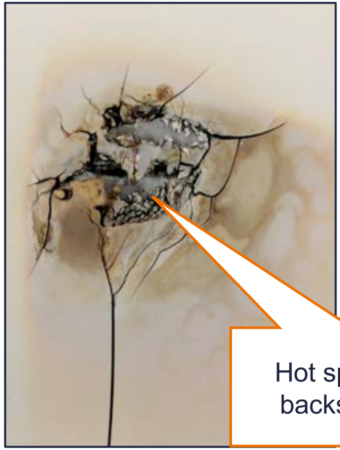
- Project constructed in 2011
- The modules used were:
  - Covered by step performance guarantee for power loss – not linear
  - Covered by 5-year product warranty for workmanship
  - Produced by a financially unstable manufacturer
- Operations began in late 2011



“Unforeseen” Issues Arise

- Original owner sold the project to a third party in 2016
- Cell cracks soon began to cause hot spots and subsequent backsheet burns
- **This created a safety hazard that had to be immediately remedied**

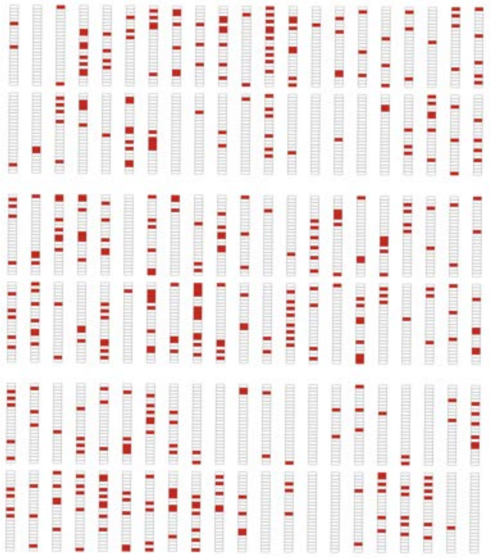




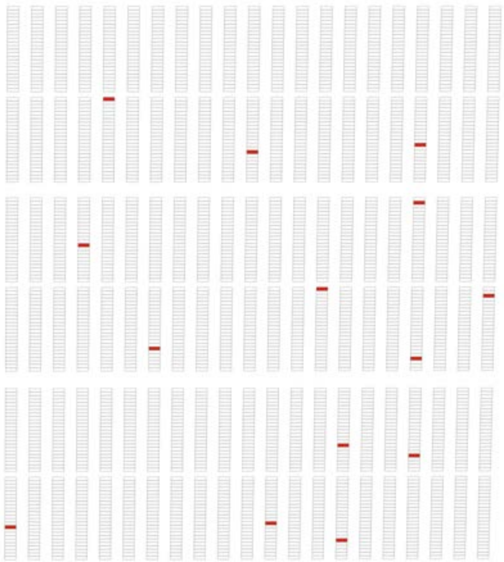
Issues observed after 5 years in field

Results of Heliolytics' Thermal Aerial Scan are Troubling

- Owner conducts aerial thermal scan to quantify module defects
- Half the site had excessive hot spots throughout; the other half had far fewer hot spots



Module Batch #1
Source: Heliolytics



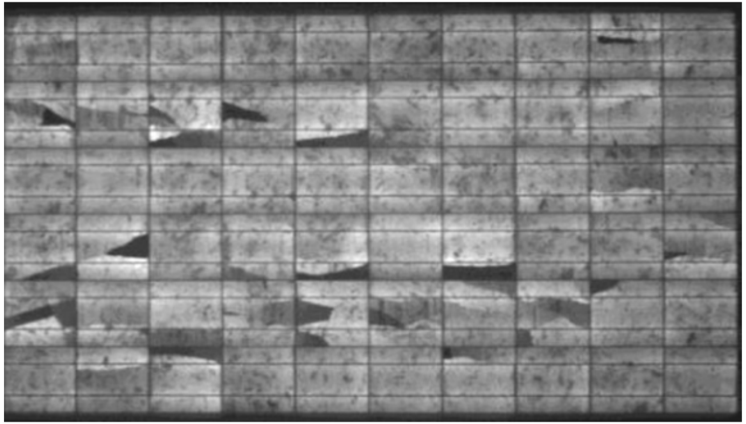
Module Batch #2
Source: Heliolytics

Module Replacement Woes

- Insolvent manufacturer with an uncooperative new owner
- Insufficient warranty protection
- 5-year workmanship warranty had just expired
- Frame size and power class no longer available on the market, so needed to re-engineer for replacements
- Replacing the worst cases of hot spot modules cost hundreds of thousands of dollars – adding up to more than two years of the entire **portfolio's** O&M budget

Quality Issues Were Identified During Module Production

- In 2011, PVEL completed serial defect testing for a batch of modules used in project
- EL images of most samples showed signs of excessive cell cracks originating at the cell bus bars, pointing to a soldering-related root cause
- Thermal cycling caused the potential power loss to be realized
- **PVEL's results were not fully considered and the module installation proceeded**



