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WORKSHOP - RELIABILITY, COST AND PERFORMANCE RISK OF PV CONNECTOR FAILURES

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NOTICE AND DISCLAIMER

Connector Reliability Across the US Solar Sector

DOE Solar Energy Technologies Office Agreement 38531

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Electric Power Research Institute: Tapasvi Lolla, Wayne Li
NREL: Andy Walker, Vignesh Ramasamy, Jal Desai

Our investigation has four parts

1. Fact Finding/ Field Inspections

2. Forensics Analysis

3. Techno-economic Analysis

4. Outreach & Knowledge Transfer

Sandia National Laboratories

ELECTRIC POWER RESEARCH INSTITUTE

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Part 1. Field Inspections (national campaign)

In 2023, Sandia visited six PV power plants (20-100MW) in 3 states (effort is ongoing).

Many examples of poor installation:

- Over-stripped cables, with wires exposed
- Mis-mating of connectors (“compatible” is a misnomer)
- Improper torquing
- Connector not matched to cable gauge

FIELD-MADE CONNECTORS

- Exposure of connectors to moisture and UV
- Loose-hanging cables subjected to mechanical stress and conductor degradation
- Overtight cable ties and over-reliance on cable ties, which have short lifespan)
- Fouling of connector prior to installation

ALL CONNECTORS

Also, field evidence for manufacturing problems:

- Cracks in connector sheath
- Different j-boxes and connectors for same make and model of PV module

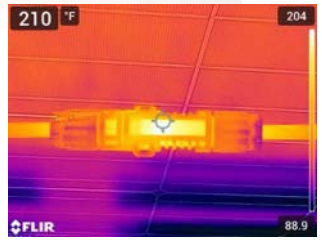
Part 2. Forensics Analysis

LEVEL 1 – Non-destructive (Sandia)

- Acquisition and curation of COTS connectors
- Acquisition of fielded connectors via site visits or mail-in program
- Inspection and characterization
  - Electrical (IEC 62852)
  - Polymeric sheath (imaging, FTIR)
  - Quality of assembly (crimping; o-ring; cap nut; end cap torque)

Thermal distortion of fielded connector →

High resistance: operating temp of 99^{0}C →



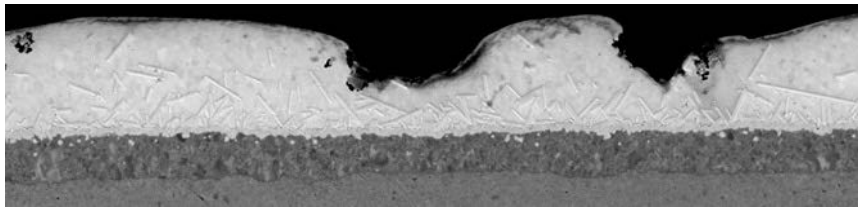
- Maintenance of confidential database including site metadata and lab results for each connector

LEVEL 2 – Destructive (EPRI) – *Early stages (baseline characterization)*

- Metallographic sectioning and scanning electron microscopy for analysis of:
  - Inclusions in metallic composition of pin/sleeve matrix
  - Surface coating morphology

