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Impacts of PV Module Connector Failures on Cost and Performance of Utility Scale Photovoltaic Systems

Andy Walker,[1] Vignesh Ramasamy,[1] Jal Desai,[1] Laurie Burnham,[2] Bruce King,[2] Steven DiGregorio,[2] Tapasvi Lolla,[3] and Wayne Li[3]

1 National Renewable Energy Laboratory
2 Sandia National Laboratories
3 Electric Power Research Institute

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List of Acronyms and Symbols

α	Shape factor of Weibull distribution indicating how spread out the probability of failure is over the years, obtained from heuristic failure data. (dimensionless)
β	Scale factor of Weibull distribution indicating over which years of the analysis period the failure distribution is highest, obtained from heuristic failure data. (dimensionless)
CAPEX	Capital Expenditure ($)
d	financial annual discount rate (%/year)
DOE	U.S. Department of Energy
g	annual degradation rate (%/year) in system energy delivery
i	financial annual inflation rate (%/year)
ITC	Investment Tax Credit (%)
k	an index referring to the number of the term in a polynomial expansion (dimensionless)
kW	kilowatt, direct current (DC) unless specified alternating current (AC)
kWh	kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
LCOE	levelized cost of energy
MW	megawatt
N	number of a certain type of component (for example N = 10,000 connectors in a system)
n/N	Fraction of total number of a specific type of component covered by reserve account in order to achieve desired probability that reserve account will be sufficient in a given year.
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
P	Probability that a component will not fail in any given year, specific to that year only, according to the statistical distribution of component failure. (dimensionless or %)
PV	photovoltaic
PVROM	PV Reliability Operations and Maintenance database
Q	probability that a component will fail in a year, Q=1-P (dimensionless or %)
$R_{desired}$	desired probability (or percentage) that the reserve account will be sufficient to pay for required replacements in that year (dimensionless or %)
SETO	Solar Energy Technologies Office
SNL	Sandia National Laboratories
T	duration of the analysis period, years
WACC	weighted-average cost of capital
Y	year of the analysis period (Year 1, Year 2, and so on)

Executive Summary

The reliability, cost and performance of electrical connectors are a concern in all types of electrical systems, and demands on connectors used on photovoltaic (PV) systems include that connectors maintain electrical conductivity and physical strength, endure ultraviolet sunlight and high ambient temperature, and resist moisture and chemical intrusion over an extended (e.g., 30 year) performance period. Connector failures increase operation and maintenance (O&M) costs and reduce plant production, but connector failure can also cause safety and liability problems, which are of greater concern. This work results from a three-year collaboration between Sandia National Laboratories (SNL), the Electric Power Research Institute (EPRI), and the National Renewable Energy Laboratory (NREL) and funded by the U.S. Department of Energy (DOE) Solar Energy Technology Office (SETO) under Agreements #39035 and #38531, titled "Connector Reliability Across the US Solar Sector." a multi-pronged investigation of PV connector health across the US (see https://energy.sandia.gov/pvconnectors/).
This report presents the derivation of a Techno-Economic Analysis (TEA) that models failure modes and frequencies (how often failure occurs), estimates O&M costs and lost production associated with connector failures, and then estimates the impact of PV module connectors on the Levelized Cost of Energy (LCOE)[1].

The model is informed with initial data from quantitative assessment of failure rates, root causes and mechanisms, in-situ diagnostics and data collection, lab-based forensics, and interviews with PV connector manufacturers and plant operators. SNL conducted site inspections at multiple utility-scale sites in different climates and subjected field samples of new, used, and degraded connectors to visual and electrical characterization. EPRI conducted metallurgical analysis of the pin and socket conductors to study failure-induced morphological and compositional changes. There is in general a shortage of statistically valid data, but data from the PVROM database maintained by SNL was sufficient to ascertain failure rates and lost production as well as provide qualitative insight in its curated maintenance records. This report details the structure of the mathematical model but the sources of data to inform the model will continue to evolve.

Analysis of a 100 MW PV plant is provided as an example of the use of the model, with results indicating that connectors are responsible for Annualized O&M Costs of $71,933/year; Annualized Unit O&M Costs of $0.72/kW/year; that a Reserve Account of $187,220 should be available to fund repairs related to connectors; that connectors add $1,494,004 or about 7% to the Net Present Value of the O&M Costs (project life); and that O&M related to connectors adds about $0.00088/kWh to the Levelized Cost of Energy.

The impact of this model is to provide a tool to make the US solar sector more robust by quantifying and monetizing the reliability risks to utility-scale PV systems posed by poorly installed, mismatched and/or poorly designed and manufactured connectors. The TEA provides a model incorporating failure statistics, O&M cost data, and lost production into a single figure of merit, informing decisions and enabling practitioners to optimize cost and performance trade-offs. Stakeholders include connector manufacturers, system designers and equipment specifiers,

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[1] LCOE is a controversial metric when comparing different types of generators in different locations, seasons, and times of day- but here we are using LCOE only as a metric to unify connector cost and performance and not to compare to other types of generators.

standards bodies, installers and O&M providers, investors and insurance underwriters. This report supports continued growth of PV predicated on assurances that properly installed and maintained PV system connectors are safe and reliable.

The project team is proposing future work including accelerated testing of connectors and expanding the approach taken here to other PV system components, such as TEA for rapid shut-down devices. The cost of increased insurance (e.g., regarding fires from PV installations) and opportunity cost (e.g., loss of production time and customers base in the event of a catastrophic event) may be addressed in the future. The cost of a complete replacement of all connectors in a PV system is also not covered here, but is known to occur in the industry.

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Introduction

Electrical connectors are a focus of reliability improvements in everything from submarines to space satellites, and photovoltaic (PV) systems are no exceptions. To connect two wires seems like a simple function, but connector performance has been challenged by the need to reduce initial cost, maintain sound electrical connectivity, provide ingress protection, and ensure physical support across all environmental conditions, for a extended period of time, and to maintain the ability to be re-opened and re-closed when necessary for module replacement. Connector failures increase operation and maintenance (O&M) costs and reduce plant production, but connector failure can also cause safety and liability problems. In addition, many procurement, installation and operational decisions are made without a full understanding of failure risks and their economic implications.

This report specifically addresses the techno-economic impacts of PV connectors and presents both an analysis of maintenance costs and also the implications of PV connector degradation and failure on the long-term performance, reliability and levelized cost-of-energy (LCOE) associated with PV plants. The report includes a quantitative assessment of failure rates, root causes and mechanisms, as learned from *in-situ* diagnostics and data collection, lab-based forensics, and interviews with PV connector manufacturers and plant operators. Failure modes and frequencies (how often failure occurs) are used to estimate O&M costs and lost production associated with component failures. O&M cost and lost production are then used to calculate the effect that PV module connectors can have on Levelized Cost of Energy (LCOE).