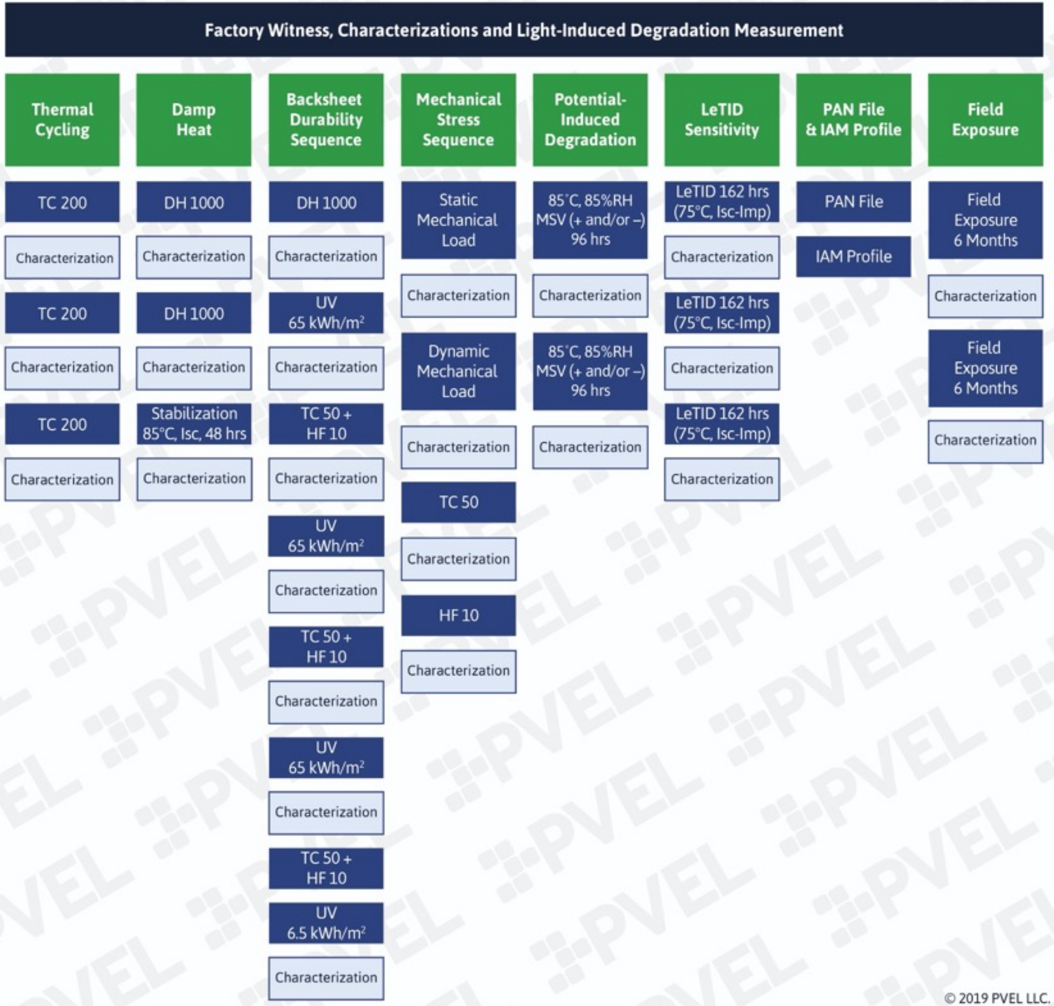
Post Thermal Cycling 200
Source: PVEL

How To Avoid

- Groundwork Renewables
- PVEL
- PI
- Heliolytics

Site Characterization	Vendor Selection	Manufacturing of Equipment	Installation and Commissioning	Ongoing Operations
Resource Monitoring & Assumptions - Groundwork	Reliability & Performance testing via PQP Specifying the tested BOM - PVEL	Batch Testing FAT Oversight - PVEL	Baseline EL - PVEL	Incident Response EL - PVEL
		Pre production factory audit Production Oversight - PI	Thermal Aerial Inspection - Heliolytics	Thermal Aerial Inspection - Heliolytics
				Ongoing resource measurement - Groundwork

PVEL's Module Product Qualification Program (PQP) Test Sequences



PVEL

MAKE DATA MATTER.

THANKS!

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NREL’s Solar + Storage Technoeconomic Analysis Portfolio

Component Manufacturing Costs ($)

Modules

Crystalline Silicon

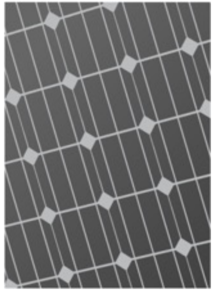


Illustration by Al Hicks, NREL

Thin-Film

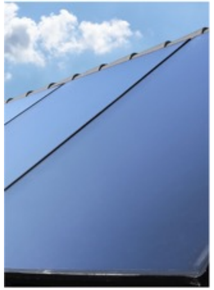


Photo from iStock, 1033236964

Storage

Batteries

Photo by Dennis Schroeder, NREL 56318

Solar Fuels

Photo from iStock, 932140864

System Capital Costs ($)

PV Systems

Photo from iStock, 938053682

PV Plus Storage

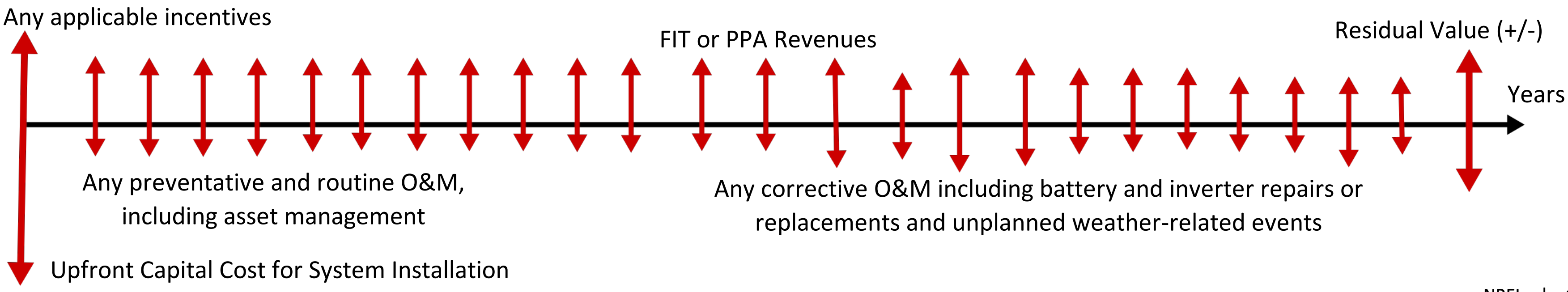
Photo from iStock, 1128871378

Project *Pro Forma* Cash Flow Analysis

Levelized Cost of Electricity (LCOE)

Internal Rate of Return (IRR)

Levelized Cost of Solar + Storage (LCOSS)



50 MW$_{(DC)}$ Single Owner Pre-Discounted Cash Flows and Calculated Project EBITDA (Aggressive Scenario)

March 3, 2020

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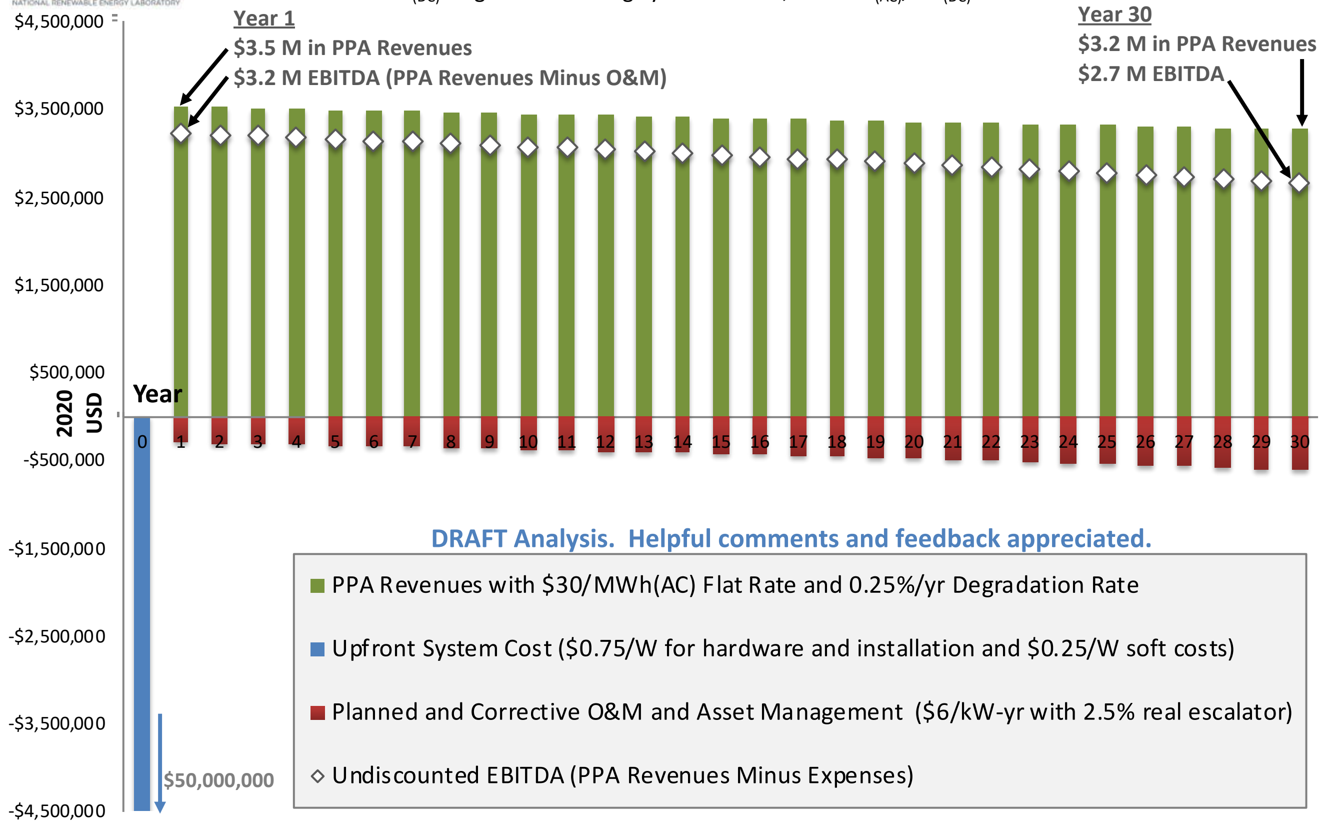
An Aggressive Accounting of Costs and Benefits for PV Systems

50 MW$_{(DC)}$ Single-Axis Tracking Systems with 2,350 kWh$_{(AC)}$/kW$_{(DC)}$ First Year Power Production.



The mean cumulative capacity-weighted capacity factor (CF) for U.S. PV projects installed from 2008 to 2018 was 27.0%

- Corresponds to 2,365 kWh$_{(AC)}$/kW$_{(DC)}$

PPA revenue projections are a function of PPA rates, energy yield, and the degradation profile.