Sample preparation prior to SEM imaging →

Non-uniformity of the outer layer of a connectors surface coating →



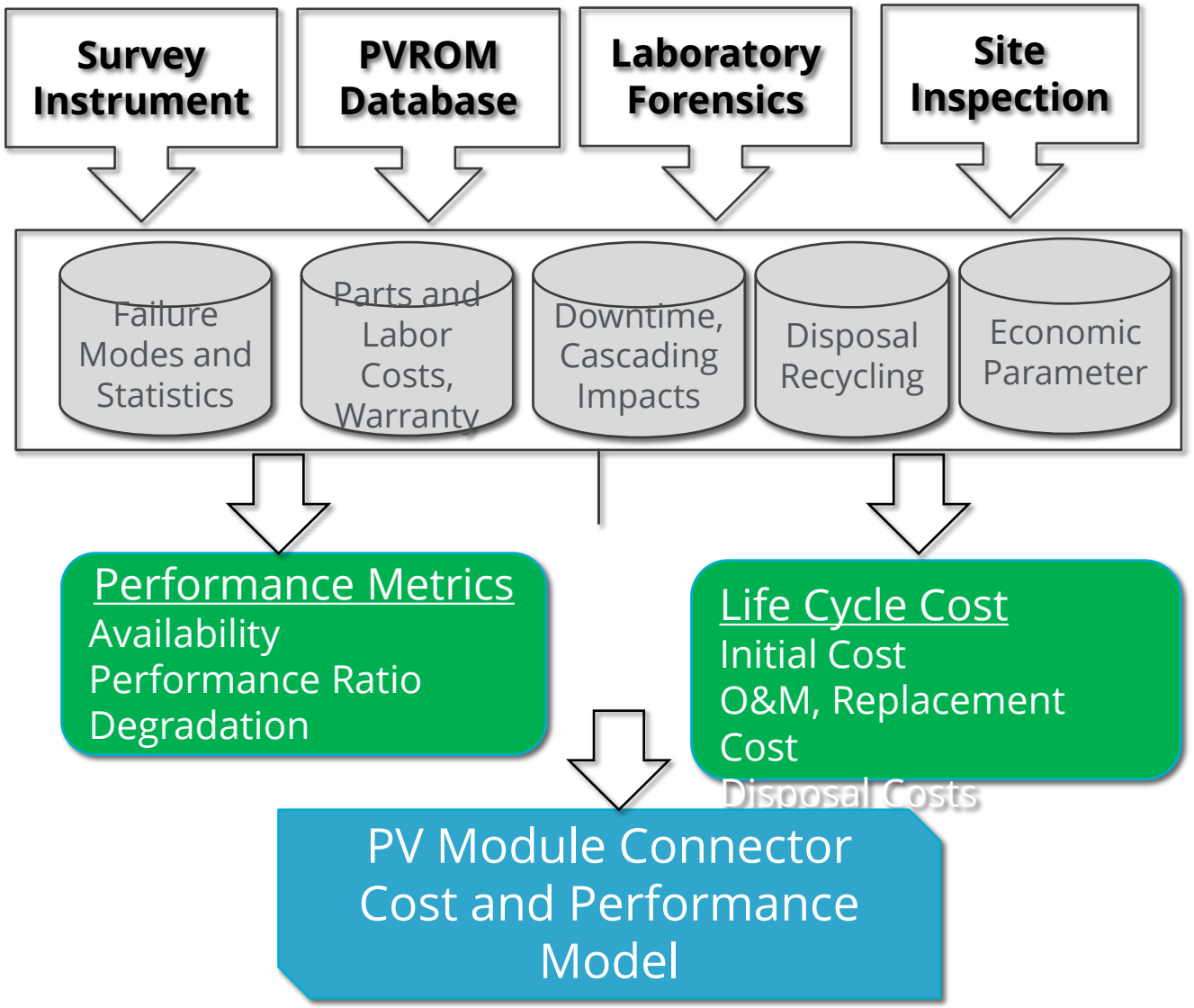
Task 3: Techno-Economic Evaluation; we need your help in this process

