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SANDIA-EPRI PV CONNECTOR RELIABILITY WORKSHOP

July 17, 2024, Charlotte NC

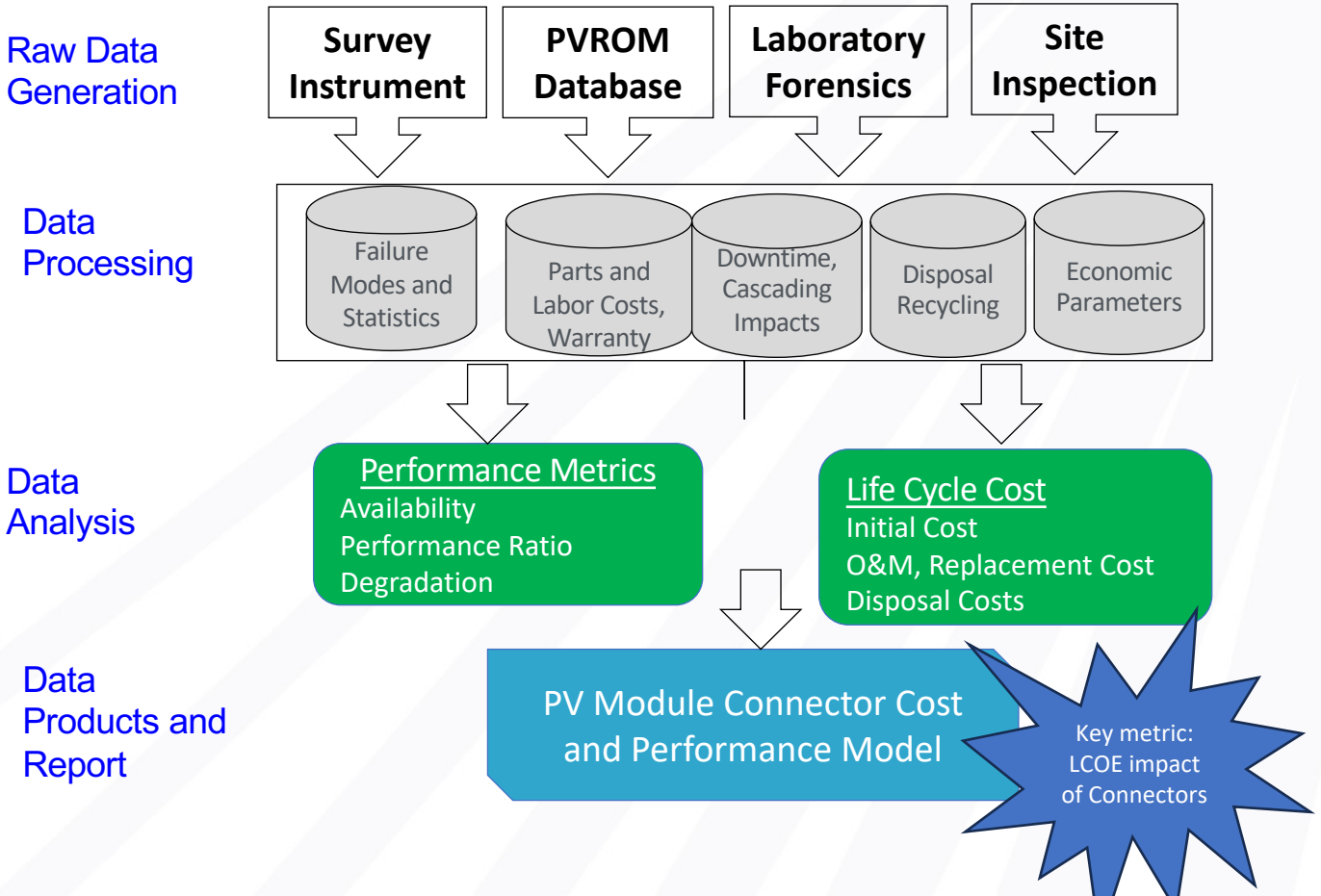
Panel Session III. The Economics of Degraded and Failed PV Connectors

Techno-Economic Analysis: Impacts of PV Module Connector Failures on Cost and Performance of Utility Scale Photovoltaic Systems

