New Field Testing Protocol

Monitoring DC Health

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CORE ENERGY WORKS

Core Energy Works' Experience with Field Testing Modules

- *Inspected >150MW in the Field at over 50 Sites*
- *Utility and Commercial Scale Sites*
- *20+ Different Module Manufacturers/Technologies*
- *Ground Mount, Roof Mount, Car Ports, Trackers*
- *All of the Testing Reported on Today is for Installed Modules*

Short Conclusion : They are almost All Good!
….Trust yet Verify

Caveat – Utility scale with no microinverters or power optimizers

Outline

Review from a Field Testing Point of View

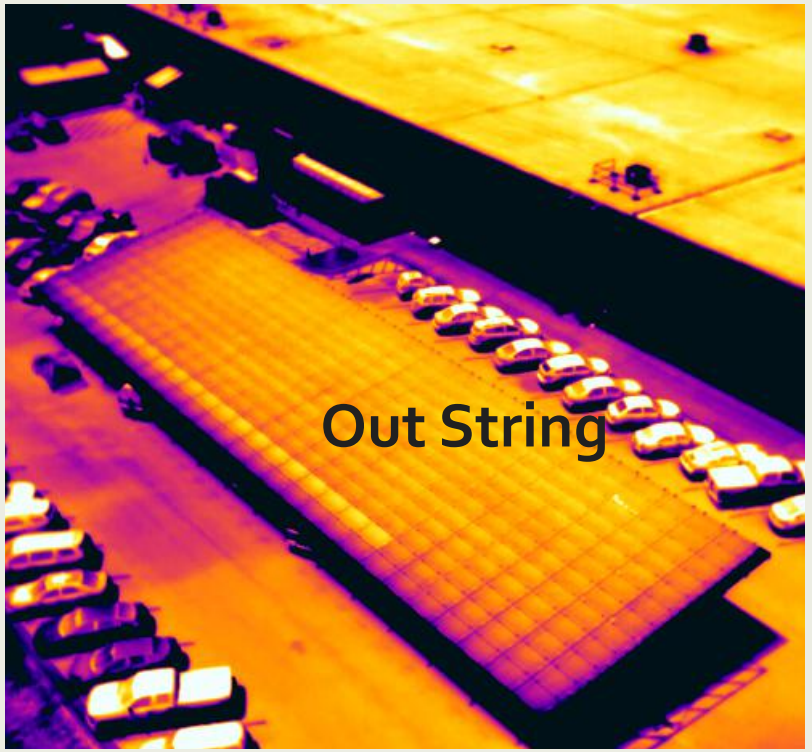
- Arial IR Imaging (by Drone)
- Electroluminescence Imaging
- IV Test