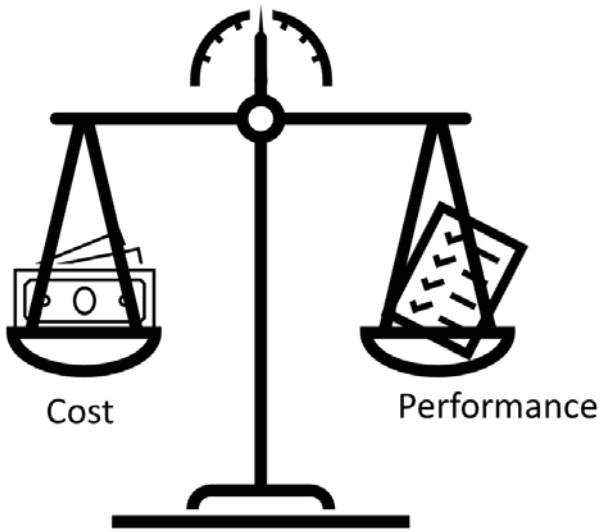
Raw Data Generation

Data Processing

Data Analysis

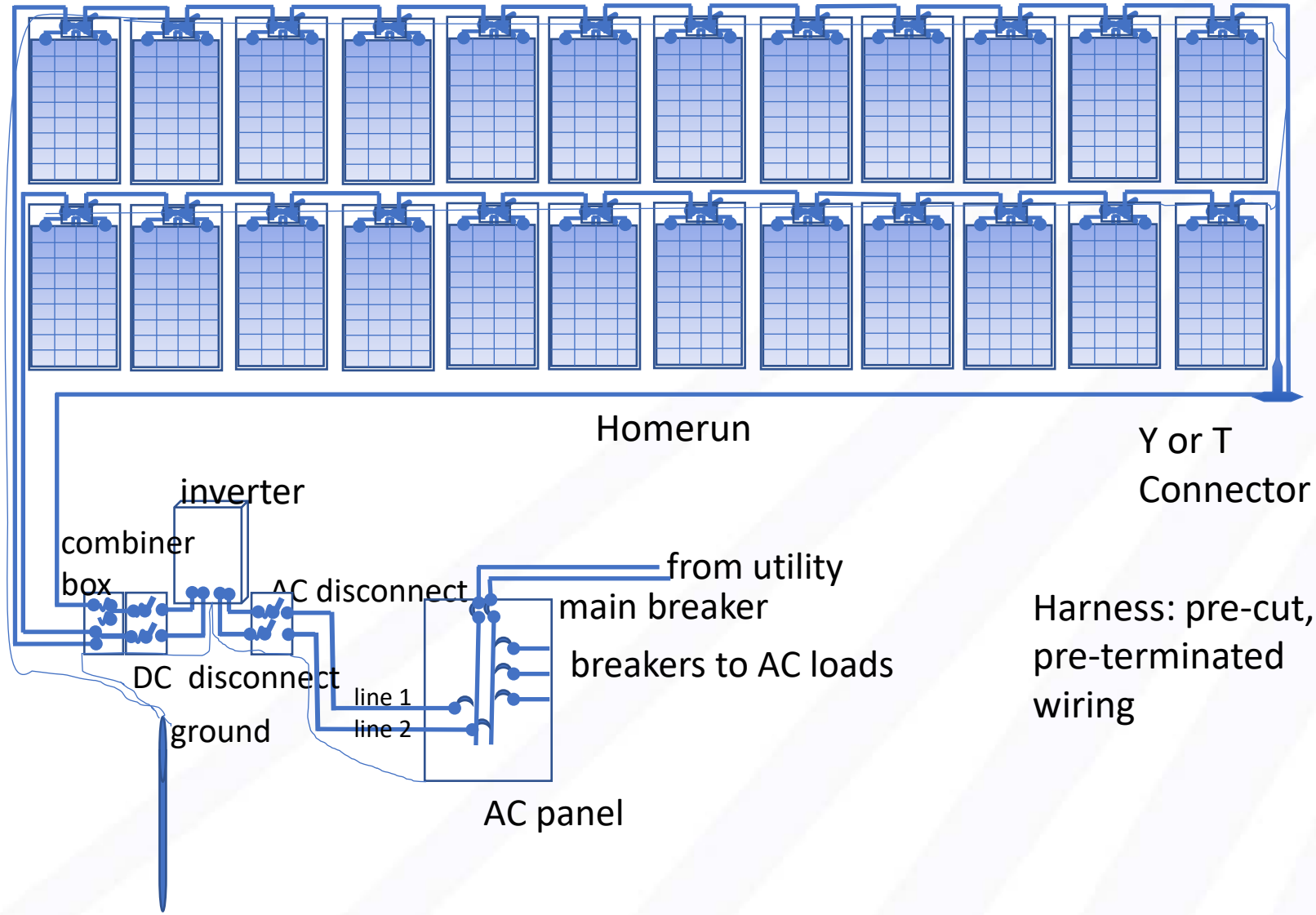
Data Products and Report





Types of Connectors

PV Module-to-Module Connector



Source: "Solar Energy: Technologies and Project Delivery for Buildings, 2013

Harness: pre-cut, pre-terminated wiring

Connector type described in 522 PV O&M Records (PV ROM)