SETO CPS Agreement # Sandia 38531 and NREL 39035

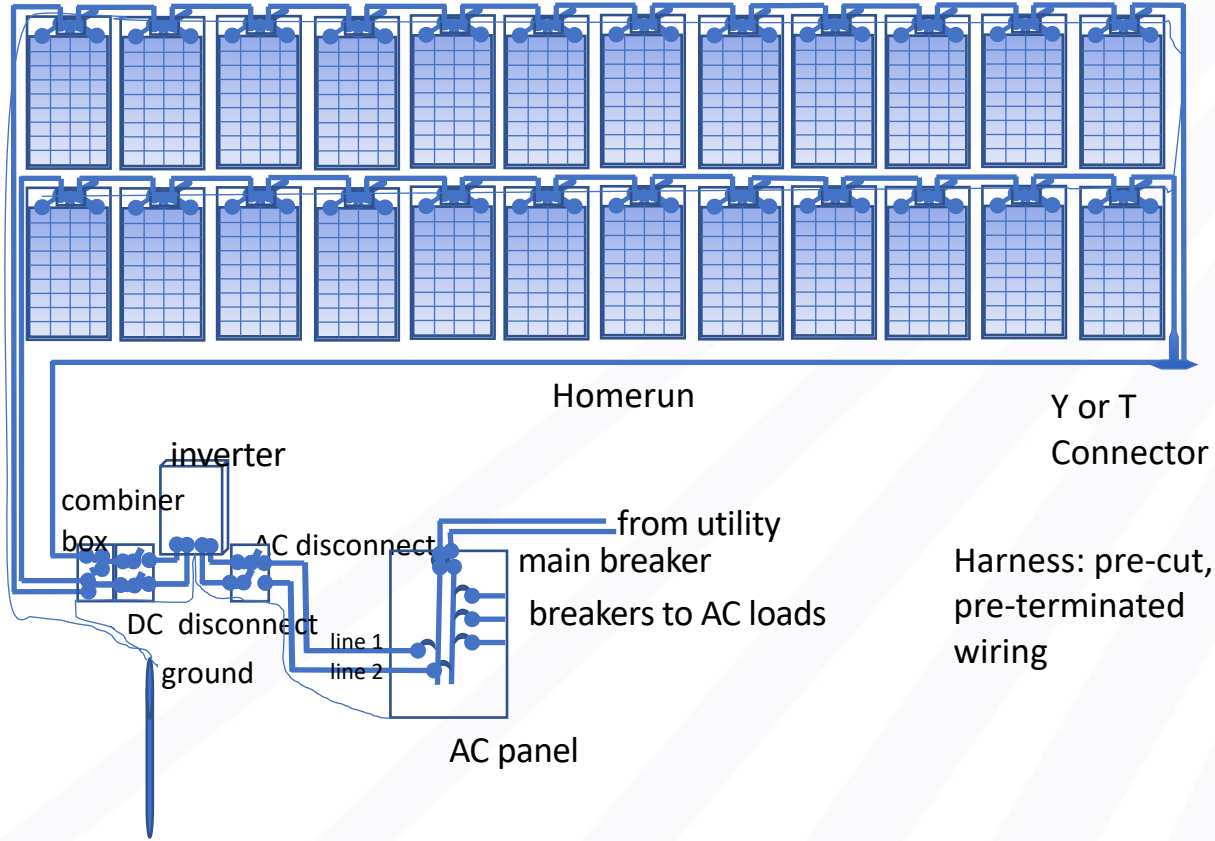
Principal Investigators: Laurie Burnham and Bruce King, Sandia National Laboratories
Other Contributors: Michael Bolen EPRI, Wayne Li ARNL, Michael Woodhouse, Vignesh Ramasamy, NREL

Process for Connector Techno-Economic Evaluation



Types of Connectors

PV Module-to-Module Connector



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

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

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

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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

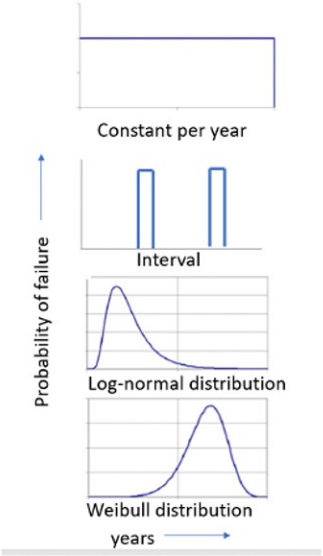
CONDITION OF CONNECTOR	
Ground Fault	136
Burn	90
Melt	56
Loose/Pulled	49
Arc Fault	40
Damage	40
Fire	32
Crimp	4

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,

Connector O&M Costs

Example Failure Distributions



Activity Description	Mean Interval (years)	Weibull or Lognormal Shape Factor	Type of Distribution	Labor hrs per unit	Material/ Other Cost per unit
Repair Connector	38	1.09	Weibull	0.10	$4
Replace Connector	20	1.43	Weibull	0.10	$4
Reset Connector	123	1.15	Weibull	0.05	$0
Modify Connector	532	0.84	Weibull	0.10	$4
Inspect Connector	10		interval	0.01	$0
Clean Connector	10		interval	0.05	$0

Repair and Modify are assigned the same cost as Replace, even though they have different failure distributions from the PV ROM data. Replace both pin and sleeve sides.

