PV O&M Cost Model and Cost Reduction

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Classifications Involving PV O&M Costs

Category	Component	Environmental Conditions	Service Category
Administration	AC Wiring	Snow	Administrator
Operations	Asset Management	Humid	Cleaner
Design	Cleaning/Veg	Hot	Designer
Preventive	DC Wiring	Pollen	Inspector
Corrective	Documents	High Wind	Inverter specialist
Decommission	Electrical	Hail	Journeyman electrician
	Inverter	Salt Air	Master electrician
	Mechanical	Diesel Soot	Mechanic
	Meter	Industrial Emissions	Network/IT
	Monitoring	Bird Populations	Pest control
	PV Array	Construction Site Nearby	PV module/array Specialist
	PV Module	Sand/Dust	Roofing
	Roof	High Insolation	Structural engineer
	Tracker		Mower/Trimmer
	Transformer		Utilities locator

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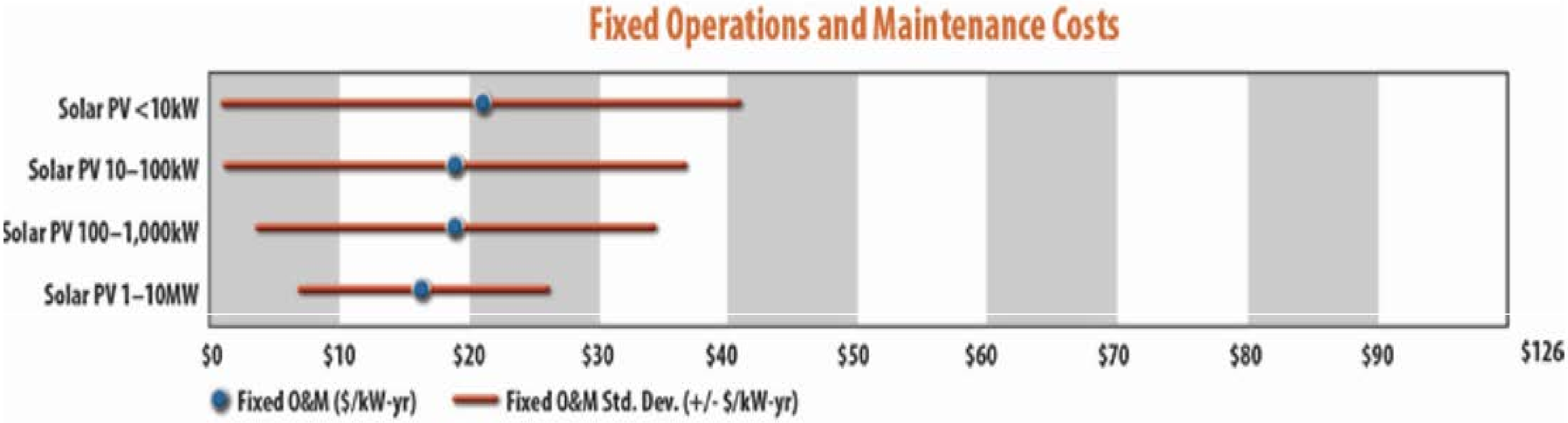
Heuristic PV O&M Costs

Often a single annual value is reported per kW or per kWh.



NREL Annual Technology Baseline

- $16.7/kWDC/yr for Utility-Scale
- $20/kWDC/yr for Residential

There is a wide range in the reported data from $0 to $110/kW/year

Source: FEMP Cost and Performance Matrix , http://www.nrel.gov/analysis/tech_cost_om_dg.html
Annual Technology Baseline, http://www.nrel.gov/docs/fy16osti/66944.pdf

Estimating PV O&M Costs

The PV O&M Working Group concentrated on three estimates related to the cost of delivering a PV O&M Program:

- Annual Cash Flows
- Net Present Value, LCOE
- Reserve Account

The working group has developed a PV O&M Cost Model that can be used to estimate O&M costs.

Weibull Failure Distribution

Q, the probability that a component will fail in any given year, y, is calculated according to the Weibull probability density function.

The equation for the Weibull probability density function is:

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

α = the "shape factor" of the distribution, indicating how spread out the probability of failure is over the years,

β = the "scale factor" of the distribution, indicating over which years of the analysis period the bulk of the failure distribution lies.