CONNECTOR TYPE	
PV Module	**277**
Homerun	**77**
Power	43
Communication	42
Sensor	29
Y or T Connector	**25**
Fiber Optic	19
Harness	**16**
IDF Connector	11
Coolant Board	7
tracker control	2
WAGO	2
Fence	1

WORD OCCURRENCE IN 522 O&M WORK ORDERS (PVROM)

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

ENVIRONMENT CONDITION	
Water	18
Snow	9
Moisture	3
Lightning	3
Wind	1
Hurricane	1
Hail	1

CAUSE OF DAMAGE	
Recall	70
Install Error	24
Broken Modules	19
Mowing	10
Corrosion	10
Vegetation	9
Animal	4
Dirt	4

CONDITION OF CONNECTOR	
Ground Fault	136
Burn	90
Melt	56
Loose/Pulled	49
Arc Fault	40
Damage	40
Fire	32
Crimp	4

DETECTION OF FAILURE	
Inspect	86
Thermal/Infrared	74
UAS/UAV/Drone	52
Aerial	25

PVROM database contains site-level operations, maintenance, and production records from 6 industry partners for more than 50,000 O&M tickets at 837 sites in United States,

Stories told in Maintenance Records…

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

- Inverter indicates fault
- Inspection reveals
  - Ground Fault
    - Connector submerged in water

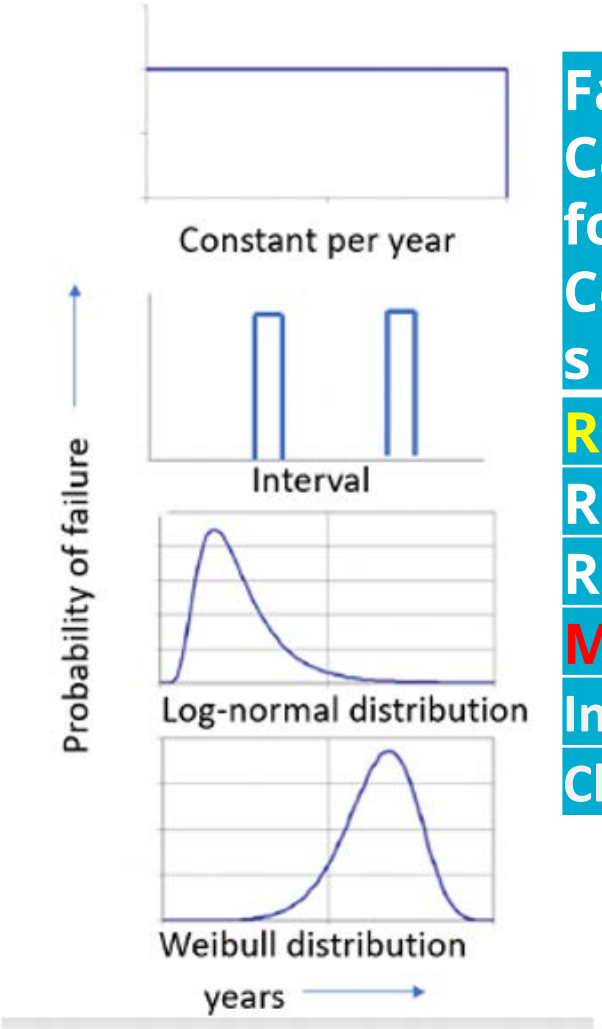
- PV Module Connectors
  - Factory installed
  - Low failure rate but very numerous
- Harness
  - Factory or local cut-and-crimp operation
  - Higher failure rates
- Homerun
  - Field installed connector
  - Highest failure rate

- Manufacturer Recall
  - All connectors in system replaced

Periodic Inspection
- Connectors visually burned or melted

- Infrared Image indicated hot string of PV modules
- Inspection reveals
  - Open circuit
    - Connector pulled off leads when snagged by Mower

FAILURE DISTRIBUTIONS FOR COST MODEL



Failure Category for Connectors	Type of Distribution	Scale	Shape
Repair	Weibull	38.24	1.0
Replace	Weibull	20.37	1.43
Reset	Weibull	123.86	1.15
Modify	Weibull	532.23	0.84
Inspect	Fixed Interval	5	
Clean	Fixed Interval	20	

"Repair" is considered the same as "Replace" in terms of cost
"Modify" is very infrequent and neglected.