Ultimately, this report aims to help make PV system performance more reliable by identifying and quantifying the economic consequences of poorly-installed, mismatched and/or poorly designed/manufactured connectors. This report is intended to inform anyone with a vested interest in the performance, reliability and safety of PV systems including system designers and specifiers, manufacturers who need to make supply-chain decisions, engineering, procurement and construction (EPC) companies who need to meet performance warranties, O&M providers, investors concerned with underperformance of systems, insurance companies who want to avoid catastrophic failures, standards bodies concerned with safety and reliability, and government agencies who want to ensure that solar energy delivers on its generation projections. These are the stakeholders with the motive and the means to mitigate the risks associated with connector performance. To that end, this report describes an integrated technical and economic analysis (TEA) to quantify the impact of connector failure on PV lifecycle economic metrics, including energy yield, O&M expenses and LCOE. This work includes the modeling of O&M expenses and energy production losses related to degraded (high resistivity and temperature) and failed (melted, arcing or open-circuit) connectors and the impact of connector degradation and failure on a plant's LCOE. This data matters because DC power losses lower the amount of kWh (energy yield) that could otherwise be converted to PV project revenues, and replacement of failed connectors impacts project O&M expenses. The results of this analysis provide insights into the importance of product quality, proper installation methods, and/or more rigorous testing standards for connector product qualification.

The analysis is implemented within the "PV O&M Cost Model" an established model for PV system O&M costs over a system life cycle [Walker et. al, 2020]. This study focuses on the method to perform the analysis, but the results that can be used to inform decision making depend on data inputs such as climate and specific production (kWh/kW), location-specific labor costs, differing warranty coverages and production guarantees, and differing PV system descriptions. For example, a connector failure would be of greater consequence in a string of 16 PV modules than it would in a string of 10. Here we seek to identify default values for input data that represent general conditions and that result in reasonable estimates that can be interpreted generally, but the recommendation is that users confirm the defaults or replace default values with site-specific or project-specific data to inform decisions.

Background

This work results from a three-year collaboration between Sandia National Laboratories (SNL), the Electric Power Research Institute (EPRI), and the National Renewable Energy Laboratory (NREL) and funded by the U.S. Department of Energy (DOE) Solar Energy Technology Office (SETO) under Agreements #39035 and #38531 "Connector Reliability Across the US Solar Sector." a multi-pronged investigation of PV connector health across the US (see https://energy.sandia.gov/pvconnectors/).

The study considers failure rates and their associated causes as well as the implications of connector degradation and failure for short- and long-term performance and LCOE calculations. Work includes a quantitative assessment of failure rates, root causes and mechanisms, involving *in situ* diagnostics and data collection, lab-based forensics, as well as the economic costs and LCOE impacts of under-performing/failed connectors. The four main objectives, are to:

1) Investigate and document the operational functionality of connectors across the US solar infrastructure by conducting field inspections at PV sites representing a diversity of climates, designs and operational age;

2) Conduct forensics analysis on new, degraded, and failed connectors to identify compositional differences, failure mechanisms and root causes;

3) Calculate the economic losses attributable to degraded and failed connectors;

4) Disseminate knowledge, including risk reduction recommendations and best practices to industry stakeholders.

The project is structured in four tasks. For the first task, SNL is conducting site inspections at multiple utility-scale, utility-owned sites in different climates and geographies. SNL has amassed a large and growing inventory of field samples, representing sites across the US; different makes and models of connectors; and varying degrees of degradation and other anomalies. SNL has subjected new, used, and degraded connectors to visual and electrical characterization, considering both connector condition and improper installation.

In the second task, EPRI conducted metallurgical analysis of the pin and socket conductors, qualifying and quantifying baseline compositions as well as failure-induced morphological and compositional changes. EPRI does this by sectioning connectors and examining them with multiple forensics tools, including x-ray tomography, scanning electron microscopy, and electron dispersive spectroscopy.

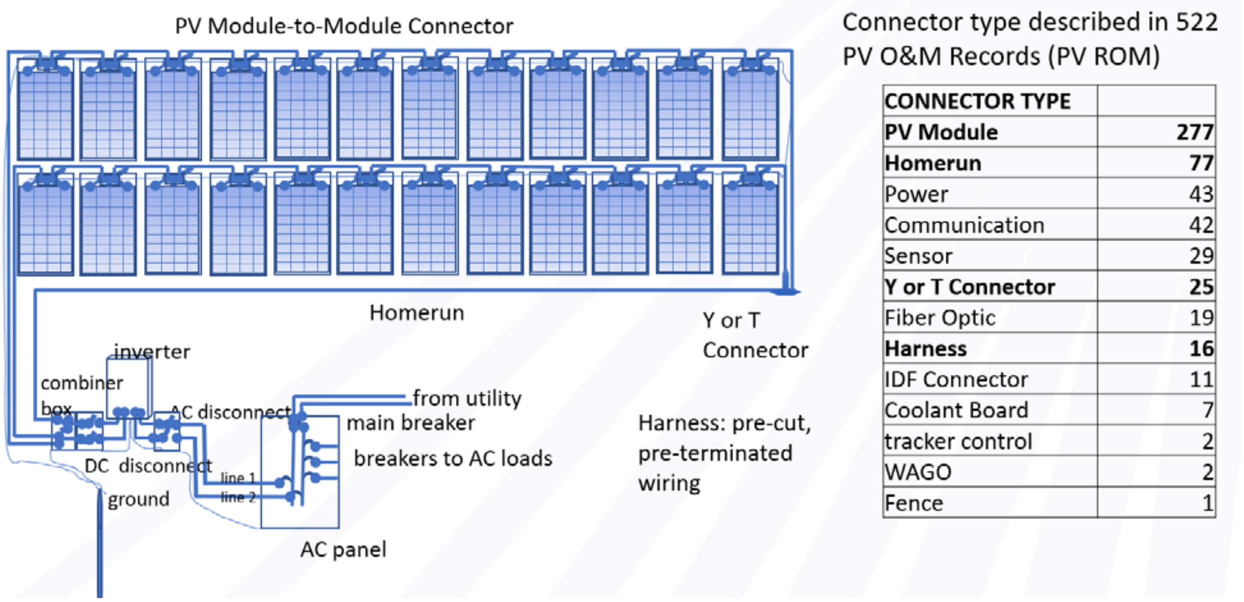
In the third task, and the subject of this report, NREL developed a connector cost and performance model to calculate the impact of connector degradation and failure on the levelized cost-of-energy. Data for the NREL economic model is divided into two main categories-of-interest: performance metrics (availability, performance ratio, and system degradation) and lifecycle cost (initial cost, O&M, replacement cost, and disposal costs).

The fourth task is Outreach and Knowledge Transfer through conference presentations, publications and stakeholder workshops.