Parameters, α and β, are obtained from heuristic failure data

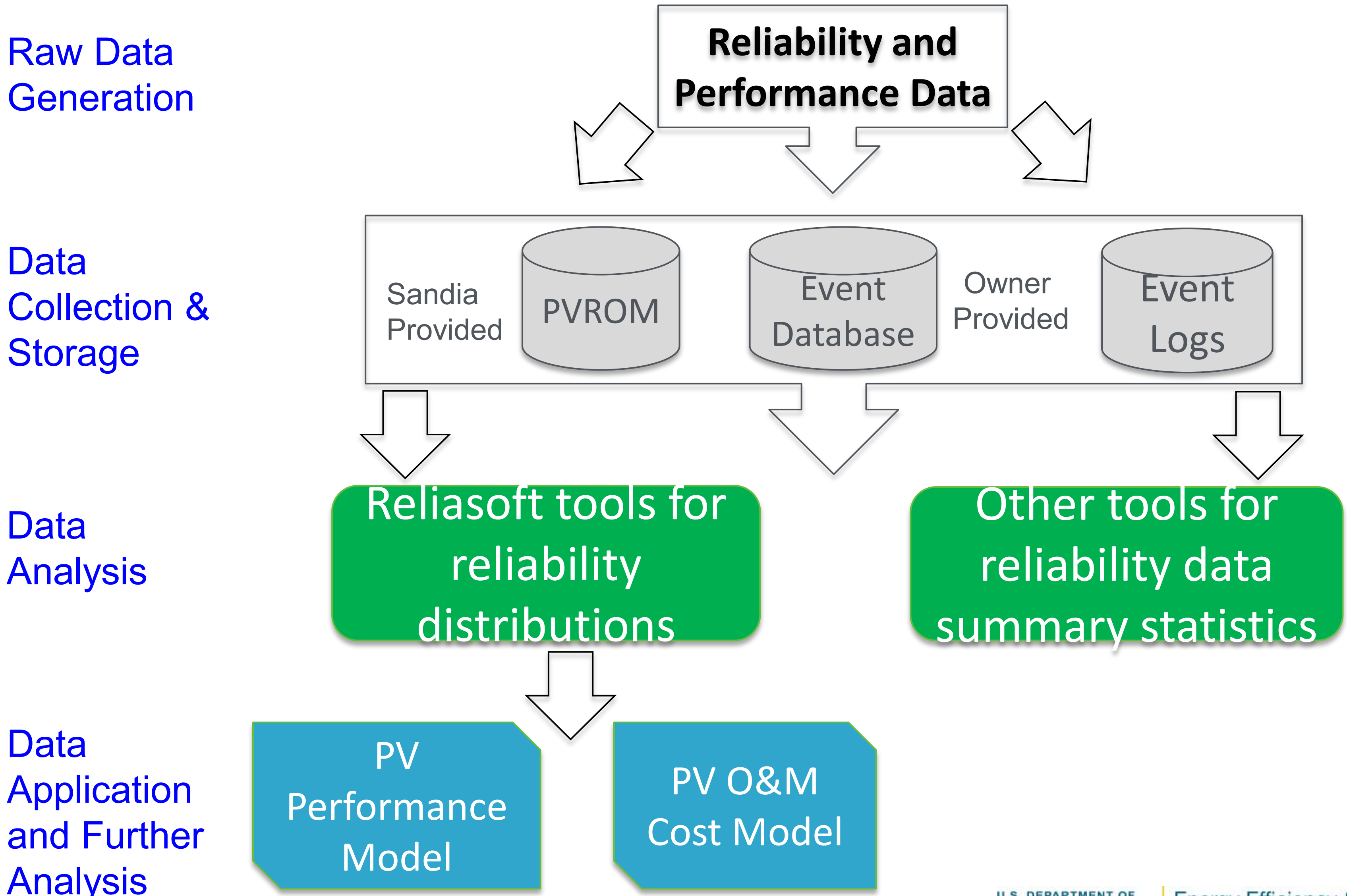
PV ROM database of failure and reliability data; Sandia National Laboratory.

MS Excel function

=WEIBULL.DIST(y,α,β,FALSE).

Source: http://reliawiki.org/index.php/The_Weibull_Distribution

Sandia's General Process for Evaluating Reliability Impacts



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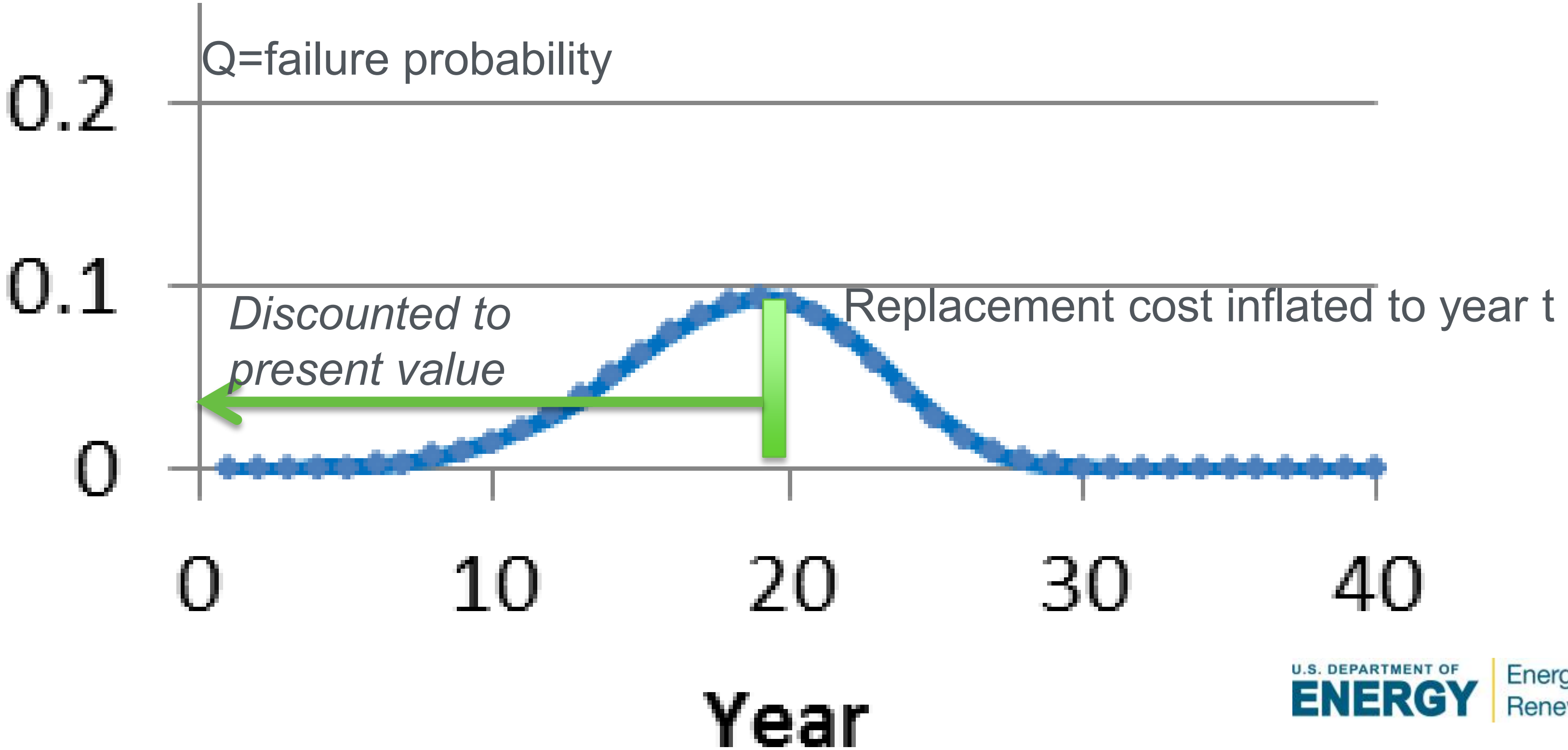
Source: Geoff Klise, Sandia National Laboratories