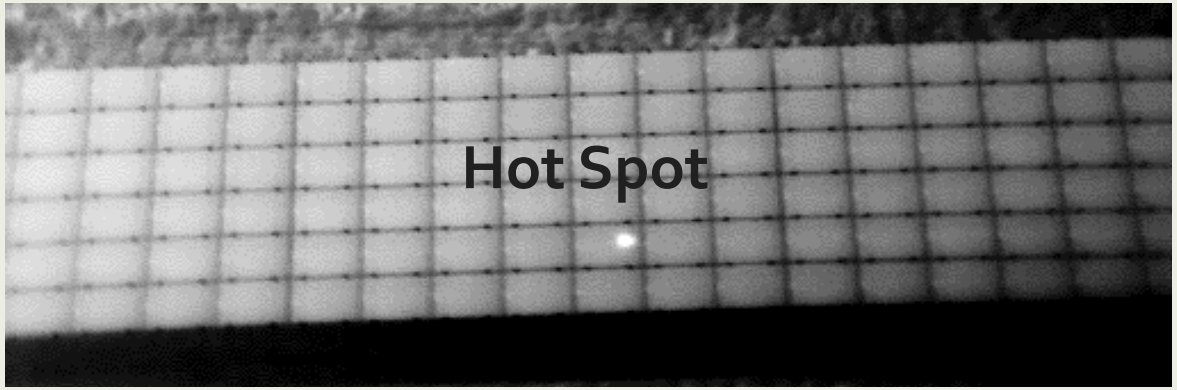
Field Testing Protocol

Case Studies

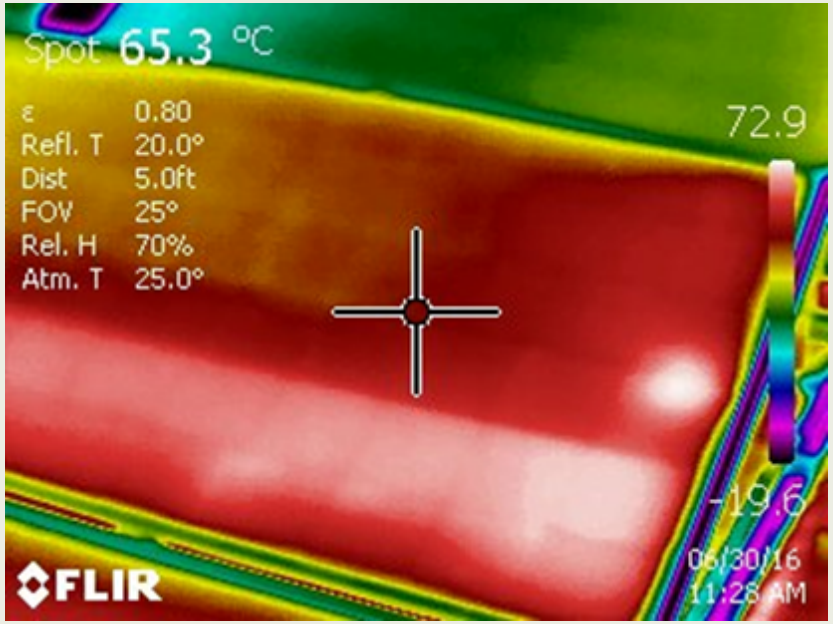
Conclusions

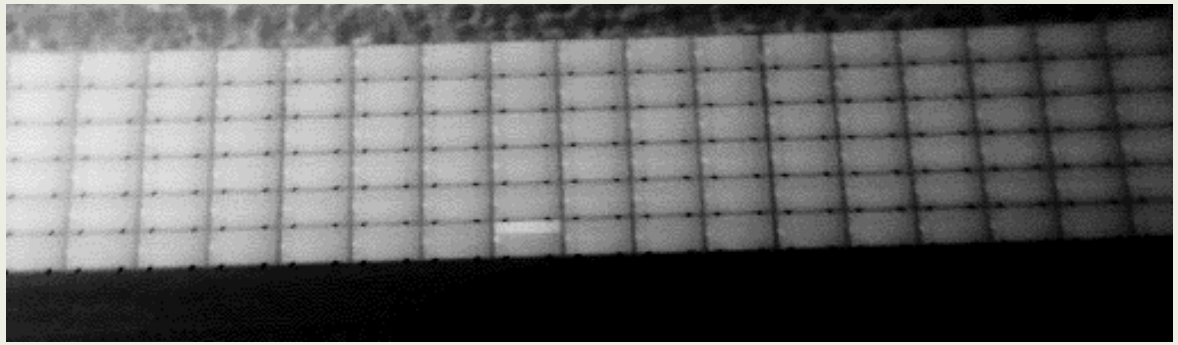
Aerial IR Imaging



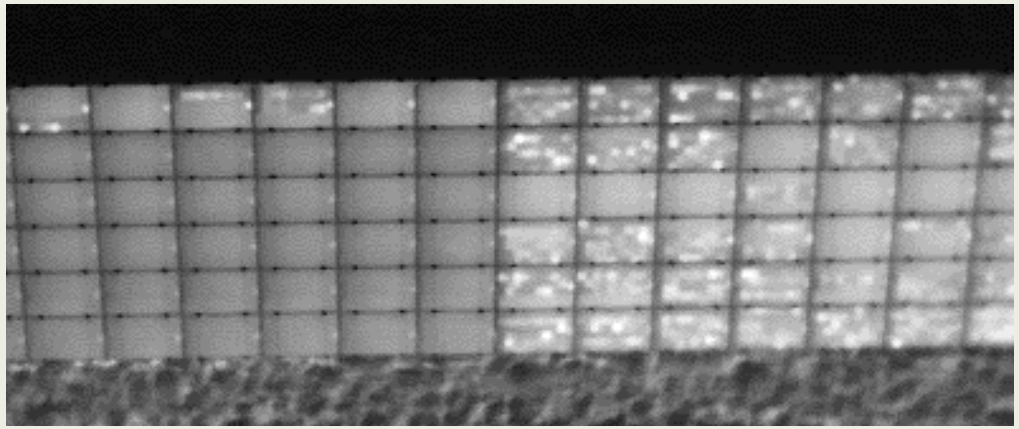


Aerial IR Imaging





Open Circuited Sub- String (OSS)



Shorted Sub-Strings(SSS) and Open Sub-Strings (OSS)

IR Imaging by Drone

Pros

100% Inspection

Fast (minimal field time)

Forgiving with the Weather

Excellent at Detecting Non-Uniformities

- Open Circuits*
- Short Circuits*

**Circuits = Substrings up to Whole Inverters*

Cons