DOWNTIME IN 522 O&M WORK ORDERS

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

PV ROM Data from T. Gunda Sandia Natl Lab 1/18/2023; 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,

LCOE represents Cost/Production.

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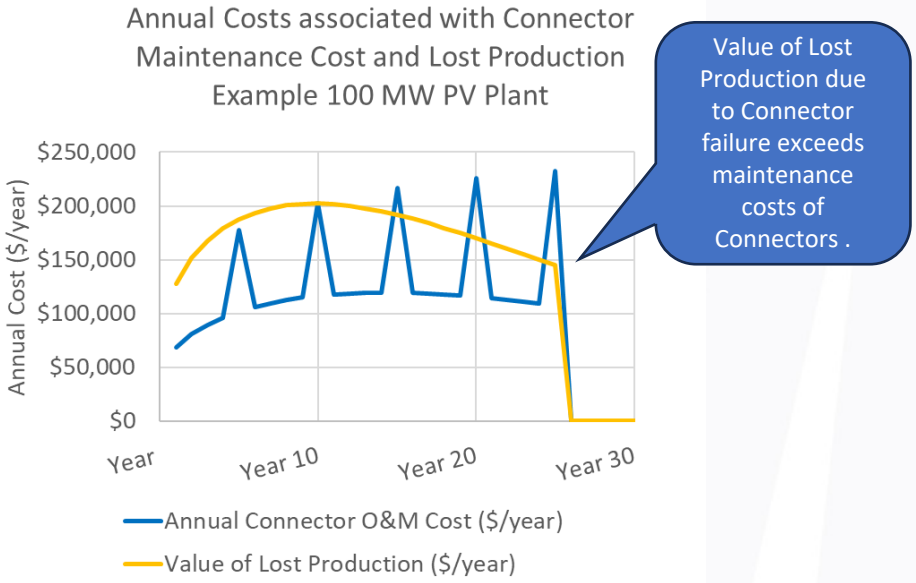
System Name	100 MW Utility-Scale PV
Results	
Annualized O&M Costs ($/year)	$1,774,563
Annualized Unit O&M Costs ($/kW/year)	$17.75
Maximum Reserve Account	$5,299,351
Net Present Value O&M Costs (project life)	$27,923,565
Net Present Value (project life) per Wp	$0.279
NPV Annual O&M Cost per kWh	$0.016

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	$103,507	$1,628,726	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	**$1,774,563**	**$27,923,565**	**100%**

Connectors about 6% of O&M cost.



Value of Lost Production due to Connector failure exceeds maintenance costs of Connectors .

Levelized Cost of Energy Analysis

$$LCOE = \frac{I + \frac{F^n}{(1+R)^n} - \sum_{n-1}^{N} \frac{(D+DF)^n}{(1+R)^n} \times (T) - \frac{Rv^n}{(1+R)^n} \times (1-T) + \sum_{n-1}^{N} \frac{O}{(1+R)^n} + \sum_{n-1}^{N} \frac{Pr}{(1+R)^n} + \sum_{n-1}^{N} \frac{Ir}{(1+R)^n}}{\sum_{n-1}^{N} \frac{P \times (1-Dr)^n}{(1+R)^n}}$$

I = Initial Capital Investment
F = Follow-on investments (inverter, battery replacements)
D = Depreciation of assets (which may include depreciation from follow-on investments)
R = discount rate
T = Tax rate
O = PV system related O&M
Dr = Degradation PV
Rv = Residual value (if any)
P = Initial annual system production
Pr = Principal Payment
Ir = Interest Payment