Net Present Value of Replacement Cost

$C_{replacement}$ = Cost to replace Component in year 1
Q= probability of failure of component in each year t
d=discount rate (%/year)
i=inflation rate (%/year)
t=number of year

Present Value=$C_{replacement}$ x Q x (1+i)^t / (1+d)^t



Calculation of Reserve Account - Background

- Weibull distribution of failure gives us a good estimate of life-cycle cost and levelized cost of energy (LCOE), but the method spreads the costs over the years and show a rather uniform average cost per year.

- Financiers are asking for a tool that calculates "maximum exposure"; in other words, what dollar amount of a "reserve account" or "line of credit" would a bank offer to sell to a project?"

- Reserve account is calculated for each year of the analysis period.

Definition of Terms

- P= the probability that a component will not fail in any given year, specific to that year only according to the Weibull distribution of component failure.
- Q= the probability that a component will fail in the same year;
- (P+Q)=1
- R= the desired probability that the reserve account will be sufficient to pay for required replacements in that year.
- N=the number of a certain type of component (for example N=10 inverters, N=500 combiner boxes, or N=50,000 PV modules)

Start With a Simple Example…

Consider two inverters:

N=2

Replacement Cost (Year 1):

$C_{replacement}$ =$10,000 each

Weibull Failure Distribution:

Mean Interval (years) β=20

Shape Factor α=5.0

In year 20:

P = probability of non-failure

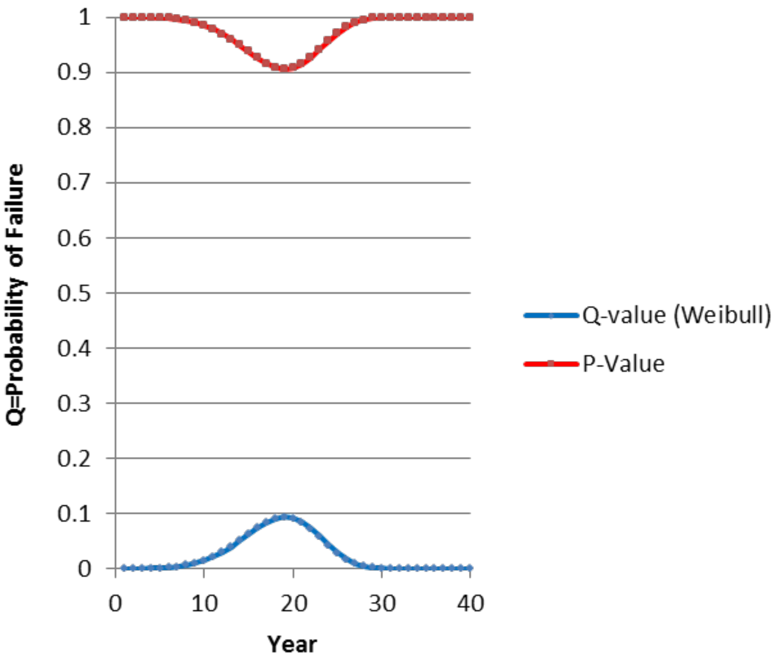
P = 0.908

Q = probability of failure

Q = 0.092

Weibull distribution

=WEIBULL.DIST (Year, Shape Factor, Mean Interval)