Question: There is a bell-shaped curve with some failures even the first year, but would you agree that on average a connector is replaced after 20 years?

Connector Replacement Costs

All connector measures (repair, replace, reset, modify, inspect, clean) are performed by Journeym[illegible]

Question: Is $24/hour (from NBLS) a reasonable assumption for labor cost?...seems low.

Service Category	Hourly Rate ($/hour)	Labor Multiplier (fully loaded)	Loaded Rate ($/hour)	Scope of Work	Qualifications
Journeyman electrician	$17	1.38	$24.12	Connector repair, replace, reset, inspect, clean	(estimated) 50 OSHA Card; training in arc-flash, lock-out/tag-out, and other special protective equipment and procedures; NABCEP PV Installer certification; experience in the design of medium voltage electrical systems. 5+ years experience with PV systems; color vision.

Activity Description	Labor hrs per unit	Material/ Other Cost per unit
Replace Connector	0.10	$4
Inspect Connector	0.01	$0
Clean Connector	0.05	$0

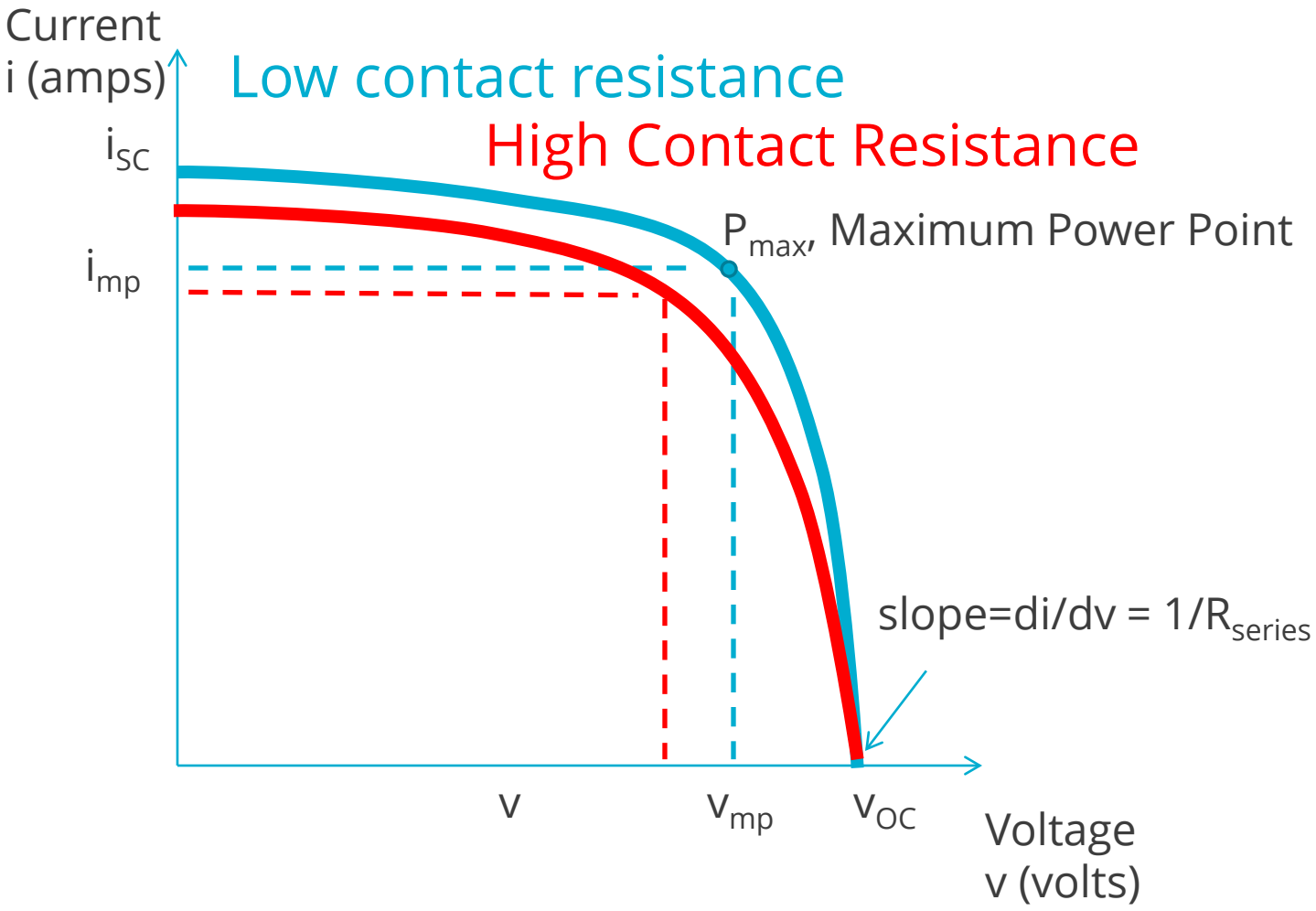
Question: Is $4/connector reasonable cost per replacement part?