Uniform Degradation Mechanisms are Undetectable

Limited Ground Verification

Hot Spots are Common and Can be Hard to Interpret

Electroluminescence (EL)

Pros

Very Useful for Root Cause Determination
Surprising Compatible with Field Testing
You have to Work at Night

Cons

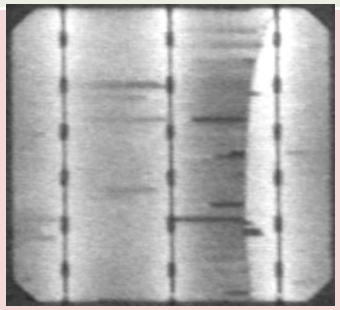
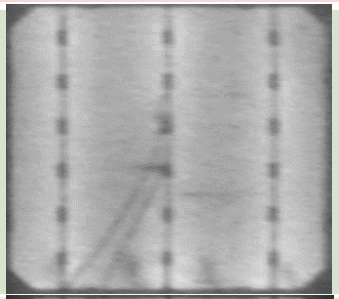
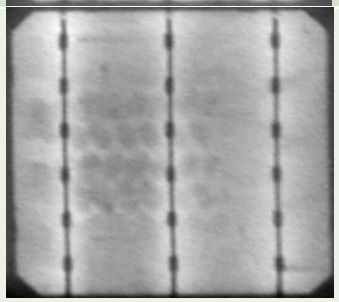
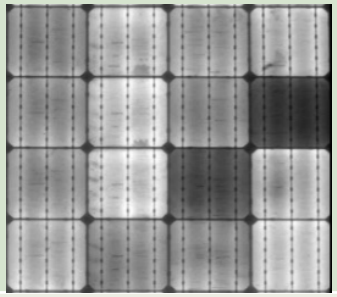
Slow and Therefore Expensive
but getting faster all the time
Experience needed to Interpret the Results