Mind Your P's and Q's…

- Spare in Reserve for NEITHER of the two inverters:
  Reserve Account: $0
  $P_1P_2 = P^N=(0.908)^2=0.824$ (you get this level of availability for free)
- Spare in Reserve for EITHER ONE of the two inverters:
  Reserve Account=$10,000
  $P_1P_2 + P_1Q_2 + P_2Q_1 = 0.824+(0.908*0.092)* 2 =0.991$
- Spares in reserve for BOTH of the inverters:
  Reserve Account= $20,000
  $P_1P_2 + P_1Q_2 + P_2Q_1 + Q_1Q_2$
  $=0.824+0.300+ (0.092)^2=1.00$
- So in this simple example; the result would be "within a 99.1% chance your maximum exposure any year will be less than the cost of one inverter", or $10,000.
- Notice that if we raise the desired probability from 0.99 to 0.999 (three nines), then our maximum exposure would be the cost of two inverters in the year, or $20,000.
- The cost model is coded such that the desired probability is an input, with a default of 0.95, and the calculation returns the required amount of Reserve Account

Desired Probability that Reserve Account is Sufficient	Reserve Account
0.824	$0
0.991	$10,000
1.000	$20,000

General Polynomial Expansion

Binomial Theorem, 1666, Sir Isaac Newton

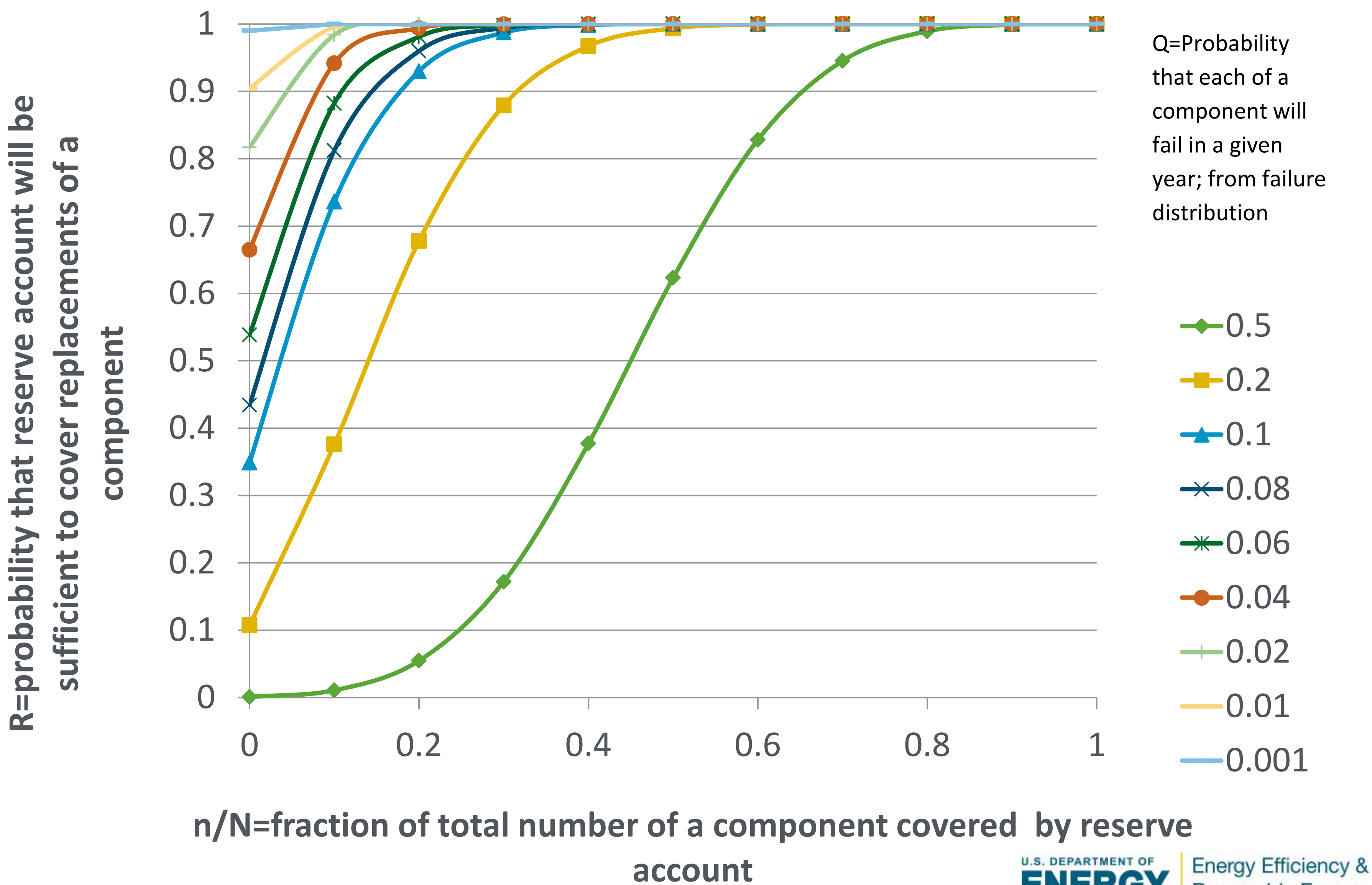
$(P+Q)=1$

Total number of components = N
Number of components funded in reserve account=n

$(P+Q)^N = 1$
$P^N + NP^{N-1}Q + N(N-1)P^{N-2}Q^2/2! + \ldots + Q^N = 1$

Add up the first n+1 terms to find the probability that n components will be operational ($1<n<N$).
Polynomial Expansion form changes with N, and computationally intense to evaluate at large values of N

Reserve account graph



Example Calculation of Reserve Account

In this example we consider 10 components, each with a replacement cost of $1000 in a given year, and with a Weibull failure probability of Q=0.05 in this given year.