The impact of this project is to make the US solar sector more robust by 1) identifying and quantifying the risks to commercial- and utility-scale PV systems in the US posed by poorly-installed, mismatched and/or poorly designed/manufactured connectors; and 2) conveying information, such as project data and overall findings, to stakeholders, including standards bodies, manufacturers, EPCs, investors and underwriters, who have the tools and means to mitigate the risks. Ultimately, this work is high impact, as it enables the continued growth of, and public support for, PV in the US, support that is predicated on assurances that solar energy is a safe, reliable, and economic alternative to other generation sources.

The project team is proposing future work including accelerated testing of connectors and expanding the approach taken here to other PV system components, such as rapid shut-down devices.

Types of Connectors used in PV Systems



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

Figure 1 Different types of Electrical Connectors employed in a Photovoltaic System [Source: "Solar Energy: Technologies and Project Delivery for Buildings, 2013]

Figure 1 shows the different types of electrical connectors found in a PV system. All types of connectors are possible failure points, but this report focuses on PV module-to-module connectors, home-run, and harnesses that connect to the string of PV modules, which are all of the same pin-and-socket type. As shown in the table of Figure 1, this type of connector is the most common among O&M records, but other types of connectors, such as the ribbon connectors (insulation displacement, or IDF connectors) used for communications and control are recommended for future study because they often result in central inverter downtime and whole-system downtime.

Each PV module comes from the factory with wire leads with a pin end on one wire and a socket end on the other wire to plug modules together into a string. At both ends of the string, another connector would connect the string to a “homerun” wire to take the circuit back to a combiner box or string inverter. So, the number of pin/socket paired connectors is equal to the number of PV modules in a system. In addition to making parallel connections in a combiner box, using a wiring “harness” with a Y or a T branch connector to combine two strings into one are increasingly common. Even if the reliability of each connector is high, the large number of connectors in a system ensures that at any given time the possibility of failure.

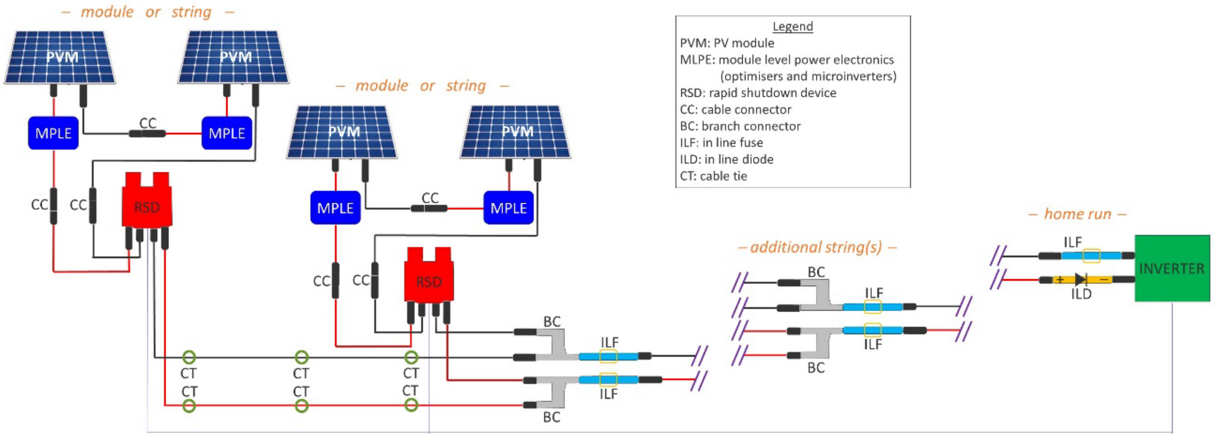


Figure 2. Use of Connectors in PV system circuits showing module-to-module, homerun, and harness locations of connectors. (figure by David Miller of NREL, used with permission).

Methodology

Figure 3 shows a flowchart of the techno-economic analysis. Data collection from the listed sources feeds into performance analysis, to cost analysis, and combination of technical and economic analysis resulting in an estimate of the impact that PV connector performance has on LCOE. LCOE is adopted as the single metric that incorporates both cost (in the numerator) and performance (in the denominator).

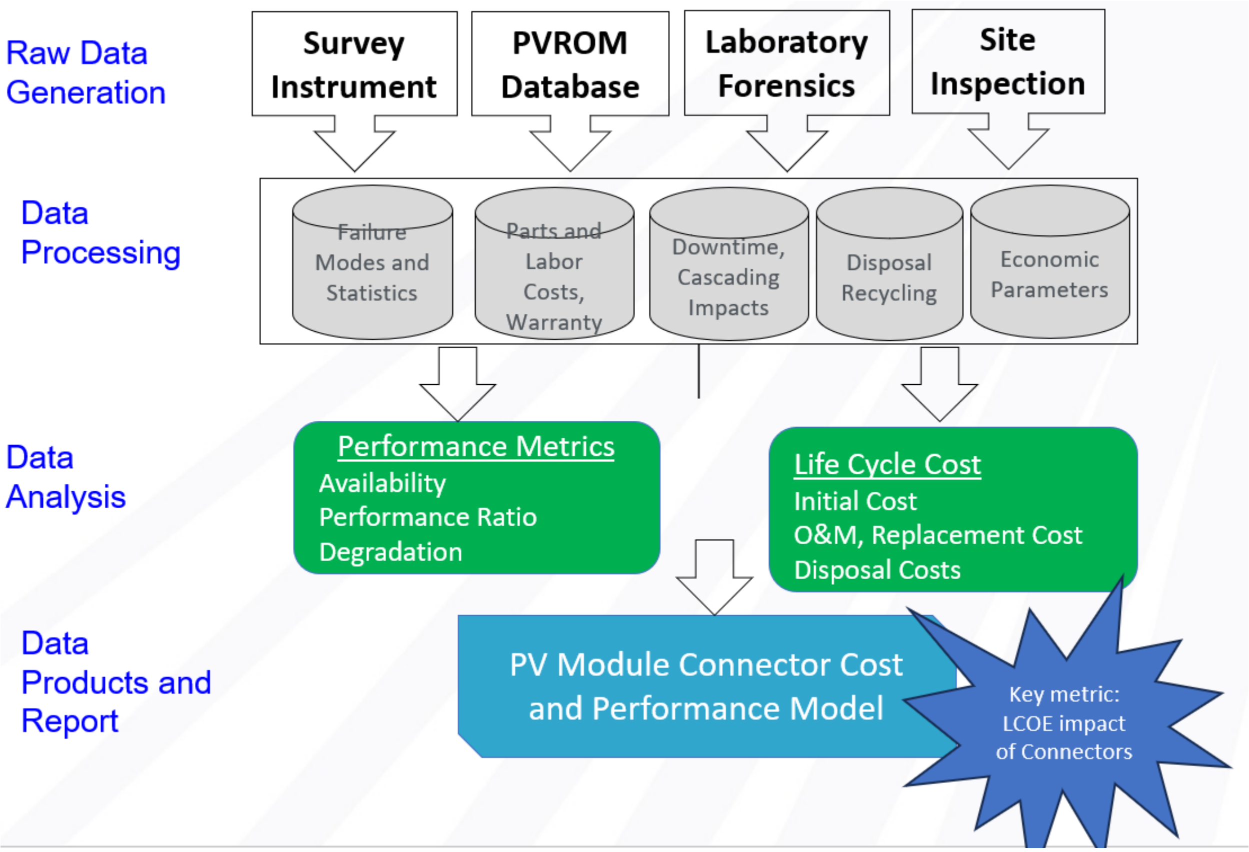


Figure 3. Schematic representation of the analysis including data collection, performance metrics, cost estimates, and combined technical and economic analysis resulting in an estimate of impact on PV plant LCOE..