Modified consumer camera

DC power supply

~1-2kW Ac Generator

EL

Non-isolating crack		**Interior cracks where all regions of the cell still have a direct path to a busbar are non-isolating and typically will not significantly degrade performance over time.**
Isolation via multiple cracks		Although not yet isolated in this example, multiple cracks are forming an interior region of the cell that can become isolated as thermal expansion/contraction stress continues
"Tire Track Pattern"		This is a cell processing phenomenon occurring during the metallization firing step due to the belt pattern of the belt furnace "transferring" to the cell (probably due to a thermal shadow from the belt).
Degraded cell efficiency (LID or PID)		The dim cells are less efficient. In this case, an exacerbated form of LID associated with p-type CZ cells is suspected, although PID is possible.

Current-Voltage (IV) Traces

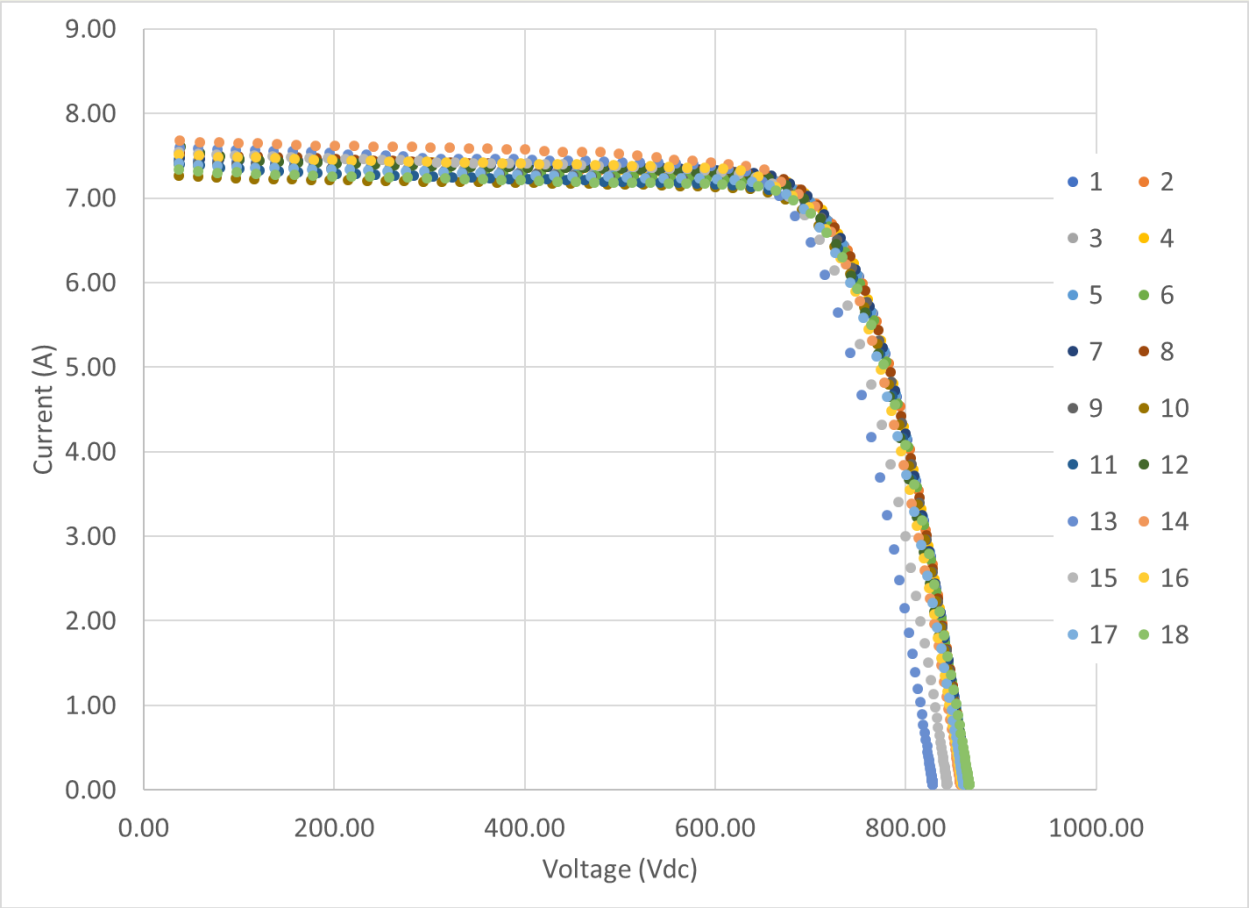
At the String Level (working in the Combiner Box)