The desired probability that the reserve account will be sufficient is R=0.999 (99.9% certainty).

INPUTS

N= 10

$C_{replacement}$= $1,000

Q= 0.05

R= 0.999

The resulting dollar amount to keep in the reserve account to cover failure of this component in the given year is (0.303)*(10)*($1000) or $3,030.

OUTPUTS

Required n/N=0.303 (required fraction of total number of component covered by reserve account in order to achieve desired probability that reserve account will be sufficient in a given year)

C reserve account = $3,030 (amount in reserve account for this type of component in this given year)

Implementation of NPV and Reserve Account in Cost Model

Continue example of two inverters

Inputs

Number of Inverters: 2

Replacement Cost (each): $10,000

Desired Confidence that Reserve Account Sufficient: 0.900000

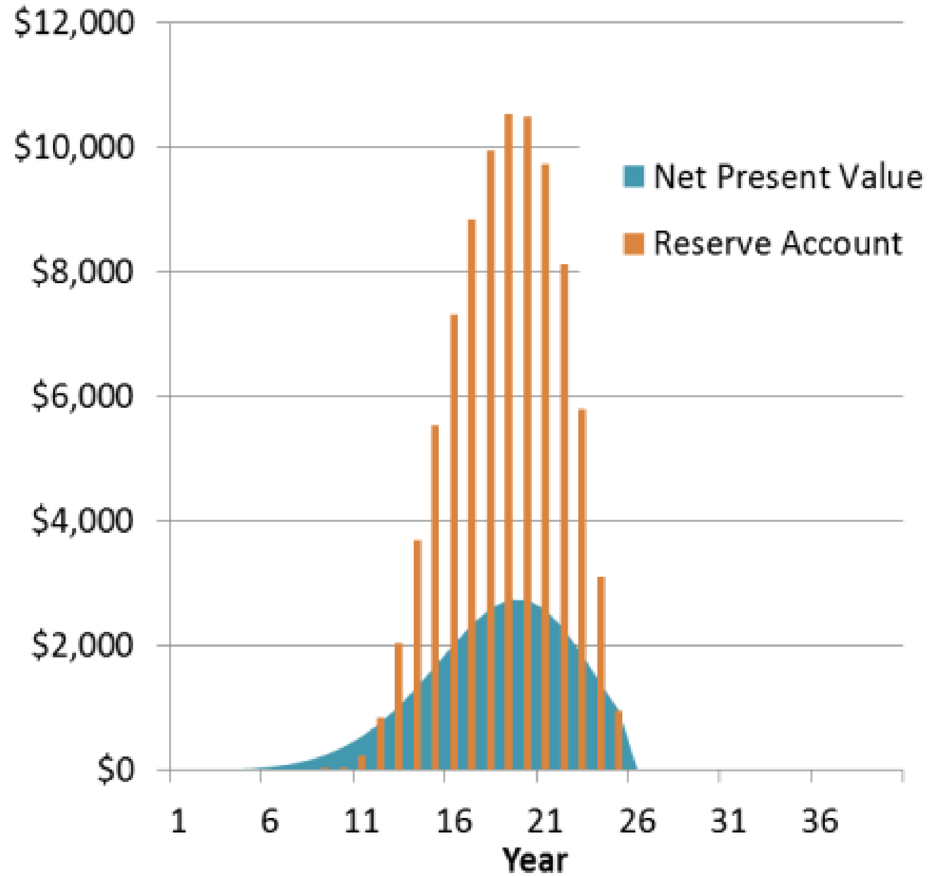
Mean Interval (years): 20.00

Weibull Shape Factor: 5.00

Analysis Period: 25 years

Discount Rate: 7.00% per annum

Inflation Rate: 2.00% per annum



Outputs

Net Present Value of Replacement Costs $8,284

Maximum Amount Reserve Account $10,501 in year 20

Calculation of Net Present Value and Reserve Account

- Annual Cost and Reserve Account both modified by:
  - Within analysis period?
  - Within warranty period?...type of warranty?
  - Fixed interval or Weibull distribution?
  - Yearly inflation of costs.

- This is done for each measure in the PV O&M Cost Model (PV module replacement, inverter replacement…all) and added up to calculate the total amount in the Reserve Account for each year of the Analysis Period.

Inputs

General Inputs		
Analysis Period (Project Life)	25	years (40 max)
Discount Rate	7.00%	% per annum
Inflation Rate	2.00%	% per annum
Desired Confidence that Reserve Covers Cost	0.92	
Working Hours/year	2,080	