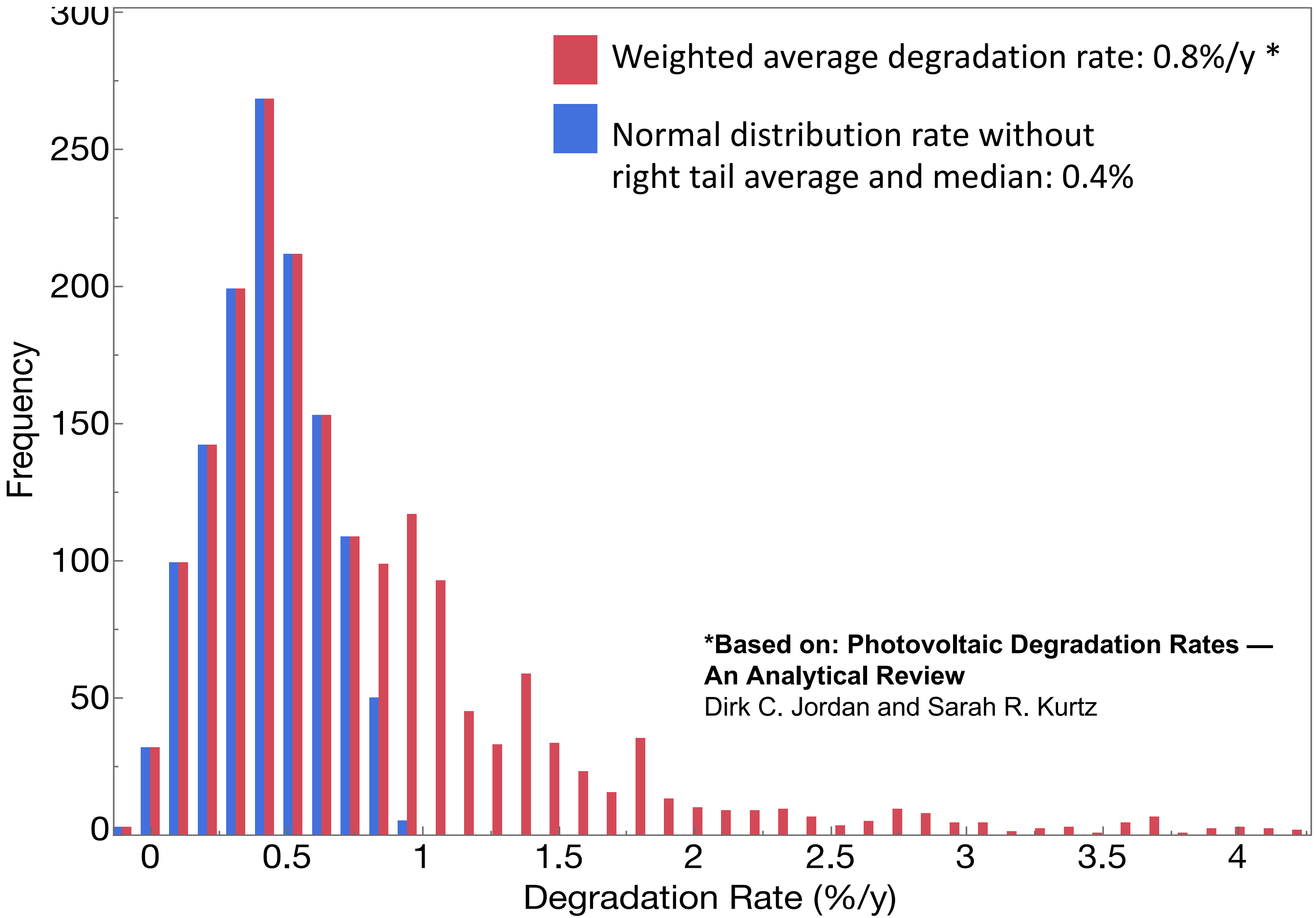
- The average levelized price of PPA's signed in 2018 was $31/MWh (Data compiled by LBNL from FERC Electric Quarterly Reports)

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

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

Calculated Nominal After-Tax IRR with 26% ITC and Flat $30/MWh$_{(AC)}$ PPA Rate: 7.0%