Pros

- Useful for Site Acceptance
- Catches Many (Most) Field Wiring Errors
- Reasonable in terms of Cost and Expertise Needed
- Evaluate mismatch loss (if done very carefully)

Cons

- Cannot diagnose module issues
- Weather Dependent
- Translation to STC Expands the Error Bars



Current-Voltage (IV) Traces

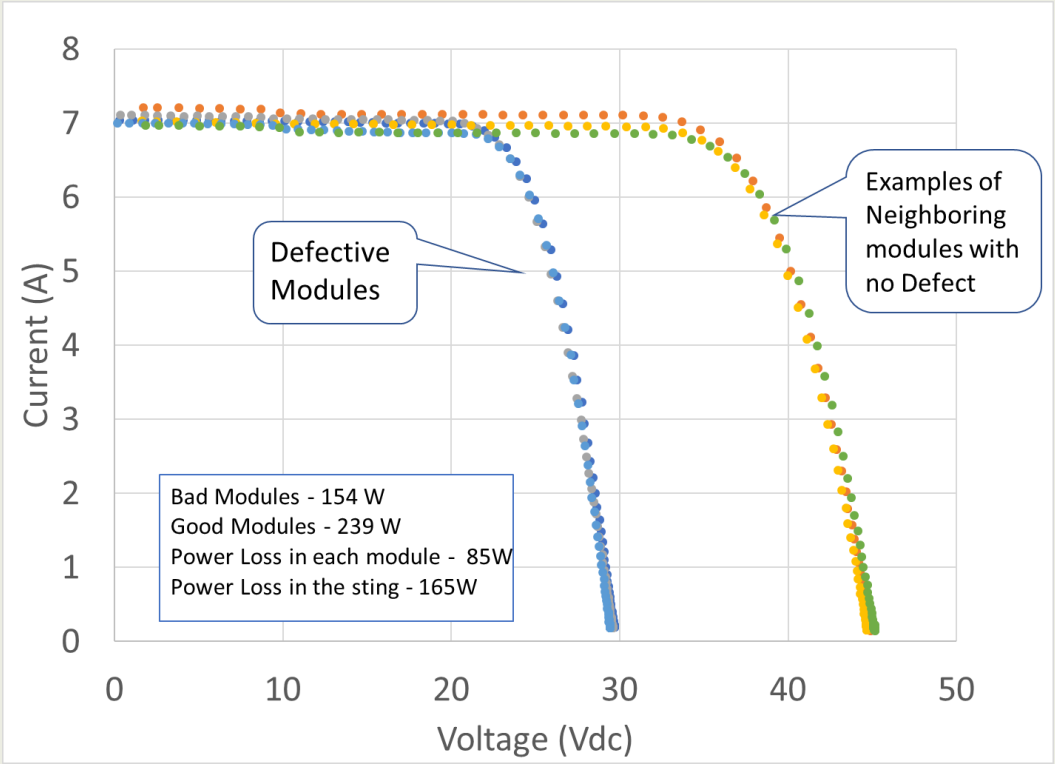
At the Module Level

Pros

Very Good for Diagnosing Module Issues

Cons

Slow and Expensive
Weather Dependent
Expertise Needed
for Translation to STC
for Sufficient Accuracy to Consider Warranty Issues



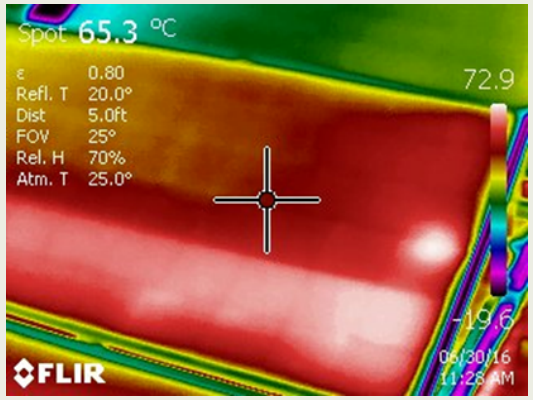
The Tail of the Distribution has an Out Sized Impact to Overall System Performance