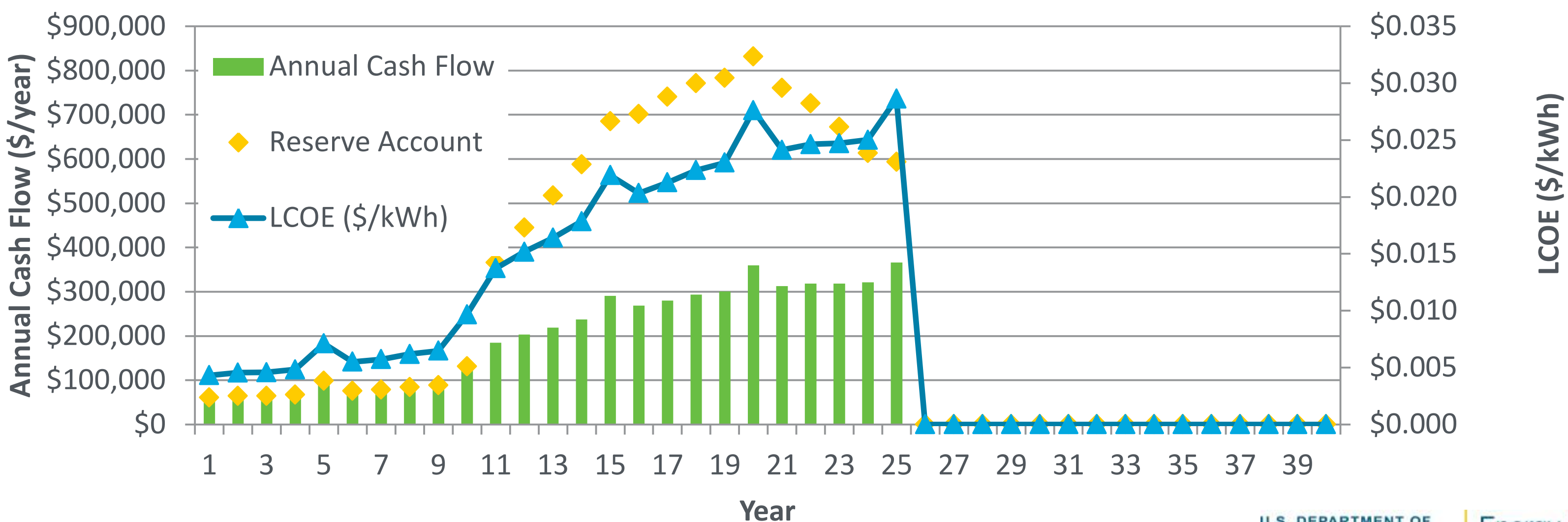
System Inputs		
Name of System	Ground Mount Tracking	
Location	Denver, CO	
System Size (kWp DC)	10,000.0	
Energy Yield Year 1 (kWh/kWp/year)	1,400.0	
System Installed Cost	$3,000,000	
Module Efficiency	16.0%	
Module Power (W STC)	305	
Array Area (m2)	62500	
Number of Modules	32787	
Module Type/ Degradation	Mono-crystal silicon: 0.36%/year	
Degradation Rate per year	0.0036	
Modules per String	14	
Number of Strings	2342	
Strings per Combiner Box	15	
Number of Combiner Boxes	157	
Combiner boxes per DC disconnect	1	
Number of DC Disconnects	157	
Inverter Type	Central Inverter	
Inverter Replacement Cost/ Wp	$0.190	
Number of Inverters	10.0	
Inverter Capacity (kWp)	1,000.0	
Number of Transformers	10.0	
Inverter Warranty (years)	10.0	
PV Module Product Warranty (years)	10.0	
Other equipment (EPC) Warranty (years)	1.0	
Purchased monitoring contract (years)	0.0	Enter '0' if not applicable

Market Sector	Utility (1 MW)
Mounting Location	Ground Mount
Roof Slope	Sloped, 4:12
Type of Roofing Material	Composite Shingle
Mounting Type	Attached
Inspection technique	Arial
Array Area per Roof Attachment (m2)	2.0
Number of Roof Attachments	31250
Ground Coverage Ratio (GCR)	33%
Site Area (acres)	52.6
Modules/Row	200
Total Rows:	164
Tracking or Fixed	1-axis Tracking
Rows per Tracked Block:(ignore untracked)	16
Total Tracking Blocks:(ignore untracked)	10.2
Foundations per row: (ignore rooftop)	10

Environmental Conditions	
Indicate "1" if condition applies to project, "0" if not applicable	
Snow	0
Pollen	1
Bird Populations	0
Sand/Dust	0
Humid	*Not yet implemented*
Hot	*Not yet implemented*
High Wind	*Not yet implemented*
Hail	*Not yet implemented*
Salt Air	*Not yet implemented*
Diesel Soot	*Not yet implemented*
Industrial Emissions	*Not yet implemented*
Construction Site Nearby	*Not yet implemented*
High Insolation	*Not yet implemented*

PV O&M Cost Model Results

Results	
Annualized O&M Costs ($/year)	$126,471
Annualized Unit O&M Costs ($/kW/year)	$12.65
Maximum Reserve Account	$831,685
Net Present Value O&M Costs (project lif	$1,800,124
Net Present Value (project life) per Wp	$0.180
NPV Annual O&M Cost per kWh	$0.011



High LCOE in Late Performance Period

- Warranties have expired
- Inflation has raised parts and labor prices
- The Weibull failure distributions show high failure rates in later years
- The performance had degraded (0.5%/year)