Practical Consideration: Distribution of Failure Rates for PV Systems



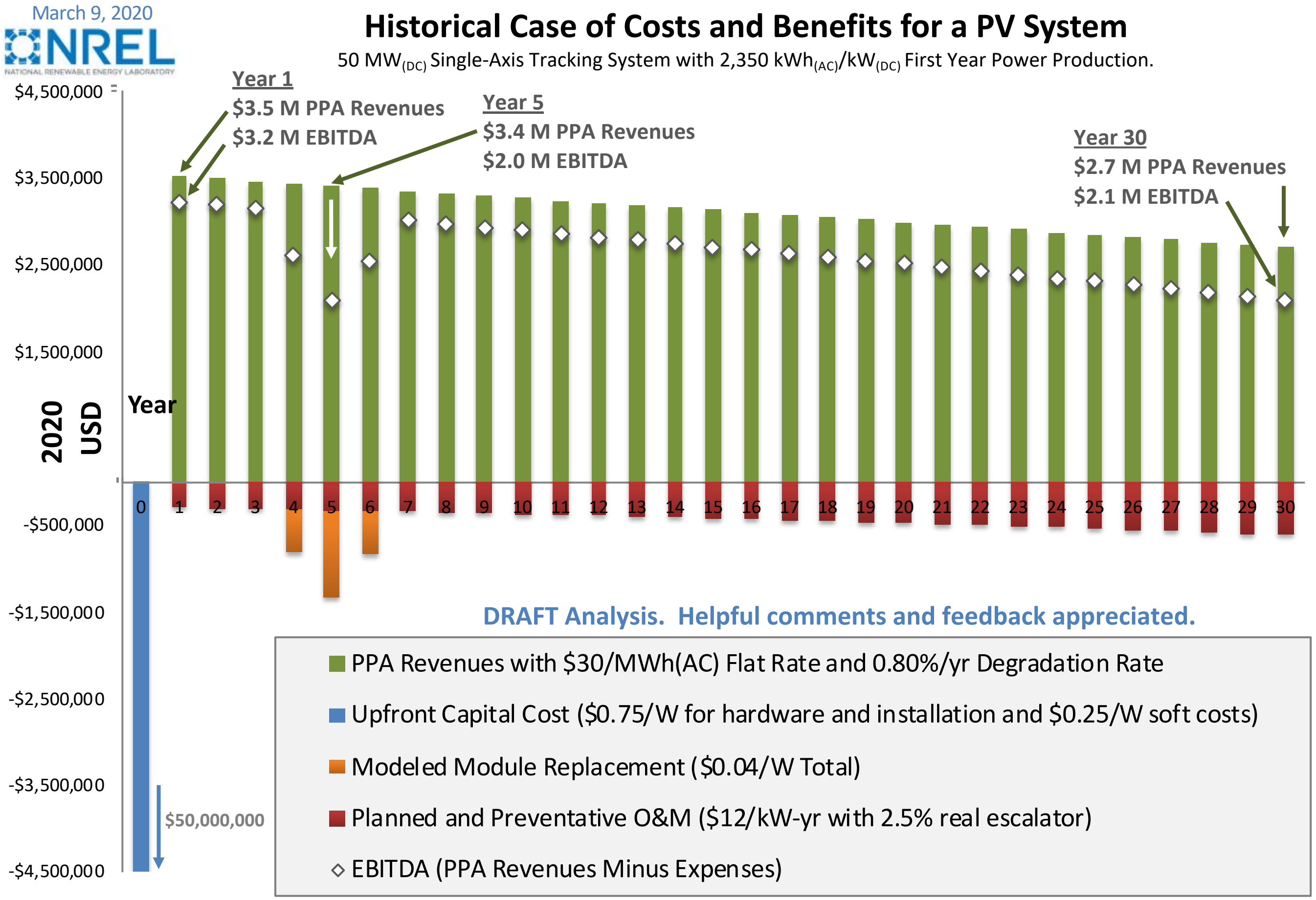
Impact to O&M Budgets and Projec ts

	1-GW PV Project Portfolio (Roughly $1B Investment)		50-MW PV Project (Roughly $50 M Investment)	
	$6/kW-yr (TBD)	**$10/kW-yr** (TBD)	**$6/kW-yr** (TBD)	**$10/kW-yr** (TBD)
Annual Operations and Maintenance (O&M) Budget	$6,000,000	$10,000,000	$300,000	$500,000
Impact to Project or Portfolio for $2M Corrective Issue	• Roughly $4M remaining in O&M budget, but portfolio LCOE and IRR negatively impacted • Decreased project uptime and lower energy yield • Potential warranty claim hassles	• Roughly $8M remaining in O&M budget, but portfolio LCOE and IRR negatively impacted • Decreased project uptime and lower energy yield • Potential warranty claim hassles	• No remaining O&M budget for roughly 7 years • Decreased project uptime and lower energy yield • Potential warranty claim hassles	• No remaining O&M budget for roughly 4 years • Decreased project uptime and lower energy yield • Potential warranty claim hassles

50 MW$_{(DC)}$ Single Owner Pre-Discounted Cash Flows and Calculated Project EBITDA (Scenario with Historical Precedent)

March 9, 2020

NREL



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

March 9, 2020

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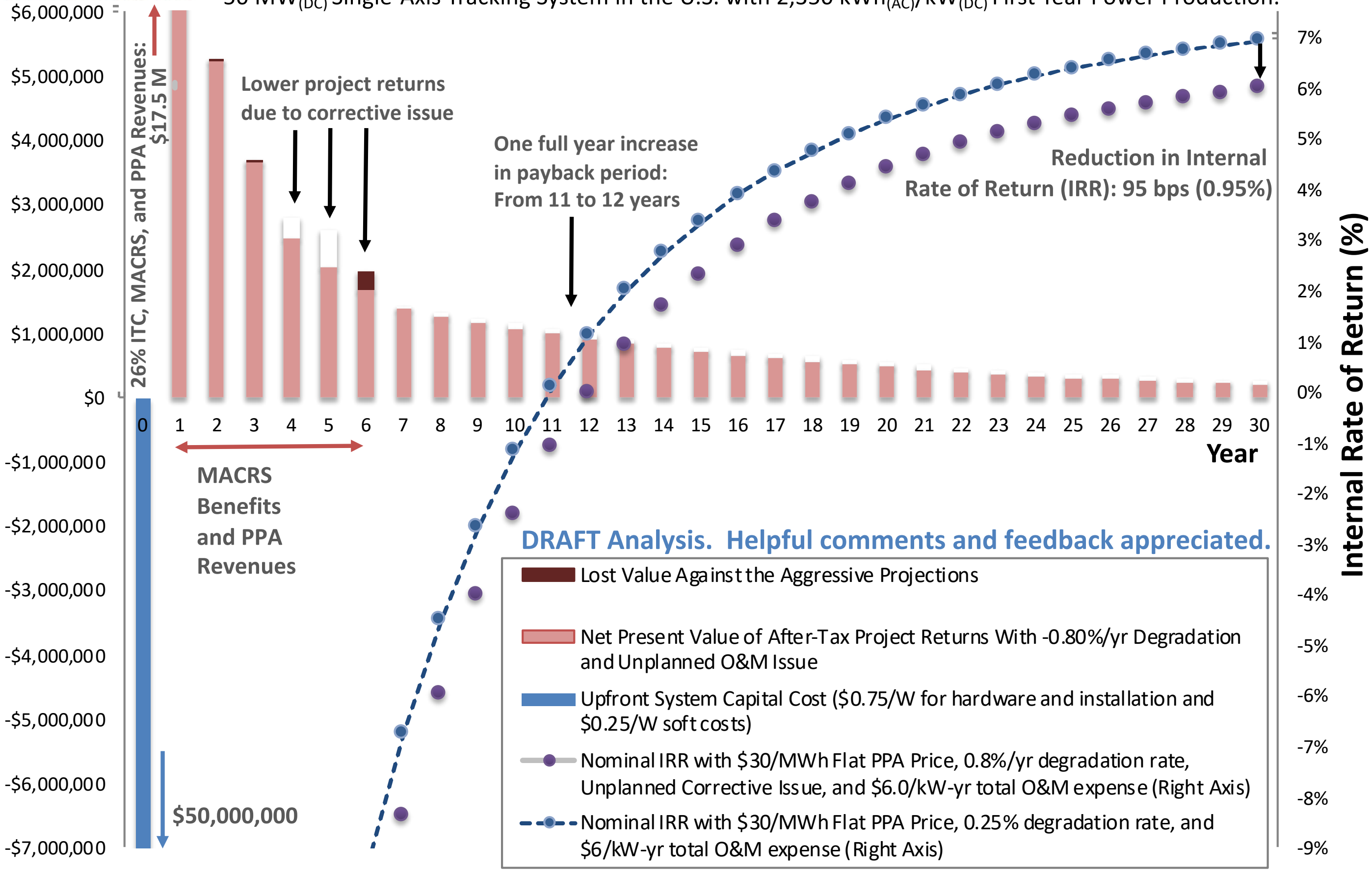
After-Tax Discounted Returns From the PV System

50 MW$_{(DC)}$ Single-Axis Tracking System in the U.S. with 2,350 kWh$_{(AC)}$/kW$_{(DC)}$ First Year Power Production.



Total Value of Losses Against Projected Performance (2020 USD)

Aggressive assumptions: 0.25%/yr degradation rate and $6/kW-yr O&M.

PV systems with 0.80%/yr degradation rate and unplanned corrective issue

$2.8 M
$0.056/W
(50 MW$_{(DC)}$)

$56 M
$0.056/W
(1 GW$_{(DC)}$ portfolio)

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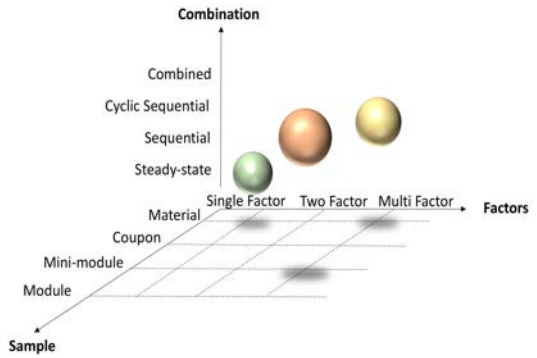
Combined accelerated stress testing (C-AST): Motivation

- **Numerous field failures seen in modules that pass qualification testing (IEC 61215)**
  - We create mechanism-specific tests only after the failure mode has been found in the field
- **Numerous parallel tests getting time consuming and expensive**
- **Stakeholders considering buying into new technologies, materials, and designs incur residual risk, increasing LCOE**
  - Risk of new designs/materials (like PERC, n-PERT, TOPCon)
  - Risk from incremental changes (like going to thinner cells)
  - Risks from failure of critical parts (like an edge seal for moisture-sensitive PV cells)
- **PV module reliability standards subject to interests of those contributing**
  - More objectivity sought
- **$US Billion industry. Risks as well as benefits of progress are substantial**
- **Addressing this, differing PV testing paradigm required**

Combined accelerated stress testing (C-AST): System



Factors

- Heat
- Light (Xe)
- Humidity
  - Condensing
  - Non-condensing
- Mechanical pressure
- System voltage
- Reverse bias *(in progress)*

In-situ Metrology

- *I-V*, EL

Modified Atlas XR-260 Weatherometer

Discover potential weaknesses in module designs, both known and not *a-priori* recognized, reduce risk, accelerate time to market, bankability and reduce costly overdesign, to lower the levelized cost of electricity.