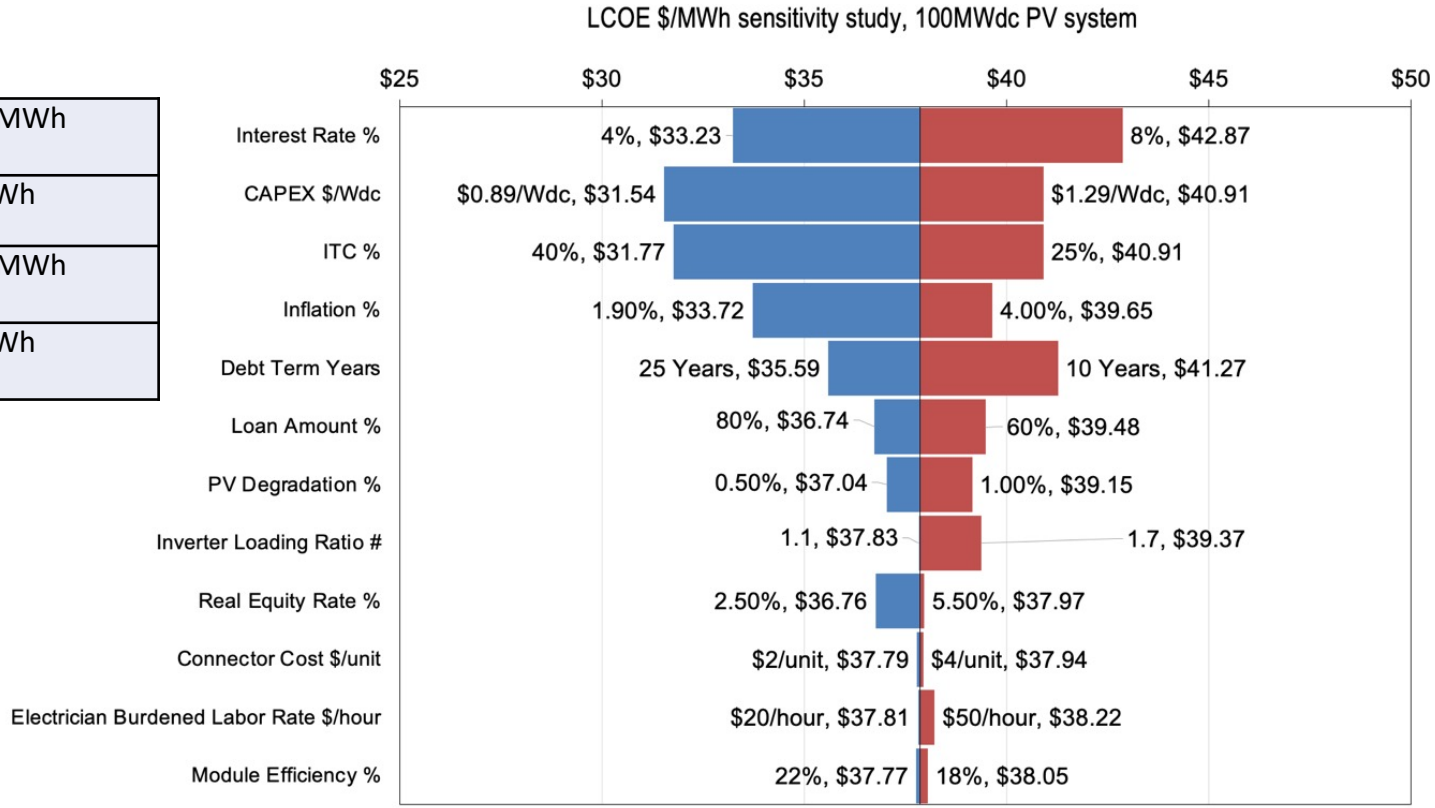
Average connector related O&M cost (30 Years) – 1.29 $/kWdc/yr (continuing 100 MW ground mount example)

Example Life Cycle Cost: 100 MW Fixed Tilt

	Cost with Connectors	Cost without Connectors	Impact due to Connectors
Annualized O&M Costs ($/year)	$ 1,361,350	$ 1,289,417	$ 71,933
Annualized Unit O&M Costs ($/kW/year)	$ 13.61	$ 12.89	$ 0.72
Maximum Reserve Account	$ 5,216,127	$ 5,028,907	$ 187,220
Net Present Value O&M Costs (project life)	$ 28,274,335	$ 26,780,331	$ 1,494,004
Net Present Value (project life) per Wp	$ 0.28274	$ 0.26780	$ 0.01494
NPV Annual O&M Cost per kWh	$ 0.01259	$ 0.01172	$ 0.00088

LCOE Impacts Analysis

LCOE with connector	$37.86 /MWh
Total O&M cost	$12.8/MWh
LCOE w/o connector	$36.64 /MWh
Connector O&M cost	$1.22/MWh



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”

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

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

Conclusions:

- Failure data has been collected and failure distributions by year quantified
- Cost of connector O&M has been calculated by year
- Cost of lost production has been calculated by year
- Life Cycle Cost and Levelized Cost of Energy has been calculated
- Model available to inform decisions related to cost and performance of connectors.

Future Work:

- Continue to collect and update input information (cost and failure data)
- Address Liability Risks
  - Current TEA represents issues related to connector COST and LOST PRODUCTION
  - Stakeholders interviewed were equally concerned about LIABILTY, and the cost and availability of increasing levels of liability insurance.
- Expand TEA analysis to include other PV system components
  - Other types of connectors (IDC)
  - Rapid Shutdown Devices
  - Eventually all components

Thank you!!!

- Andy Walker PhD PE
- Andy.walker@nrel.gov