Raw Data Generation

Data was collected through interviews with industry representatives and O&M practitioners, PVROM database (see description below) , laboratory forensics, and site inspections. Practitioners were more concerned about liability (possibility of an arc causing a fire) than they were about the maintenance cost or lost production associated with connectors (covered in this report), and investigation of liability is a recommendation for future work.

While all four data collection efforts provided qualitative data resulting in understanding and insight, the PVROM database was the source of quantitative failure data informing the analysis.

Laboratory Forensics

Scientists at EPRI have provided metallurgical analysis of the pin and socket conductors and quantification of baseline composition and failure-induced morphological and compositional changes. This data and images resulting from microscopy were important for understanding how it is that connectors fail, which helped interpret the failure data from the field.

Site Inspections

SNL staff conducted seven site inspections to observe connector conditions and collect connector samples. SNL staff visited 7 utility-scale plants in New Mexico, Florida and Louisiana and one distributed-generation-scale plant in Indiana. Site visits provided the practitioner contact information for the data-collection questionnaire, and added to qualitative understanding of failure rates and impacts of connectors on plant performance.

PVROM Database

SNL maintains a database called PVROM for PV reliability, operation, and maintenance. PVROM database contains site-level operations, maintenance, and production records from six industry partners for more than 50,000 O&M tickets at 837 sites in the US.. Natural Language Processing was used to sort 522 records related to connectors and to identify the mode of failure. The PVROM data provides an estimate of the failure rates for connectors. The time between the entry and closure of the trouble ticket was used to estimate lost production.

Data collected is processed to quantify parameters required to conduct the techno-economic analysis. For example,

The records include a narrative description of the issue and some common observations from the records or interviews include:

- Inverter indicates fault and subsequent inspection reveals ground fault where connector is submerged in water.
- Many records indicated the occurrence of a manufacturer recall where all connectors in system were replaced.
- Many records were created during periodic inspection where connectors were visually burned or melted.
- Infrared inspection reveals a string of hot modules, and inspection reveals an open circuit where connector was pulled off in mowing operation.

PV connectors that were factory installed on PV modules had low failure rates but are very numerous in each system; harnesses that are fabricated in a local cut-and-crimp operation had higher failure rates; and connectors on home runs that were field installed had the highest failure rate.

Word occurrence in 522 O&M work orders in PV ROM related to connectors results in the following counts that help identify common issues. SNL staff used Natural Language Processing to determine that certain words were indicative of different type of connector failures. The number of records including these words is listed in the following tables.

Table 1. Number of O&M Records associated with each Environmental Condition

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

Table 2. Number of O&M Records associated with each Cause of Failure

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

While "Recall" is not a cause of damage in itself, a recall results from product defects which have or could result in failure. Recall may include portions to the entirety of the PV system. Similarly, "Broken Module" also is not a result of connector damage in itself, but rather because the new module comes with a new connector.

Table 3. Number of O&M Records associated with each Condition of Connector

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

The words used are provided by the O&M service provider and many may be synonymous: burn, melt, arc fault, and fire might be considered to describe the same type of observed damage to a connector.

Table 4. Number of O&M Records associated with each way that Failure was Detected.

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

The words used to describe detection of failure were provided by the O&M service provider and may be synonymous. Detection of failure described as “inspection” often involves an inverter down with ground-fault error, and then the source traced to a failed connector (such as a connector detached from the rack and sitting in a pool of water on the ground). Thermal infrared cameras can spot a string of PV modules that have failed, and the source of that failure then needs to be traced to a failed connector. Unmanned aerial system (UAS), unmanned aerial vehicle (UAV), Drone, and Aerial inspection (e.g. by fixed-wing aircraft) are all means to obtain thermal images.

Failure Modes and Statistics

Preventive maintenance costs, such as inspection and cleaning, are incurred according to a specified fixed interval that stipulates a service will be performed on a periodic schedule (for example, every 10 years). But corrective maintenance services, such as replacement of a connector, depend on the probability that a component will fail in any given year, Q, which is calculated according to a probability density function, where year, Y, is the only variable. Once the data has been processed and associated Time to Failure (TTF) and Time to Repair (TTR) values are calculated, goodness-of-fit data are applied to different distributions to determine which distribution function best represents the data. For data used in this analysis, the Weibull distribution function was selected because failure occurs primarily because the failure probability increases with age and the standard deviation of the lifetime is so large which precludes the use of the log-normal distribution.

The equation for the Weibull probability density function is presented in Equation 1 (Green and Bourne 1972):

Equation 1

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

Where α = the “shape factor” of the distribution, indicating how spread out the probability of failure is over the years, and β = the “scale factor” of the distribution, indicating over which years of the analysis period the bulk of the failure distribution lies. The parameters α and β are obtained from heuristic failure provided by the PVROM database of failure and reliability data maintained by SNL. For the measures represented by Weibull distribution the shape and scale factors are listed in the following table, and for measures on a fixed interval the interval is listed in years. The corrective measures include: repair, replace, reset, modify, inspect, and clean as per the descriptors distilled from the maintenance records, but these terms require some interpretation. Here we consider "repair" to have the same materials and labor cost as to "replace" a connector. "Modify" is so infrequent that it is not included in the techno-economic analysis (to modify a connector is also probably prohibited by safety regulations and warranty requirements). Records describing "modification" often refer to re-routing of wiring and therefore replacement connector installation. Also listed in the table are the labor hours and material costs associated with each O&M measure.

Table 5. Frequency of each Corrective Measure represented by Weibull shape and scale parameters for corrective measures and fixed interval for preventative measures.

Activity Description	Mean Interval (β, years)	Weibull or Lognormal Shape Factor (α, dimensionless)	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

Parts and Labor Costs

The cost to replace a connector is listed in Table 5 as material cost of $4 per connector (for both pin and socket sides) and labor is of Journeyman Electrician (our assumption) at 0.10 labor hours per connector (informed by industry interviews) The hourly rate from National Bureau of Labor Statistics [NBLS, 2020] and qualifications of the labor are listed in the following table. We acknowledge that replacement requires circuit shutdown and "Lock Out Tag Out" (LOTO) so is more time-consuming and expensive than just the connector replacement. The additional cost of LOTO depends on number of connectors being replaced and their location.