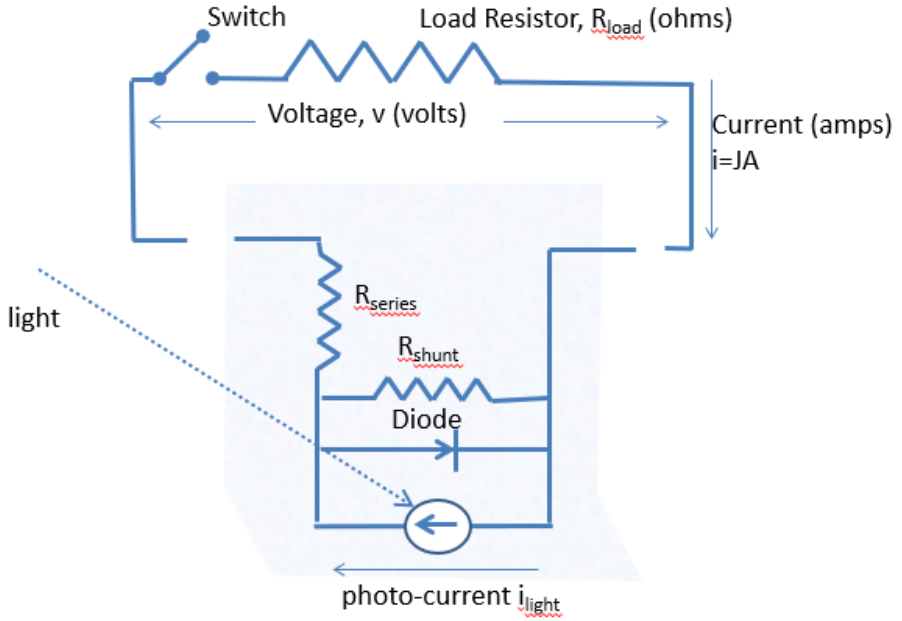
Example:O&M Cost for 100 MW Utility-Scale PV System

Lifetime NPV by Component Type			
Component	Avg. Cost/Yr	NPV (Life)	% of Total
AC wiring	$9,859	$155,132	1%
Insurance	$447,500	$7,041,618	25%
Asset Management	$610,731	$9,610,140	34%
Cleaning/Veg	$253,380	$3,987,052	14%
DC wiring	$18,417	$289,805	1%
Connector	$103,357	$1,626,362	6%
Documents	$22,952	$361,155	1%
Electrical	$6,719	$105,722	0%
Inverter	$84,302	$1,326,529	5%
Mechanical	$92,986	$1,463,177	5%
Meter	$16	$248	0%
Monitoring	$61	$957	0%
PV Array	$118,116	$1,858,609	7%
PV module	$5,570	$87,641	0%
Roof	$0	$0	0%
Tracker	$0	$0	0%
Transformer	$448	$7,053	0%
(blank)	$0	$0	0%
Total	**$1,774,413**	**$27,921,201**	**100%**

Question: With these assumptions the cost model predicts levelized cost of $103k/year, or 6% of total, associated with connectors.,,,is that reasonable estimate of Cost in your experience?