Modes, stress factors, and results

Mode	Stress factors
Solder bond failure leading to open circuit (→ hot spots)	Mechanical and thermomechanical stress on conductors. Current leading to joule heating in the conductors
Corrosion, cell-front delamination	Heat, sunlight, voltage and moisture
Potential-induced degradation	Heat, sunlight, voltage, mechanical stress, and humidity
Cell and glass cracks	Heat, humidity, light, system voltage bias, mechanical stress
Yellowing & module packaging optical losses	Heat, sunlight, voltage and moisture
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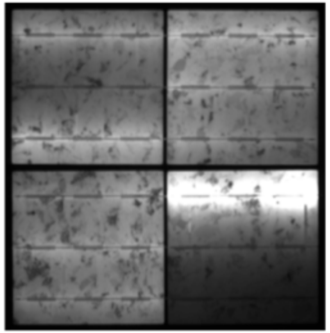

Ribbon/bus connection failure

Modes, stress factors, and results

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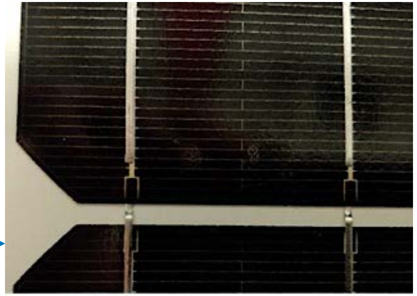
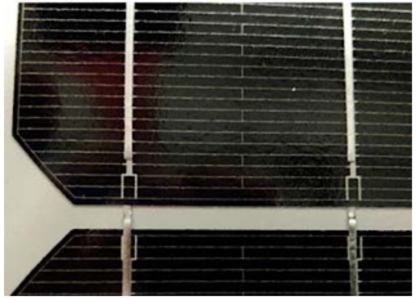


Polyamide



PVDF

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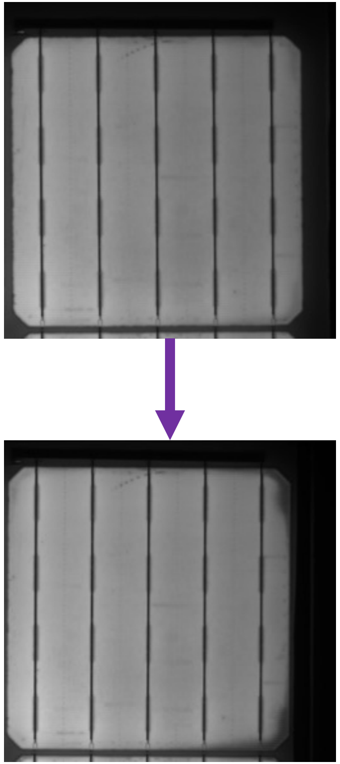

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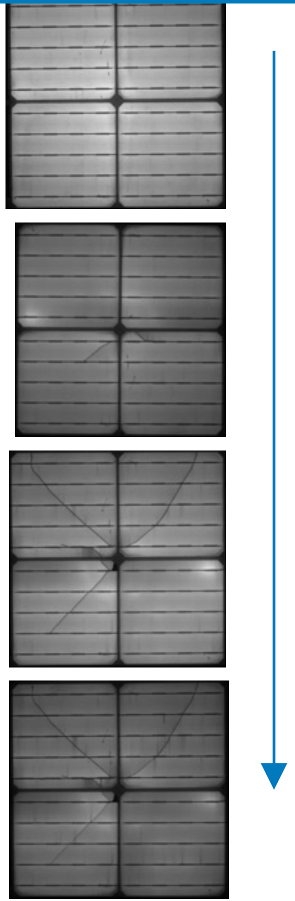

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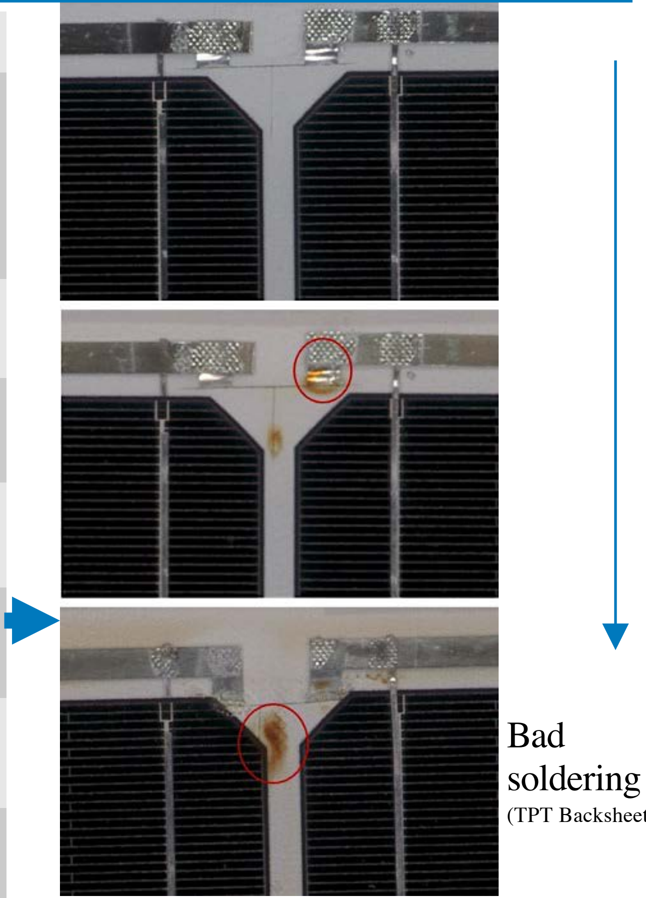

Bad soldering

(TPT Backsheet

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PA Backsheet cracking


PVDF Backsheet cracking


Silicone encapsulant delamination

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→

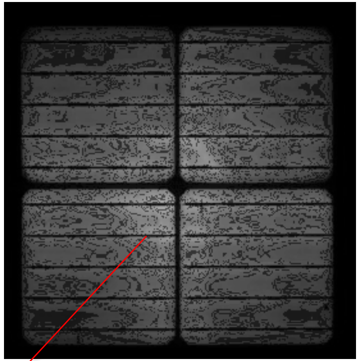
B-O LID
Light & elevated temperature degradation (LeTID)
UV LID (H, charges)

Modes, stress factors, and results: LID

- **B-O LID**
- **Light & elevated temperature degradation (LeTID)**
- **UV LID (H, charges)**

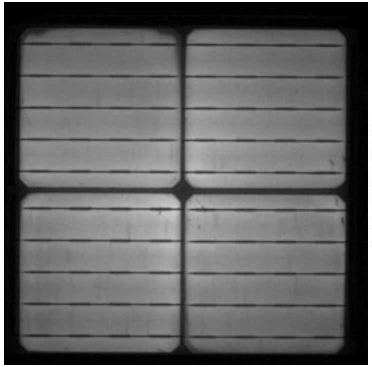
UV Pass EVA

-7.5 mV

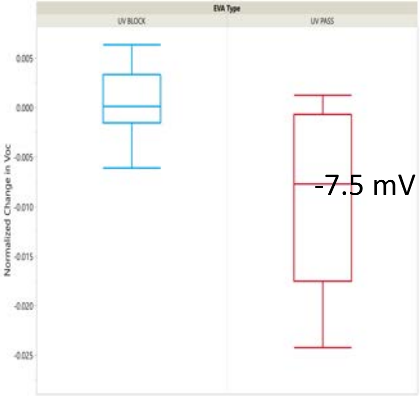


UV Block EVA

-0 mV



UV Block EVA UV Pass EVA



Shadowed region showing higher lifetime: attributed to UV degradation in tropical test