Table 6. Labor rate and overhead multiplier used in the example analysis. [NBLS, 2020]

Service Category	2020 Labor Rates	Overhead Multiplier	Qualifications
Journeyman electrician	$24.12	1.38	Training as required by OSHA; training in arc-flash, lock-out/tag-out, and other special protective equipment and procedures; NABCEP PV Installer certification; experience in work on 1000 VDC voltage electrical systems. 5+ years experience with PV systems; color vision.

Other categories of labor may be employed, but considering the safety requirements and procedures we assume that a qualified Journeyman Electrician would be reasonable expectation.

Effect of Warranties

Warranties may be offered by manufacturers of connectors (product warranty), by PV module manufacturers, or by the installation contractor (EPC warranty). The warranty will specify whether the warranty covers parts, or labor, or both the cost of the part and the associated labor. If a service occurs within a warranty period, or is covered within a service package, the cost of the hardware, the labor, or both is reduced by the warranty coverage. Notice, then, that this cost analysis does not cover the total cost of O&M, just the cost to the system owner after warranty coverage has reduced the total cost. This logic is implemented with "if" statements that compare a given year to the year that a warranty expires, and "if" statements whether parts, labor, or both are covered.

Warranty issues can be complicated, depending on whether the failure is installation-related or a manufacturing defect. Interviews conducted with manufacturers indicate that some connector manufacturers do not offer any product warranties, and those that do provide replacement at the factory, so the owner has to pay all labor and shipping associated with a product (connector or PV module with connectors) return to factory. Warranties also put limits on how connectors can be re-sold to end users and time limits on how quickly a warranty claim needs to be made after failure. Warranties typically exclude replacements resulting from tampering, misuse, neglect, improper storage, normal wear, and cases where the connectors are worked on by anyone other than workers authorized by the manufacturer. If needed, the cost of litigation (if needed to motivate a warranty) is not covered in this analysis either.

In order to expose the full cost of connector maintenance, the effects of warranties are neglected (warranty coverage for both parts and labor set to zero).

Downtime and Lost Production

Lost production is estimated based on the date at which a trouble ticket is resolved minus the date at which the trouble ticket was initiated within the PVROM database. The median and mean (average) downtime associated with each measure is shown in the following table.

Table 7. Median and Mean (average) downtime (hours) as inferred from difference between action start and end 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

It is seen in Table 7 that there is a huge difference between the median and mean downtime of each measure. This is due to "outliers" which are individual failures that take months or even years to fix. Thus, while we recognize that these outliers expose a real problem in delivery of O&M, we use the "median" values in the subsequent cost analysis as a more reasonable expectation for the purpose of techno-economic analysis.

Modules are connected in a series string, so the lost production is estimated as the capacity of the series string of PV modules multiplied by the hours of downtime multiplied by the capacity factor. Since the hours of downtime is based on dates, and thus includes nighttime and low-production hours, the hours of downtime are multiplied by the capacity factor for the location in the estimate of lost production.

Cascading Impacts and Other Issues

Interviews with O&M practitioners and connector manufacturers were an important source of qualitative information to identify key issues and validate assumptions in the model. While practitioners were generally able to validate the cost and downtime approach and assumptions, they pointed out that the cost associated with connector maintenance and downtime are small compared to the exposure to liability should a connector start a fire or cause damage beyond the cost of the connector itself. Some comments from PV ROM trouble tickets are listed below.

"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 [Utility] 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 … bad connectors overheating, melting, starting ground faults or arc fault fires…"

NREL and other researchers are developing the mathematical framework to consider such hazards in life cycle analysis for PV systems. The assumption in this model is that a liability and property insurance policy will cover exposure to a hazard caused by the connector failure. The insurance premium is included in the operation costs.

Disposal and Recycling Issues

The form of the techno-economic analysis contemplates costs and impacts of disposal at the end of the performance period. Interviews with manufacturers indicate that connectors are made from materials that can be easily recycled. The tin-plated copper metal pin and socket parts can be pushed out of the plastic connector parts and recycled in non-ferrous metals stream. And some plastic parts are often acrylonitrile butadiene styrene (ABS) which is easily recycled. Since ABS can be easily melted and reformed at least one manufacturer told us in interview that they had plans to take the parts back to the factory for recycling. Other plastic components may be composed of silicone (PDMS), polypropylene, polyamide, or polycarbonate, not all of which are as readily recycled [Miller et.al., 2024]. However, SNL site visits revealed that connectors are most often disposed of without recycling. In this analysis, we include no special costs for either recycling or disposal of connectors.

Economic Parameters

Economic analysis and life cycle cost analysis are prepared according to standard methods and assumptions [NIST, 2022]. The approach is to estimate cost to replace connectors and to escalate that cost to the year in which the cost occurs according to an "inflation rate", *i*. Then the cost in each future year is discounted down to a present value according to a "discount rate", *d*. The number of years in the analysis period is given the symbol *T*. Net Present Value of life cycle cost is thus the key metric in life cycle cost analysis.

Calculations and Data Analysis

Annual O&M Cost associated with Connectors.

When applicable program logic (IF statement) compares the year under consideration with the warranty period to determine whether the warranty is in effect. Indicators of whether the warranty covers materials, labor, or both, are used to adjust the cost of parts and labor that occur in the warranty period. Initial cost of labor and materials is escalated to the year under consideration according to the specified inflation rate. The number of hours specified for a service is multiplied by the labor rate of the service provider to estimate labor cost. The estimated cost of a service is multiplied by the calculated probability of that service occurring in the year under consideration as per the Weibull distribution for a failure or the specified fixed interval for a preventative measure such as inspection and cleaning. To calculate the net present value the annual costs are discounted according to the discount rate, *d*. The calculation is repeated for each service and is repeated for each year in the analysis period to estimate annual cost associated with connector O&M from year to year.

This calculation of annual cost based on failure distribution serves as a basis for estimating net present value of O&M expenditures. Net present value is useful in a life cycle cost analysis to estimate cost indicators and metrics, such as cents/kilowatt hours (kWh) delivered or levelized $/kW/year associated with connectors.

Net Present Value of O&M Costs associated with Connectors

The net present value of connector O&M costs represents the annual costs each year appreciated to the year that they were incurred according to an inflation rate, *i*, then discounted to their present value according to the discount rate, *d*, and summed over the years of the analysis period.

Net present value O&M cost ($) is useful for informing life cycle cost decisions, such as choosing among alternatives. For example, a connector might have a lower initial cost but a larger annual O&M cost or more downtime than an alternative, and a life cycle cost analysis would be required to compare the two.