Lost Production
High connector resistance causes losses
I^2R losses plus losses due to I-V curve





$$J_{sc} = J_{light} - J_o\left[e^{\frac{q(J_{sc}R_{series})}{kT}} - 1\right] - \frac{J_{sc}R_{series}}{R_{shunt}}$$

Approximation for short circuit $I_{sc}=I_{light}$ as we apply an increased R_{seried} and decreased voltage, v, the potential barrier that electrons must overcome increases, and fewer electrons have energy to do this

PV ROM Data from T. Gunda Sandia Natl Lab 1/18/2023
Maintenance ticket close date minus open date.

Failure Category for Connectors	Median Downtime (Hours)	Mean Downtime (Hours)
Repair	190.9	759.8
Replace	226.5	1578.6
Reset	28.0	424.1
Modify	39.5	282.5
Other	331.3	1559.0

Question: To estimate lost production, should we use the 9 days median or 65 days average downtime per replaced connector? How to consider outliers with very long down-times?

PVROM database contains site-level operations, maintenance, and production records from 6 industry partners for more than 50,000 O&M tickets at 837 sites in United States,

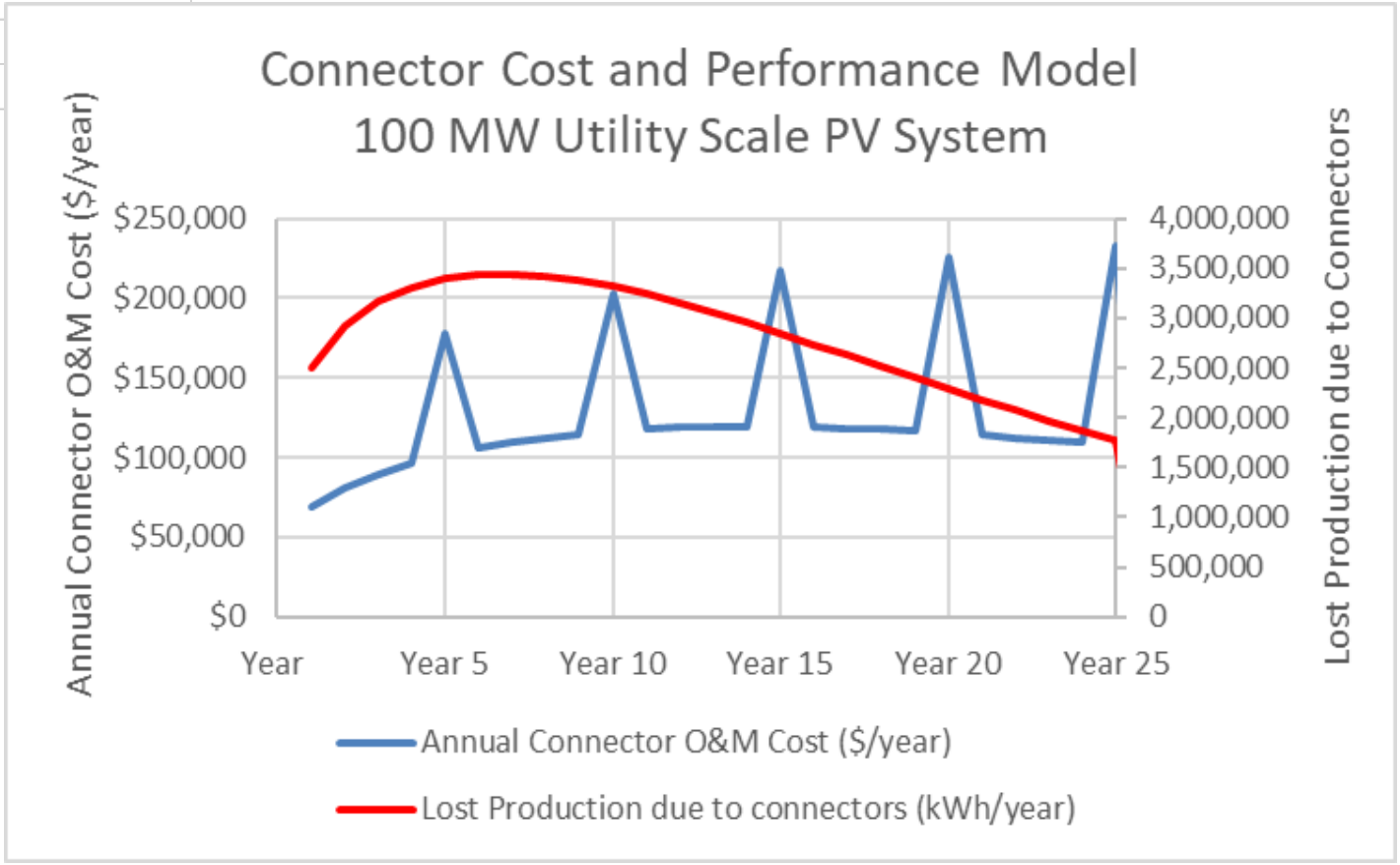
Production Impacts of Each Connector Failure