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Methodology and Approach for Bottom-Up Cost Modeling

MODULE TESTING PROTOCOLS

IEC-61215

Potentially Replaced by C-AST

- Visual Inspection
- Insulation test
- Measurement of temperature coefficients
- Performance at STC*
- Performance at low irradiance*
- Outdoor exposure test
- Hot spot endurance test
- UV preconditioning test
- Thermal cycling test
- Humidity freeze test
- Damp heat test
- Robustness of determinations
- Wet leakage current test
- Static mechanical load test
- Hail test
- Bypass diode testing
- Stabilization/Light induced stabilization
- PID (forthcoming in 61215 Ed. 4)

*With optional *in situ* I-V

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 and elevated temperature induced degradation testing
- In situ monitoring of power
- **Combined Accelerated Stress Testing (C-AST)**

TESTING COST OF OWNERSHIP (COO) INPUTS

Inputs by Step

- 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

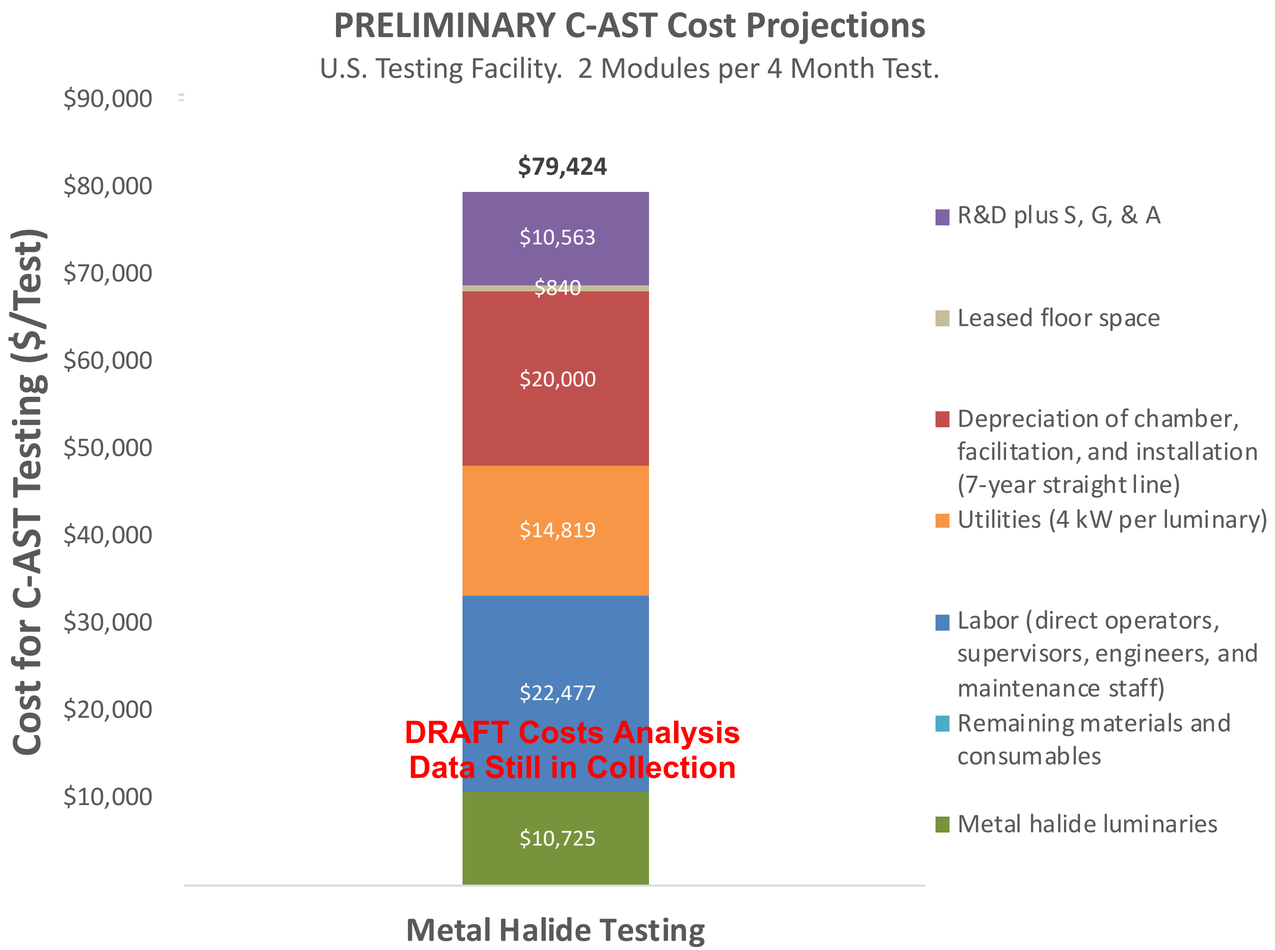
- Equipment
- Building and facilitation

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

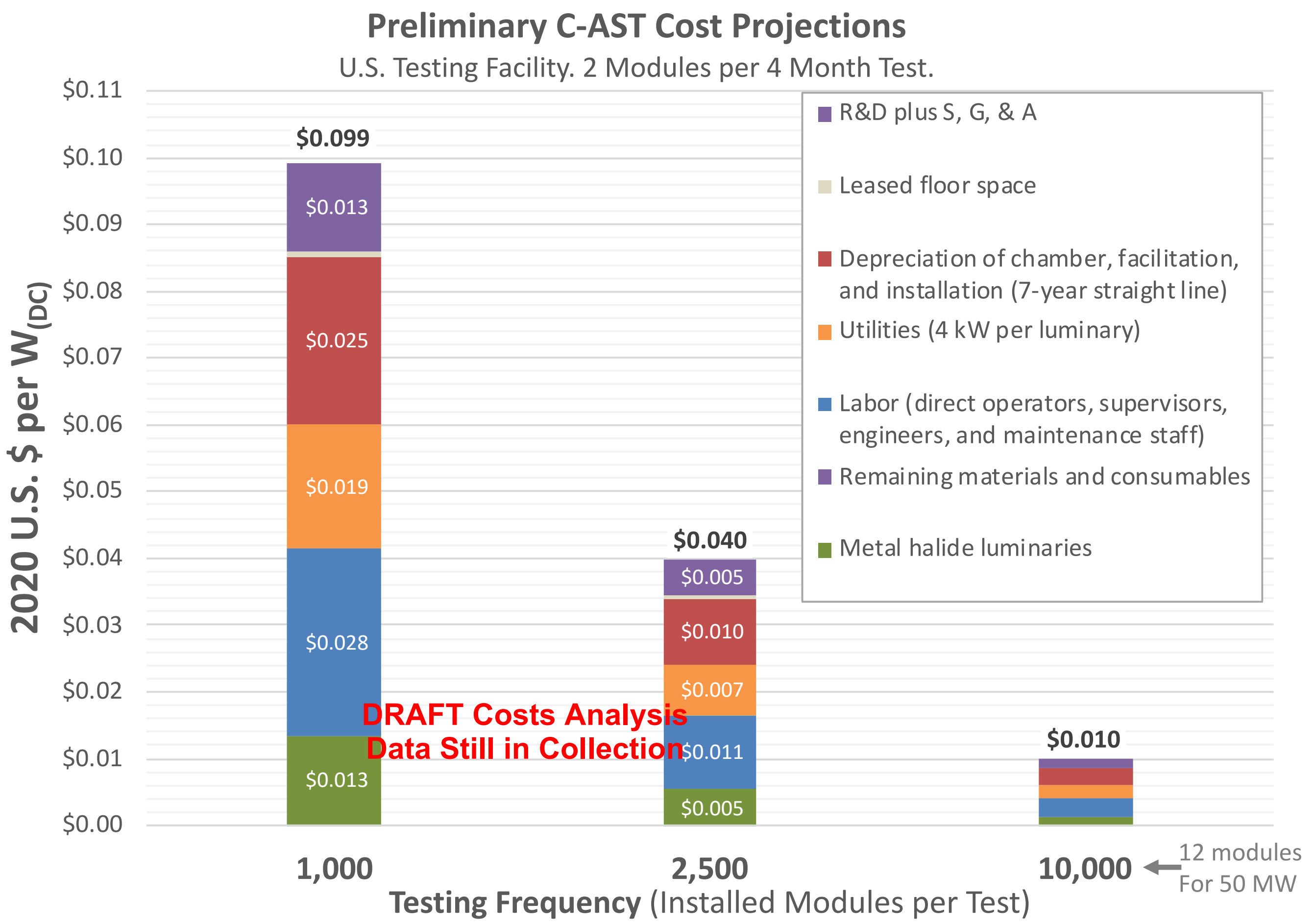
Total Module Testing Costs

PRELIMINARY Results for Bottom-Up Cost Modeling of C-AST



- 6 full-sized modules per year tested in each C-AST chamber
- 2018 industry medians: 2% of revenues budgeted for R&D plus 11% of revenues budgeted for S, G, & A
- $180/m^2 per year facility leasing costs
- 7-year straight line depreciation of investment in C-AST chambers
- $0.08/kWh electricity price
- 5 C-AST chambers per direct operator, 4 shifts
- 20 C-AST chambers per supervisor, 4 shifts
- 20 C-AST chambers per engineer, day shifts only
- 200 hours of maintenance time per chamber per year

PRELIMINARY Results for Bottom-Up Cost Modeling of C-AST