Annualized Life Cycle Cost of O&M Costs ($/Year):

The annualized life cycle cost of O&M costs ($/year) is calculated as the net present value divided by a present-worth factor calculated using the inflation and discount rates. So even though the cost varies considerably from year to year based on scheduled preventative measures and failure distributions, this provides the annual value levelized over all the years of the analysis period. The annual O&M cost ($/year) is the schedule of costs in each year of an analysis period, including variations from year-to-year caused by warranties, scheduled prescriptive measures, and failure probabilities. These costs are discounted according to the discount rate and summed to calculate net present value. Then the net present value is divided by a present-worth factor (calculated from inflation rate, discount rate, and analysis period) to get annualized life cycle cost of O&M cost. Annualized life cycle cost of O&M cost is a smoothed-out, levelized version of annual O&M cost, and is presented in Equation 2.

Equation 2

$$Annualized\ O\&M\ Costs\ = \frac{Net\ Present\ Value\ O\&M\ Costs}{[(\frac{(1+i)}{(d-i)})(1-(\frac{(1+i)}{(1+d)})^{T})]}$$

Annualized Unit O&M Costs ($/kW/Year):

The annualized unit O&M costs ($/kW/year) represents the annualized O&M costs divided by the plant size (kW) and the rated DC nameplate capacity of the plant, as in Equation 3.

Equation 3

$$Annualized\ Unit\ O\&M\ Costs\ = \frac{Annualized\ O\&M\ Costs}{Plant\ Size(kWp\ DC)}$$

Net Present Value (Project Life) per Watt:

The net present value per watt of rated capacity (DC) is the net present value divided by the rated plant size (W DC), as in Equation 4.

Equation 4

$$\text{Net Present Value (Project Life) per Watt}\ = \frac{Net\ Present\ Value\ O\&M\ Cost}{Plant\ Size(kWp\ DC)}$$

Levelized O&M Cost per kWh Delivered ($/kWh):

The levelized O&M cost per kWh delivered ($/kWh) represents the net present value O&M costs divided by the net present value of the energy delivery, which is the energy delivery for each year reduced by a specified degradation rate (default value = 0.7% per year), then discounted to present value according to the discount rate and summed through all years of the analysis period, as in Equation 5.

Equation 5

$$\text{Net Present Value (Project Life) per kWh} = \frac{Net\ Present\ Value\ O\&M\ Cost}{\sum_{y=1}^{life}\left[Annual\ Production\ (\frac{kWh}{year})\ \frac{(1-g)}{(1+d)^{y}}^{y}\right]}$$

Reserve Account

The failure distributions assign a rather small probability (often 1 or 2%) each year that a connector will fail, and yet we know from interviews with O&M practitioners that in reality there will be years with many failures and years with few. It is useful to estimate a "reserve account", such as a line of credit or cash reserve, that should be kept available so that repairs are not delayed by funding delays. The reserve account amount each year is estimated based on the number of connectors and the failure rate in each year. The details of this calculation are described in [Walker, 2020].

Example Analysis for 100 MW Utility Scale PV Plant

To demonstrate the method and calculations, consider a 100 MW Utility-Scale PV plant. The number of connectors is estimated as two per string plus one per PV module, for a total of 217,688 connectors in this example. For the estimate of lost production, the capacity factor for the location is taken to be 20.4%. Also, for the lost production calculation, we consider 14 modules in series, 525 W each, for a string power of 7.35 kW that is unavailable during downtime caused by a single connector. With these assumptions, and with other parameters such as failure distribution as discussed above, the key indicators with connectors and without connectors are compared to isolate the impact of connectors as shown in the following table.

Table 8. Impact of Connectors on Key Indicator in the example of 100MW Utility Scale PV Plants.

	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

In the example of this 100 MW Utility-Scale PV system, the annual maintenance cost varies from year to year as shown in Figure 4. There is an upward escalation of corrective maintenance costs caused by: 1) inflation increasing the cost of O&M; and 2) Weibull distributions showing increasing failure in later years. Every five years the cost of cleaning and inspection is visible in the figure. The "annualized" value (life cycle cost/year) is $72k/year associated with connectors. Dividing by plant size gives $0.72/kW/year additional O&M costs for connectors. A reserve account of $187k would be arranged to quickly repair larger-than-average correctional maintenance costs (such as storm damage). Over the 25 year analysis period connectors represent almost $1.5M in life cycle cost.

In addition to the maintenance costs of the above paragraph, connectors contribute to downtime and lost production (kWh not generated due to connector failure). In dividing by reduced production, the per-kWh-delivered of $0.00088/kWh includes the cost of maintenance and also the lost production of connector maintenance and underperformance and represents about 7% of the maintenance cost per kWh.

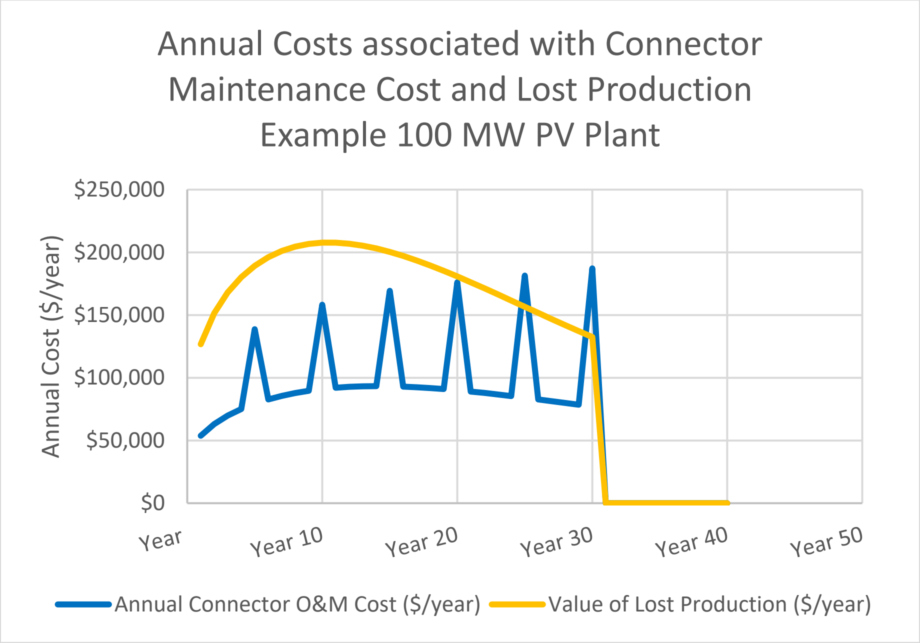


Figure 4. Graph of Maintenance Cost and Value of Lost Production ($/year) for example of 100 MW Utility-Scale PV System.

Failure of connectors, which affects both maintenance cost and lost production, is low initially but increases as the probability of failure increases due to the Weibull distribution. In our simple model, once a connector fails and is replaced it is no longer subject to failure. To model compound probabilities of failure requires a complicated simulation, which has not been done here. Lost production follows the failure distribution but lost production is a fraction of total production, and the total production declines from year to year due to the degradation rate of the PV system, which is assumed to be 0.7%/year in this example. Just due to this degradation rate, annual lost production will be 20% less at the end of the 30 year analysis period than at the beginning.