Activity Description	Component Downtime (hours)	Rated Power (DC) of Plant affected by each Component Downtime (kW)	Whole-system Downtime (hours)
Repair Connector	191.00	5.74	0.00
Replace Connector	226.00	5.74	0.00
Reset Connector	28.00	5.74	0.00
Modify Connector	39.00	5.74	0.00
Inspect Connector	0.00	0.00	0.00
Clean Connector	0.00	0.00	0.00

Question: Each connector failure results in loss of DC power of one string of modules (could overestimate lost production)?
No whole-system downtime?

LCOE represents Cost/ Production.

System Name	100 MW Utility-Scale PV
Results	
Annualized O&M Costs ($/year)	$1,774,563
Annualized Unit O&M Costs ($/kW/year)	$17.75
Maximum Reserve Account	$5,299,351
Net Present Value O&M Costs (project life)	$27,923,565
Net Present Value (project life) per Wp	$0.279
NPV Annual O&M Cost per kWh	$0.016



Risks well beyond "lost production"

"Fire Department informed …of a small fire on site…it is two connectors that are hanging from a rack and arcing. Utility notified and requested that they open their recloser immediately…the site was disconnected on the MV side. "

"called in..to report a fire due to a short circuit at the array. It was a small fire (smaller than a campfire)…extinguished with a fire extinguisher…fire is not active. Some damage to a module due to fire"

"We are an O&M company and **have seen plenty of … lost revenue due to bad connectors overheating, melting, starting ground faults or arc fault fires…**

Question: How can we represent issues beyond connector COST and LOST PRODUCTION?

Resources: Operation and Maintenance

- Model of Operation and Maintenance Costs for Photovoltaic Systems*
  https://www.nrel.gov/docs/fy20osti/74840.pdf.
- Performance of Photovoltaic Systems Recorded by Open Solar Performance and Reliability Clearinghouse (oSPARC)*https://www.nrel.gov/docs/fy19osti/75162.pdf.
- Best Practices in Operation and Maintenance of PV Systems*, 3rd Ed.
  https://www.nrel.gov/docs/fy19osti/73822.pdf
- Severe Weather Impacts on Photovoltaic Plant Operations https://www.osti.gov/biblio/1837045-weather-impacts-solar-pv-operations-summary-current-body-knowledge-implications-further-investigation
- Insurance in the Operation of Photovoltaic Plants https://www.nrel.gov/docs/fy21osti/78588.pdf
- Best Practices at the End of the Photovoltaic System Performance Period
  https://www.nrel.gov/docs/fy21osti/78678.pdf
- PV Fleet Performance Data Initiative: Performance Index-Based Analysis
  https://www.nrel.gov/docs/fy21osti/78720.pdf
- Cybersecurity in Photovoltaic Plant Operations https://www.nrel.gov/docs/fy21osti/78755.pdf
- "PV ROM (Reliability, Operations & Maintenance) Database" Sandia National Laboratories http://energy.sandia.gov/tag/pvrom/ Reference for alpha and beta in Weibull failure distributions

For more information or to participate, please contact:

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