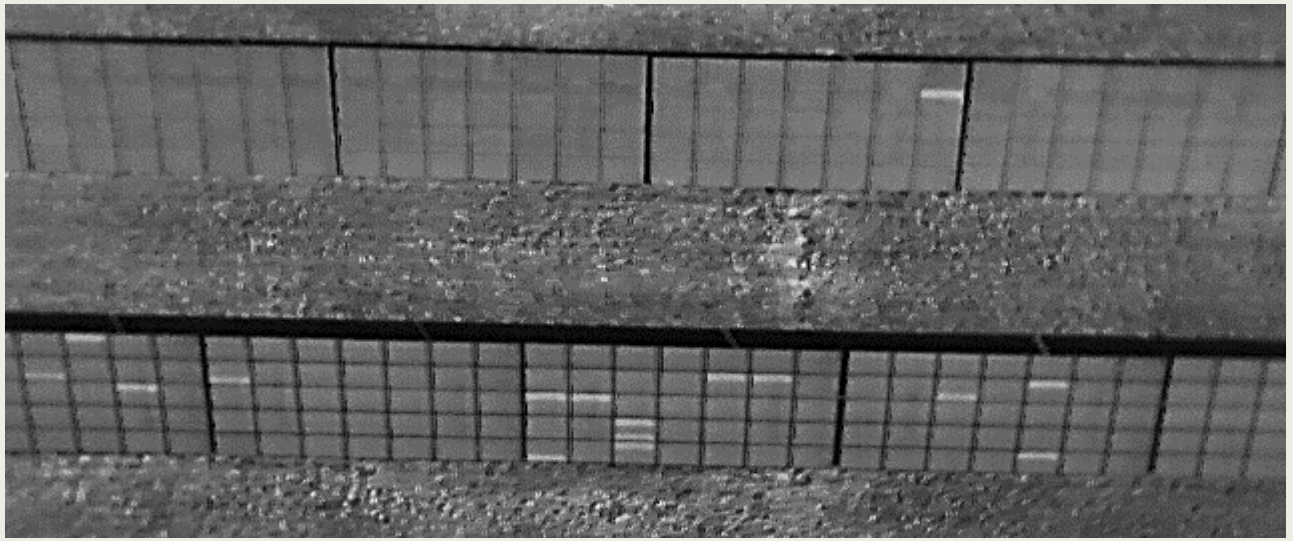
Core Energy Works Field Test Protocol

Test	Sample Size		Key Result
IR Imaging	100%		Thermal non-uniformities at the module level
Visual Inspection	2% (+/-)	300 Minimum	Module package defects such as bubbling, burn marks, delamination, and overheated Jboxes.
Module Level IV	2% (+/-)	300 Typical	Finds degradation mechanisms impacting all modules. Identifies subtle differences in big populations.
String Level IV	Small Sample	<10 Typical	Measures mismatch losses
Impact of Soiling	Small Sample	20-30 Modules	Measures soiling loss. Needed for Translation to STC
EL	Small Sample	30-60+ Modules is Typical	Connects solar cell level defects to module performance

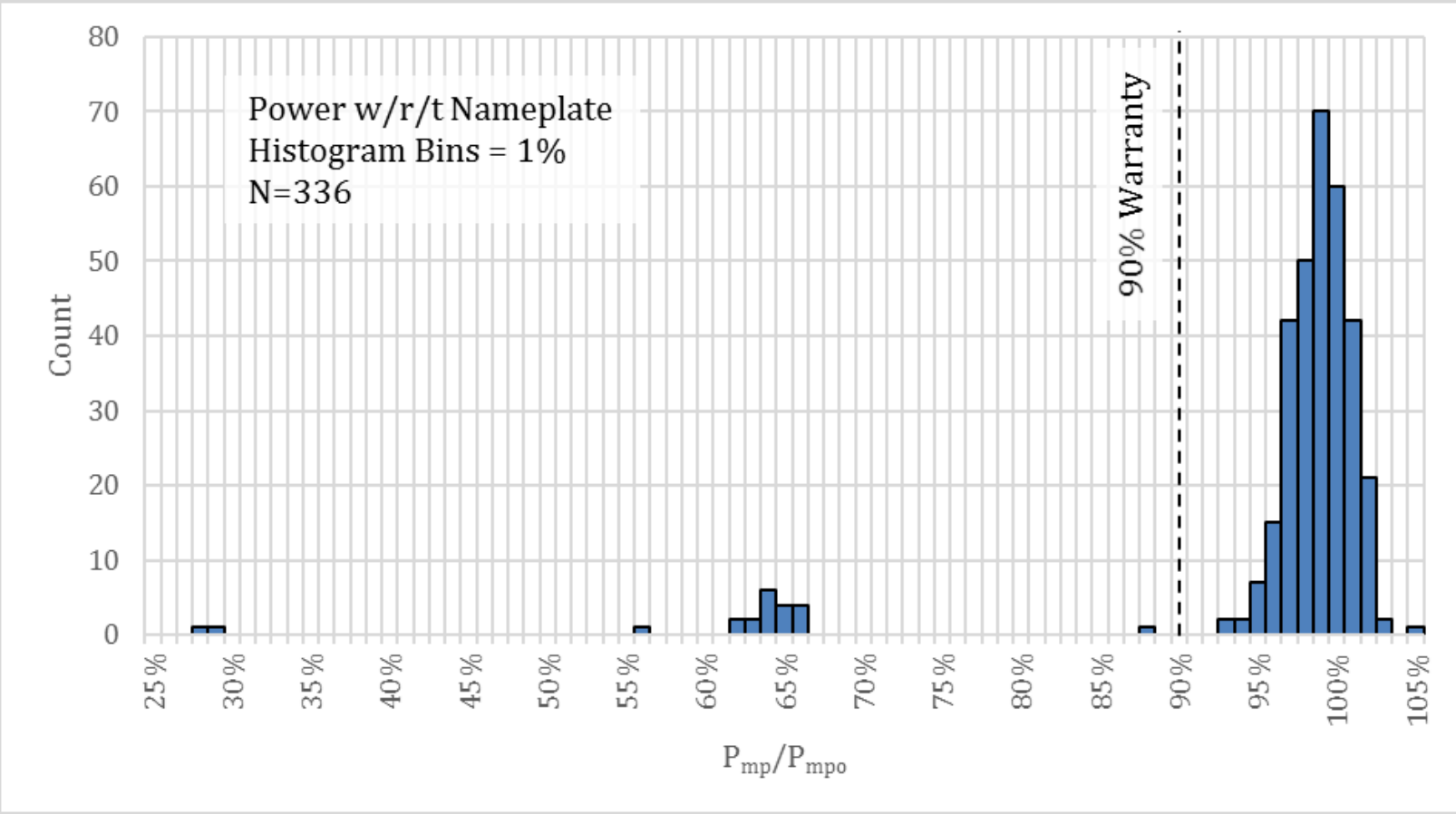
Case Studies 1 to5 Failed Solder/Weld Connections