LCOE Modeling Inputs & Assumptions

LCOE encompasses various PV metrics beyond just the initial installation expenses that play a crucial role in determining overall energy costs. Following are some of the key LCOE factors included in our analysis.

1. Capital expenditures: This includes the upfront cost of installing the PV system, encompassing panels, inverters, racking, electrical equipment, installation labor, permitting and interconnection, and any other “soft costs”.

2. O&M: Regular upkeep and maintenance are crucial for optimal PV system performance. LCOE accounts for these ongoing costs such as module cleaning, vegetation management, system inspection, components replacement including connectors, land lease, property tax, insurance, asset management and administration.

3. System lifespan: The duration of the life cycle analysis period is based on the expectation for PV modules lifespan, typically around 25-30 years. LCOE considers the total energy production over the system's lifetime, providing a more accurate picture of energy costs.

4. Financing costs and benefits: Borrowing money to install a PV system incurs interest expenses. LCOE incorporates these costs to reflect the true financial impact of installed PV system. It also takes in to account any applicable tax credit and depreciation benefits.

5. Energy production: Ultimately, the amount of energy a PV system generates is its core value. LCOE considers the system's expected electricity output over its lifetime incorporating any applicable performance degradation associated with the PV system.

To understand the techno-economic impact of failed connectors and connector replacement we carry out a simplified LCOE analysis using the following formula.

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

I = Initial Capital Investment
F = Follow-on investments (inverter replacement etc.,)
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

Table 9 below shows the modeling inputs and assumptions for our base case LCOE analysis.

Model Component	Model Input	Description	Sources
PV System size	100-MW$_{DC}$ PV	A large utility-scale system capacity	NREL 2023
ILR	1.34	Inverter Loading Ratio	LBNL 2021
Initial investment	$116,000,000	Installed overnight capital cost of the PV system	NREL 2023
System lifetime	30 years	Analysis period of PV system	NREL 2022
Interest rate	6%	Interest rate on the amount loaned	NREL 2022
Tax rate	21%	Corporate Tax Rate	NREL 2022

Model Component	Model Input	Description	Sources
Nominal Equity Rate	7.75%	Rate before taking inflation into account	NREL 2022
Real Equity Rate	5.12%	Rate adjusted for inflation	NREL 2022
ITC	30%	Investment Tax Credit	IRA 2023
Debt Term	18 years	Duration of the loan	NREL 2022
Residual value	$0	Assumed remaining value of the asset at the end of project life term	NREL 2022
Initial annual system production	1,440 kWh/kW	Average system production in year 1	NREL 2022
Average Plant O&M Expenses ($/kW/yr)	$27.34	Average O&M expense for the project life term	NREL 2023
Average connector related O&M cost ($/kW/yr)	$1.29	Modeled average connector related O&M expense for the project life term	NREL 2023
PV Degradation Rate	0.7% per year	System degradation rate	NREL 2022
Inflation	2.5%	20-year U.S. average CPI	FRED 2022

LCOE Results

To present an accurate assessment of current costs, we calculate the LCOE under the assumption of long-term, stable financing without factoring in tax credit benefits, or considering today's higher interest rates (which exceed historic average over decades). The results, outlined in the table below, indicate an LCOE of $36.64/MWh, assuming no connector failures and no energy production losses related to connectors.

However, upon incorporating the impact of connector-related issues into the analysis, the LCOE experiences a 3.3% increase, reaching $37.86/MWh. Additionally, the total estimated value of energy generated over thirty years by the PV plant, without considering connector impact, is $159 million. Conversely, the estimated value of energy lost due to connector failure amounts to approximately $4 million over the same period, with a present value of the energy lost estimated at $2 million.

LCOE w/o connector impact	$36.64 /MWh
LCOE with connector impact	$37.86 /MWh, 3.3% higher
Estimated Revenue over 30 Years	$159 MM

Estimated Lost Production Value (Total)	$3,916,272
Estimated Lost Production Value (NPV)	$2,011,195

If we assume that the Power Purchase Agreement (PPA) value aligns with the Levelized Cost of Electricity (LCOE) considering connector impact, and we incorporate a yearly escalation rate of 2% in the PPA, the estimated percentage of potential revenue lost due to connector failure is approximately 2.4%. However, when the PPA escalation rate is increased to 5%, the corresponding percentage of potential revenue lost due to connector failure rises to around 3.8%.

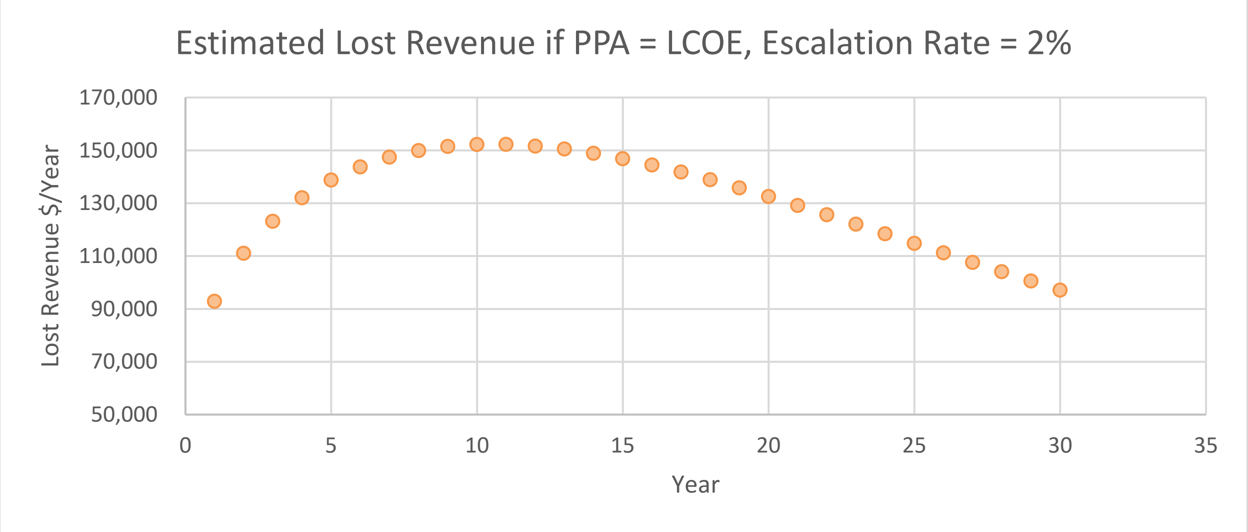


Figure 5. Lost revenue associated with lost energy production due to connector failure and down-time.