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- $0.08/kWh electricity price
- 5 C-AST chambers per direct operator, 4 shifts
- 20 C-AST chambers per supervisor, 4 shifts
- 20 C-AST chambers per engineer, day shifts only
- 200 hours of total maintenance time per chamber per year (2.2% downtime)

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3 Economic Impacts to a Portfolio of PV Projects (Mike, 15 minutes)

4 Overview of C-AST (Peter, 5 minutes)

5 Bottom-Up Cost Modeling of C-AST (Mike, 10 minutes)

6 **Conclusions, Next Steps, and Questions (Mike, 10 minutes)**

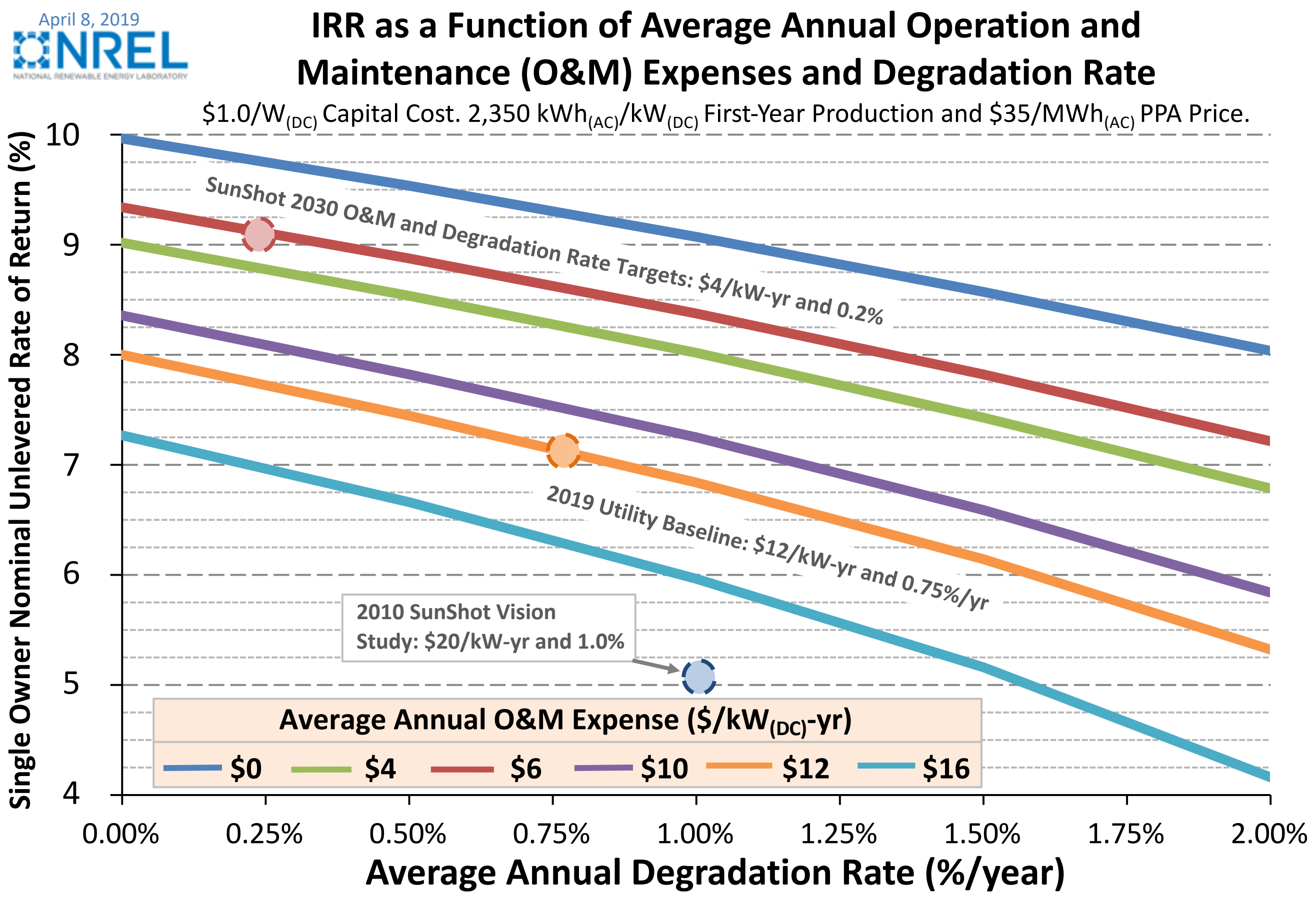
Conclusions and Proposed Next Steps

- Partial to complete module failures may lead to unacceptable declines in system performance that trigger a maintenance response such as module replacement, as well as potential loss of time and money if a warranty enforcement claim is made.
- There are warning signs that projections of PV project performance and O&M expenses can oftentimes be overly aggressive against what has been historically demonstrated. If unknown field failures and degradation profiles deviate from aggressive projections, the realized project EBITDA and IRR will most likely be negatively affected
- PV module testing protocols may be one appropriate screening method to ensure project stakeholders are buying the highest quality products that are available on the market. The IEC testing standards currently in place are meant to be rigorous, but the approaches and techniques for thorough module testing are also developing rapidly. Examining multiple stress factors at once and over a sufficient length of time (for example, with C-AST) can also help to screen for defective modules and elucidate major failure mechanisms.