Manufacturer A	8% Modules Impacted	5 Years	Failed **Off Cell** Solder Joints
Manufacturer B	3.9% Modules Impacted	8 Years	Failed **Off Cell** Solder Joints and Diode Failures
Manufacturer C	8% Modules Impacted	5 Years	Failed and Failing **Off Cell** Solder Joints (Running hot)
Manufacturer D	0.7% Modules Impacted	8 Years	Unknown
Manufacturer E	0.4% Modules Impacted	3 Years	Failed Welded Joint in Jbox

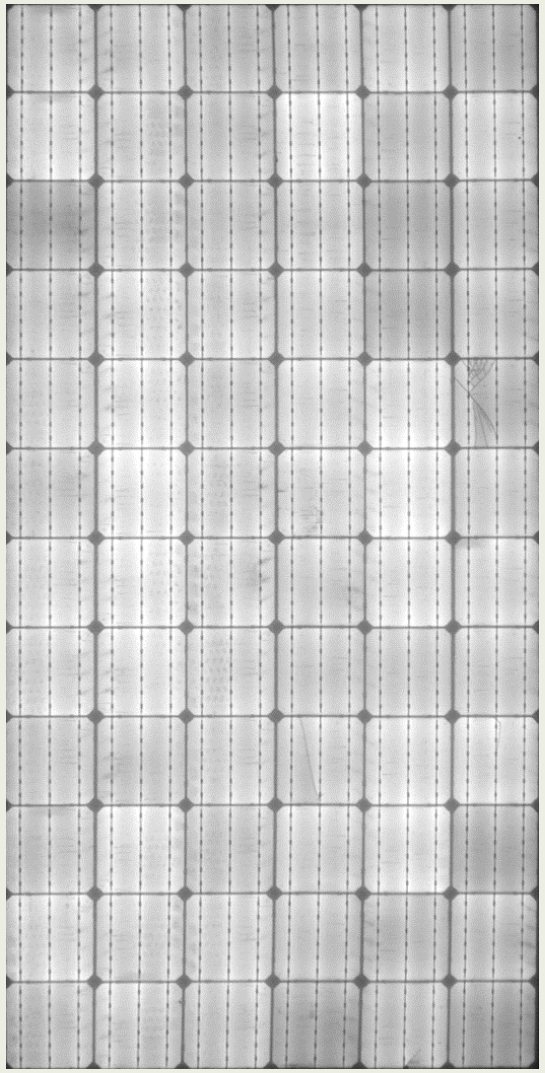


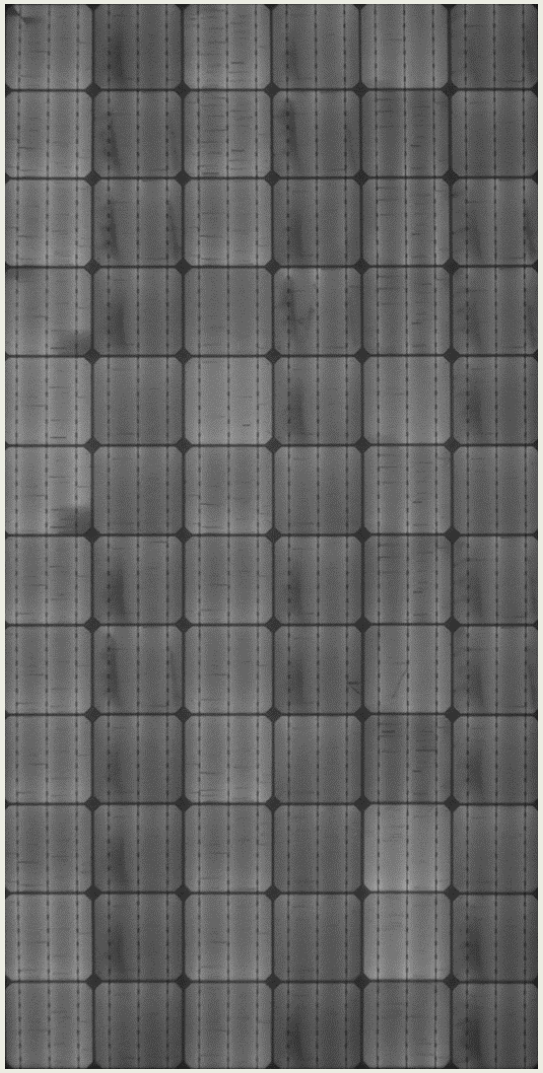


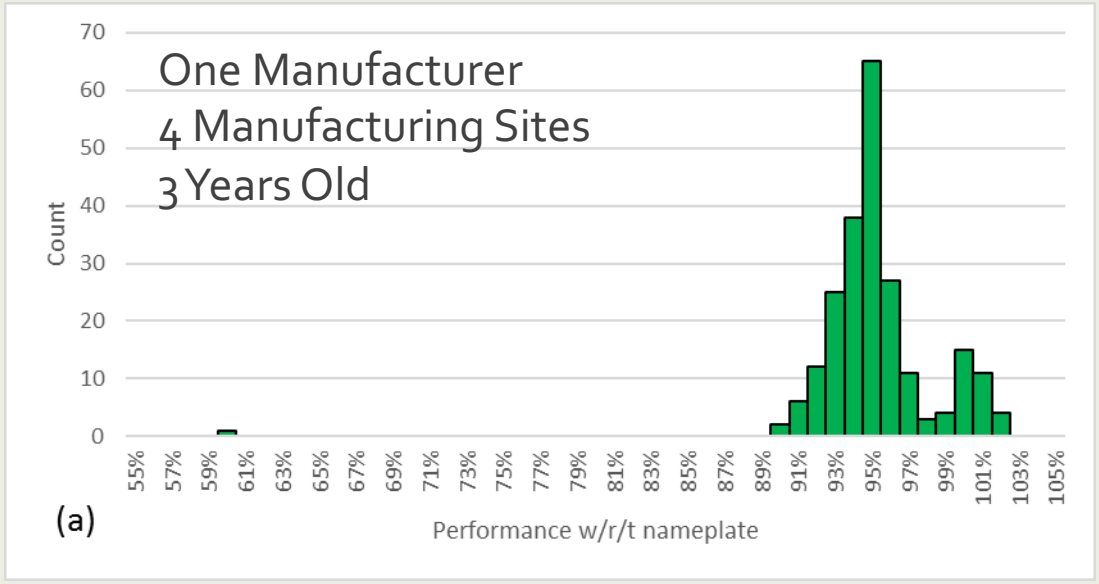
Case Studies 1-5 Failed Solder/Weld Connections