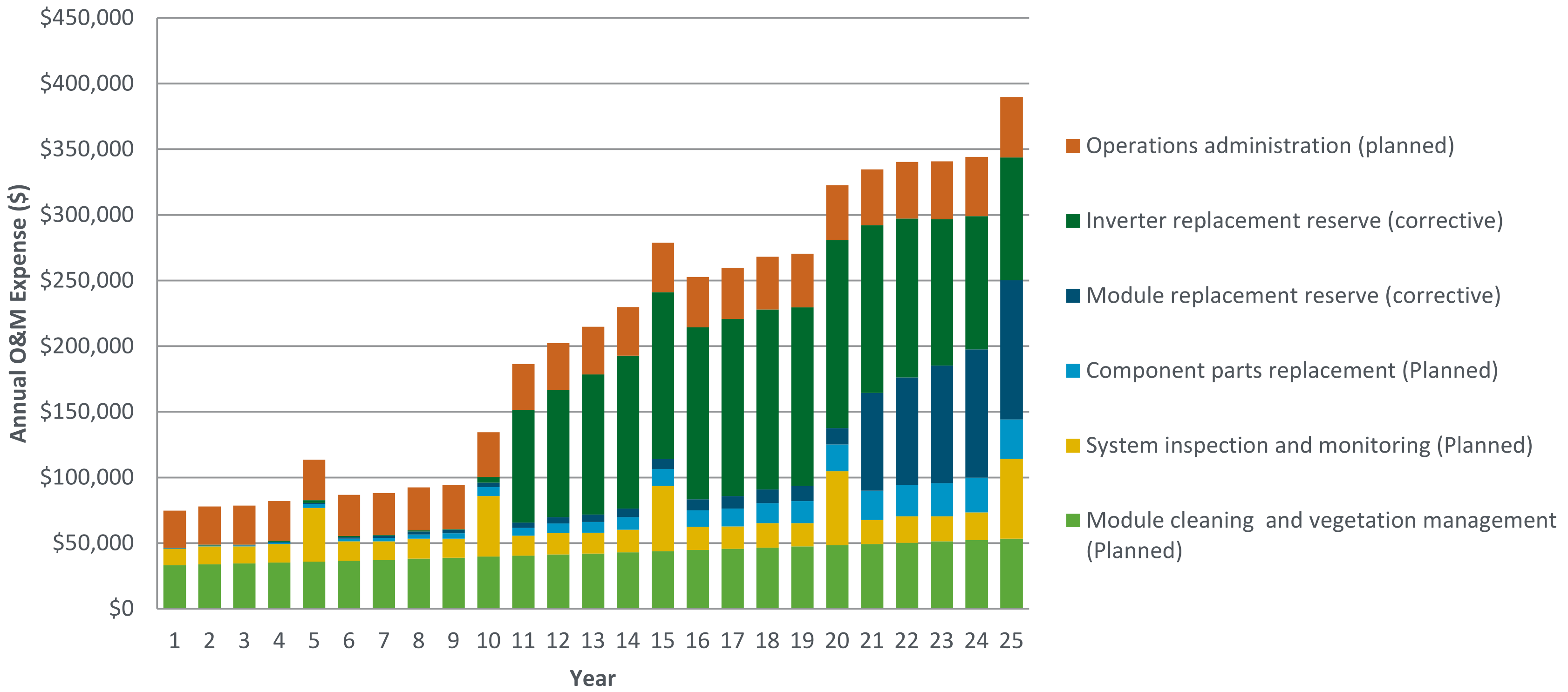
Results by Component

Lifetime NPV by Service Type			
Service	Avg. Cost/Yr	NPV (Life)	% of Total
Administrator	$8,139	$88,635	5%
Cleaner	$25,239	$274,892	15%
Inverter specialist	$71,551	$550,944	31%
Inspector	$26,850	$286,646	16%
Journeyman electrician	$29,261	$216,399	12%
PV module/array Specialist	$14,563	$114,939	6%
Network/IT	$186	$1,825	0%
Master electrician	$7,223	$53,383	3%
Mechanic	$2,132	$14,926	1%
Designer	$0	$0	0%
Pest control	$1,702	$18,536	1%
Roofing	$0	$0	0%
Structural engineer	$10	$69	0%
Mower/Trimmer	$16,424	$178,884	10%
Utilities locator	$6	$44	0%
Total	**$203,285**	**$1,800,124**	**100%**

Results by Service Provider

Lifetime NPV by Component Type			
Component	Avg. Cost/Yr	NPV (Life)	% of Total
AC wiring	$2,423	$22,299	1%
Asset Management	$4,797	$52,249	3%
Cleaning/Veg	$41,644	$453,566	25%
DC wiring	$19,160	$158,395	9%
Documents	$3,286	$35,784	2%
Electrical	$1,894	$20,351	1%
Inverter	$72,075	$555,708	31%
Mechanical	$5,607	$53,304	3%
Meter	$19	$205	0%
Monitoring	$72	$783	0%
PV Array	$12,517	$135,644	8%
PV module	$25,036	$175,764	10%
Roof	$0	$0	0%
Tracker	$7,960	$86,694	5%
Transformer	$6,795	$49,377	3%
(blank)	$0	$0	0%
Total	**$203,285**	**$1,800,124**	**100%**

PV O&M Cost Model Example: 10 MW ground-mount



Mike's Category	Annual $/kW
Component parts replacement (Planned)	$0.58
Inverter replacement reserve (corrective)	$3.84
Module cleaning and vegetation management (Planned)	$3.25
Module replacement reserve (corrective)	$0.91
Operations administration (planned)	$2.80
System inspection and monitoring (Planned)	$1.71
TOTAL	$13.09

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Recommendations for Cost Reductions

- Asset Management Software
  - Benchmarking performance
  - Continuous Performance Index
  - Curation and Quality Control on Data
  - Efficient business transactions; lower cost
  - Improved analytics
  - Knowledge management-diagnostics and troubleshooting
  - Keep track of preventative maintenance requirements
  - Calculate predictive or condition-based maintenance.