Supplementary Information

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

April 8, 2019



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**

Bottom-Up O&M Considerations 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)

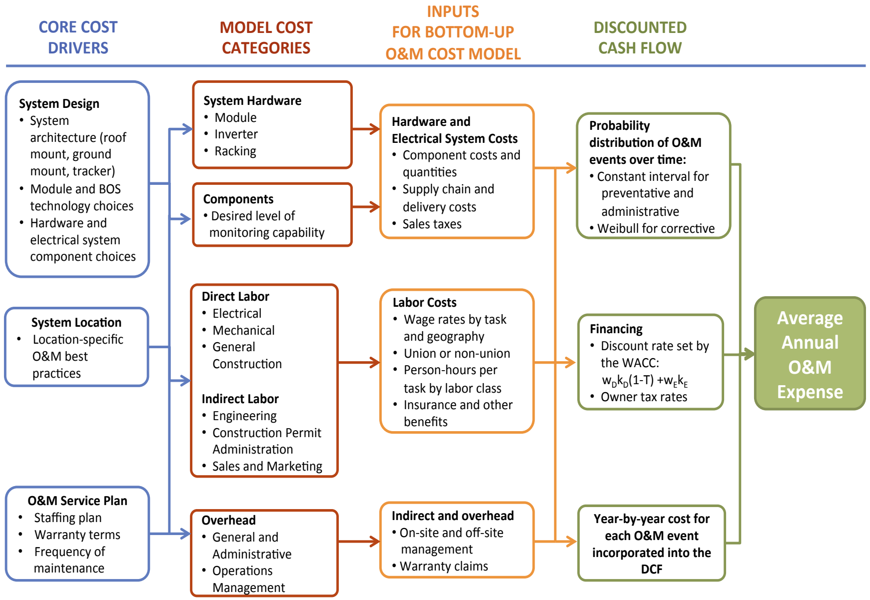
- Reset electrical disconnects and replace electrical components (variable)
- Replace parts or entire units of modules, trackers, and inverters (variable and planned)

Condition-Based Maintenance

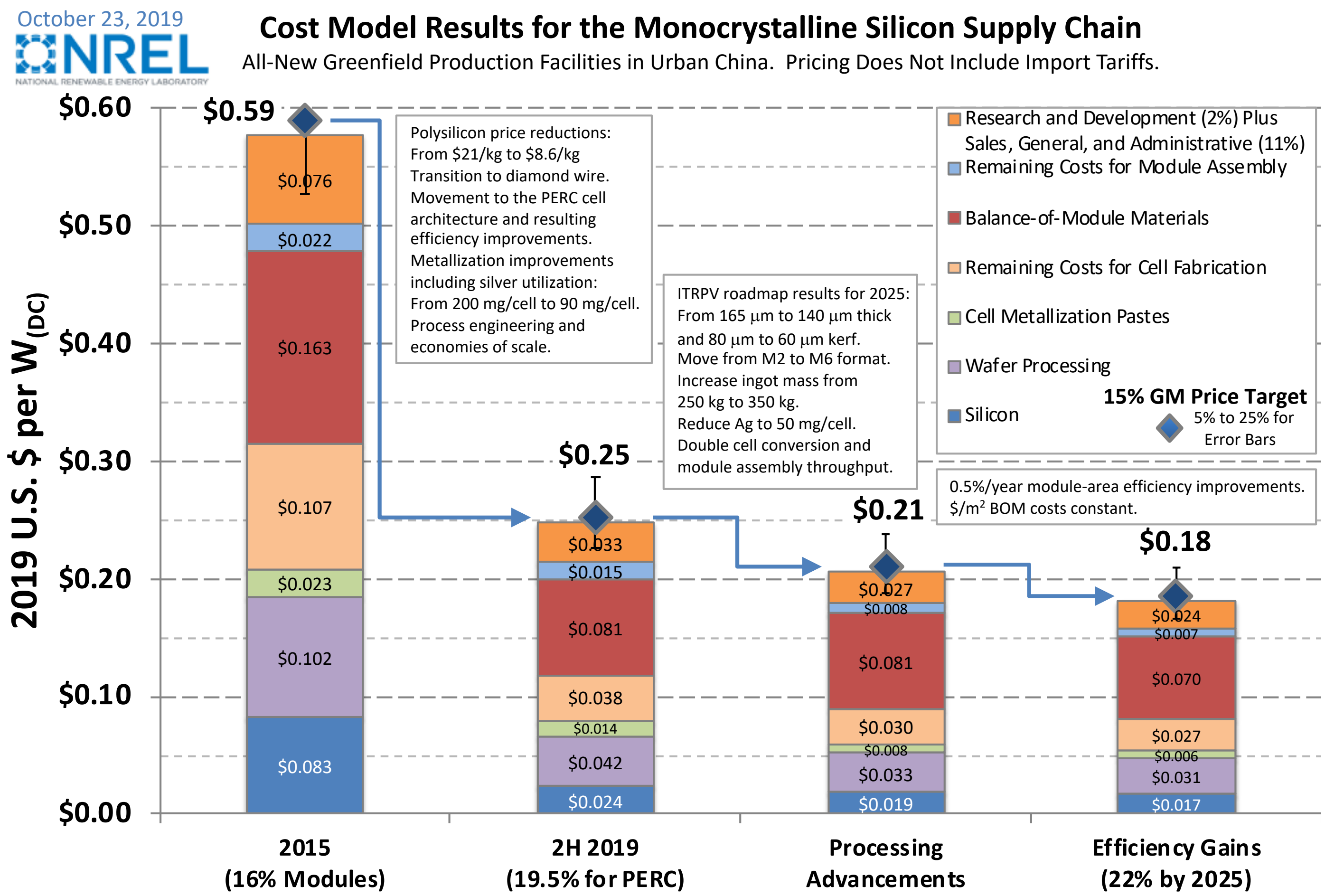
- Active monitoring
- Equipment replacement (variable and planned)

Operations Administration (Planned)

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



Historical, Current, and Projected Pricing for Mono- PERC



- Higher efficiency benefits $/W balance of module (BOM) costs and CapEx
- 2018 industry medians: 2% of revenues budgeted for R&D plus 11% of revenues budgeted for S, G, & A
- Single-value price targets based upon 15% gross margin. 5—25% gross margins used for error bars.
- Additional details given in "Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H2018 Benchmark and Cost Reduction Roadmap" by M Woodhouse, et al., *Available online*.

Major Failure Modes for PV Module Technologies

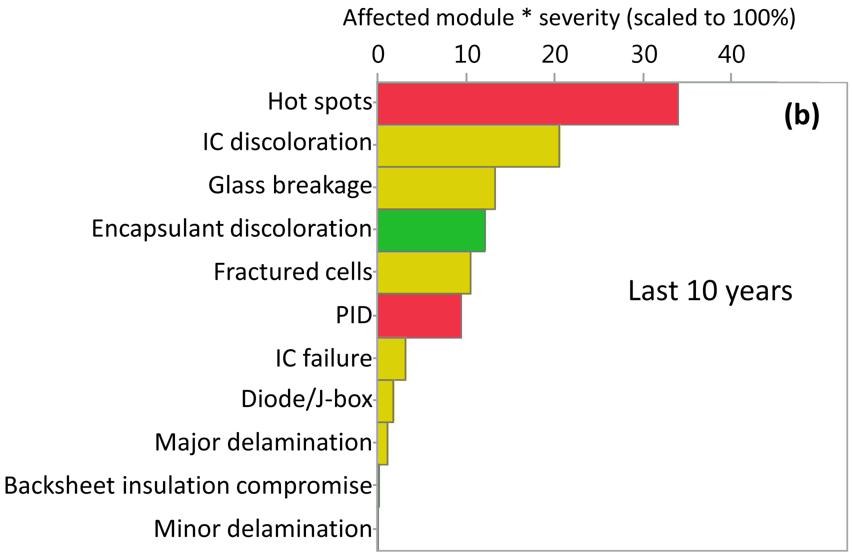


Figure source: D Jordan, T J Silverman, J H Wohlgemuth, S R Kurtz, and K T vanSant "Photovoltaic failure and degradation modes", PIP, 2017.

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 Lower LCOE by \$0.30/MWh$_{(AC)}$ (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 Lower LCOE by \$0.29/MWh$_{(AC)}$ (7.4% discount rate)