The graph depicted in Figure 5 illustrates the projected annual revenue losses attributable to connector impact throughout the project's lifetime, reflecting the effects of the Weibull failure rate and the assumed annual degradation rate. The annual revenue loss exhibits a gradual increase up to year 10, plateaus from year 11 to year 13, and then begins to decline from year 14 onwards. The initial surge in revenue loss is attributed to the higher probability of connector failure during its initial lifetime.

LCOE Sensitivity Study

Considering the prevailing market volatility and technical uncertainties, performing a sensitivity analysis becomes crucial. The benchmark scenario may not encompass the full spectrum of variability among projects concerning technological and economic factors. To gain a deeper insight into the sensitivity of key parameters, we have constructed a tornado graph, as shown in Figure 6 below. This graph explains the sensitivity study conducted on the LCOE for a 100 MW_{DC} photovoltaic (PV) system, including the impact of connector failure.

The boundaries of these sensitive parameters, both lower and higher, have been established by referencing reputable sources such as NREL's PV cost benchmark (Ramasamy, et al, 2023), LBNL's Tracking the Sun (Barbose, et al, 2023), Bureau of Labor Statistics (NBLS, 2020), and insights derived from PVROM dataset, and industry interviews.

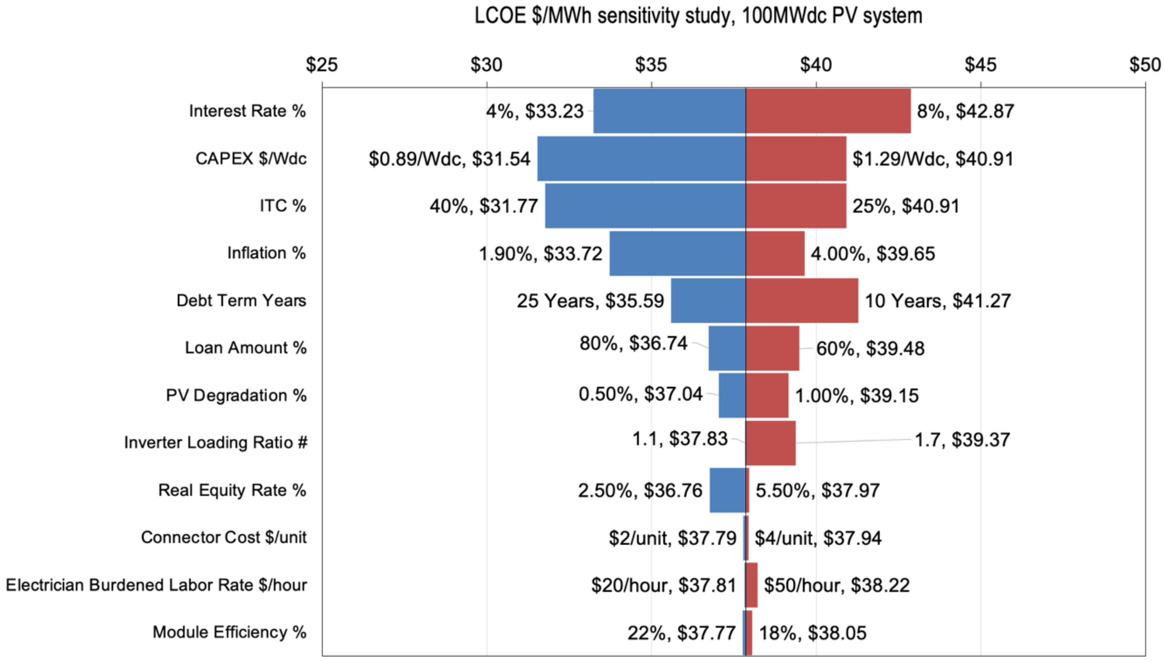


Figure 6. Results of Sensitivity Analysis showing effect of assumptions on calculated LCOE.

Our sensitivity study yielded the following key findings:

1. The interest rate emerges as the most sensitive variable, closely followed by CAPEX, ITC, and the inflation rate. This implies that alterations in these variables have the most pronounced impact on the Levelized Cost of Electricity (LCOE) for the PV system.
2. An increase in the interest rate, CAPEX, and inflation rate corresponds to a rise in the LCOE of the PV system. This relationship is due to the fact that these variables contribute to an escalation in the overall costs associated with owning and operating the PV system.
3. Conversely, an increase in ITC, debt term, loan amount, and module efficiency lead to a decrease in the LCOE of the PV system. This is attributed to these variables mitigating ownership and operational costs or enhancing the system's electricity generation capacity.
4. The LCOE of the PV system exhibits relatively low sensitivity to changes in other variables, including PV degradation rate, inverter loading ratio, real equity rate, electrician's labor rate, and connector cost.

In summary, our findings emphasize that interest rate, upfront CAPEX, ITC, and inflation rate are pivotal factors influencing the LCOE of a PV system, whereas connector-related parameters demonstrate less significant impacts on the LCOE. Nevertheless, our analysis does not encompass the cascading impacts of failed connectors and their associated value. This aspect merits exploration in future research endeavors.

Conclusions

This report presents a Techno-Economic Analysis (TEA) for PV connectors that estimates O&M costs and lost production associated with connector failures, and that calculates the effect that PV module connectors can have on key indicators such as Levelized Annual O&M Cost and Levelized Cost of Energy (LCOE). The data informing the model can be continuously updated and improved, and is informed with initial data from quantitative assessment of failure rates, root causes and mechanisms, in-situ diagnostics and data collection, lab-based forensics, and interviews with PV connector manufacturers and plant operators.

This TEA model provides a tool to quantify and monetize the reliability risks to utility-scale PV systems posed by poorly installed, mismatched and/or poorly designed and manufactured connectors. The model incorporates failure statistics, O&M cost data, and a calculation of lost production into LCOE as a single figure of merit, informing decisions and enabling practitioners to optimize cost and performance trade-offs.

An example is provided to demonstrate how the TEA model might be useful to inform decisions by connector manufacturers, system designers and equipment specifiers, standards bodies, installers and O&M providers, investors and insurance underwriters. Example analysis of a 100 MW PV plant is provided to demonstrate calculation of Annualized O&M Costs ($/year); Annualized Unit O&M Costs ($/kW/year); that a Reserve Account of a calculated amount should be available to quickly fund repairs related to connectors; the Net Present Value of the O&M Costs (project life); and the impact of O&M related to connectors on Levelized Cost of Energy ($/kWh). In the example, connectors were found to constitute 7% of annual operational expense and 3.3 % of the LCOE. While the cost of a hazard and liability insurance premium is included in the analysis, we note that the cost of increased insurance (e.g., regarding fires from PV installations), opportunity cost (e.g., customers base in the event of a catastrophic event), and possibility of a complete replacement of all connectors in a PV system including those that have not failed are not covered in this analysis.

Recommendations for future work include: accelerated testing with field validation of connectors as another source of failure rate data; and expanding the approach taken here to other PV system components, such as TEA for rapid shut-down devices, and eventually to all components of a PV system.

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