Recommendations for Cost Reductions

Warranty management practices

- Do not v**oid warranty** by mishandling or not observing instructions or conditions of the warranty.
- Curate data to **prove that a module is underperforming**,
- Plan for **labor to remove, ship, and re-install** an underperforming module.
- Try to get a warranty for the manufacturer to "**repair or replace" rather than "supplement**,"
- Consider **Insurance Backed Guarantee (IBG)** that provides that warranty claims will still be processed in the event of the liquidation, receivership, or closure of a dealer

Failure to follow "product box handling and storage requirements" can cause damage when moved and void a warranty

Photo by Andy Walker, NREL

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Recommendations for Cost Reductions

- Remote imaging, Aerial Inspection

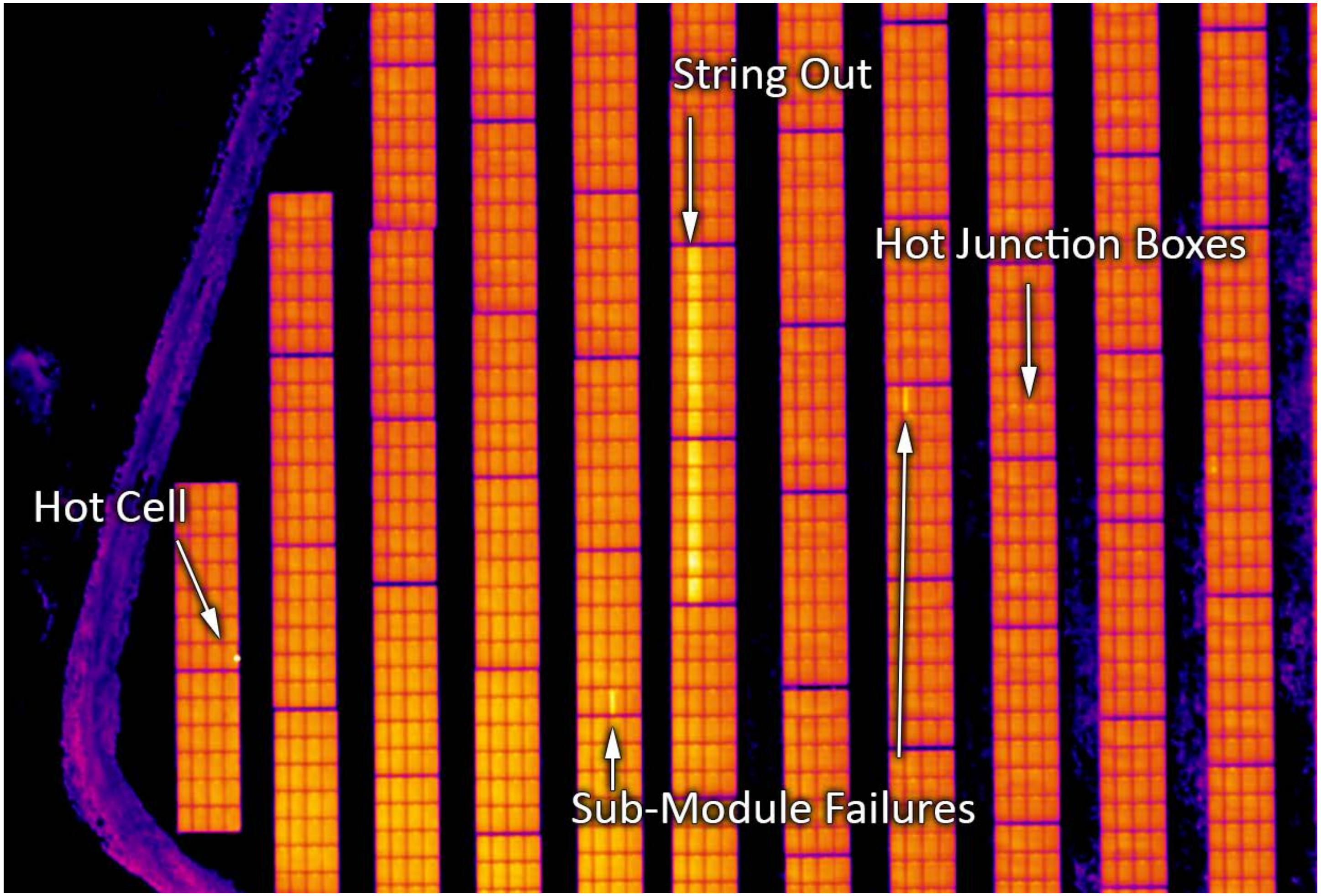

Image by Rob Andrews, Heliolytics

Recommendations for Cost Reductions

- O&M Business Models
  - "The UBER of PV O&M"
  - O&M Cooperative business structures
  - Shared facilities and inventories
- Module-level power electronics
  - Reduced production losses
  - Covers rapid shutdown requirements
  - Detailed data
  - Conventional AC wiring
- Standardization of parts, suppliers, procedures
  - Optimized reserve
  - Remove obsolete inventory and reduce inventory exceeding the maximum stocking level to reduce cost to count, move, store, secure, insure and taxes.


Thank You!