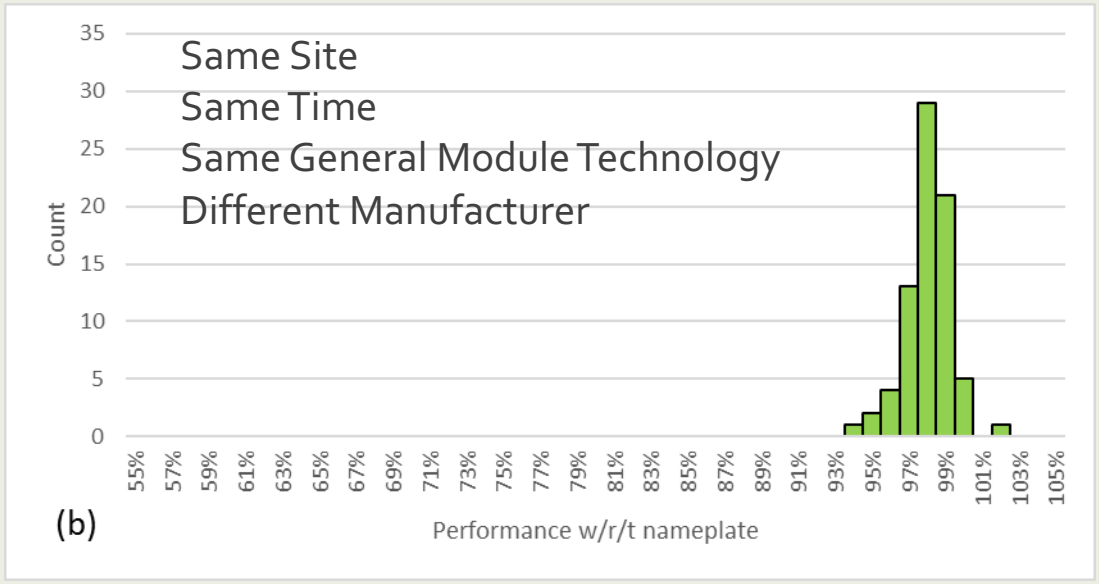


Case Study 6 Discrete Module Level Degradation









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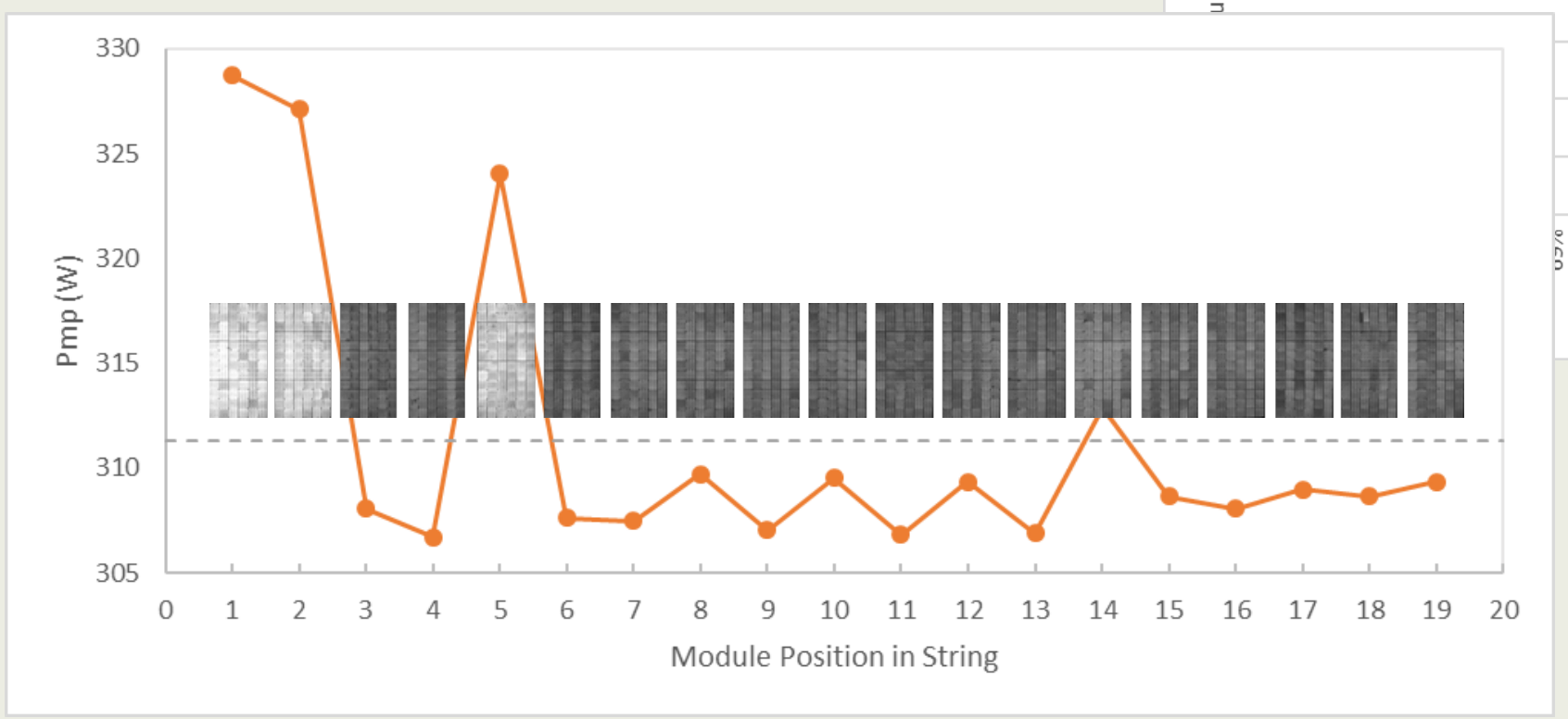
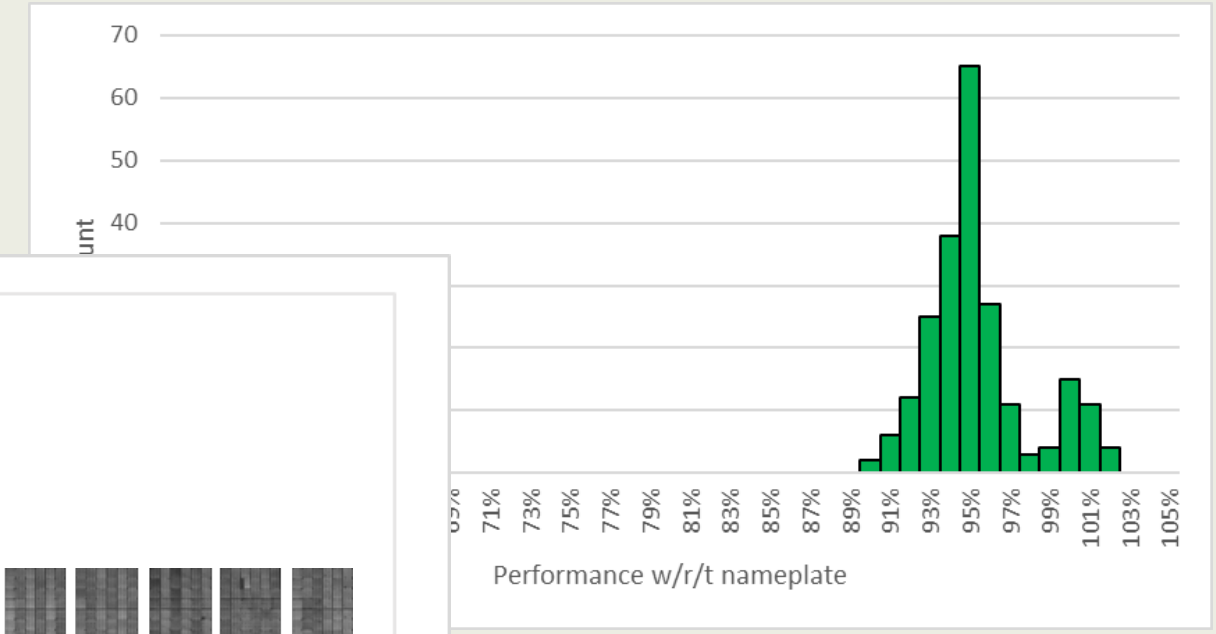
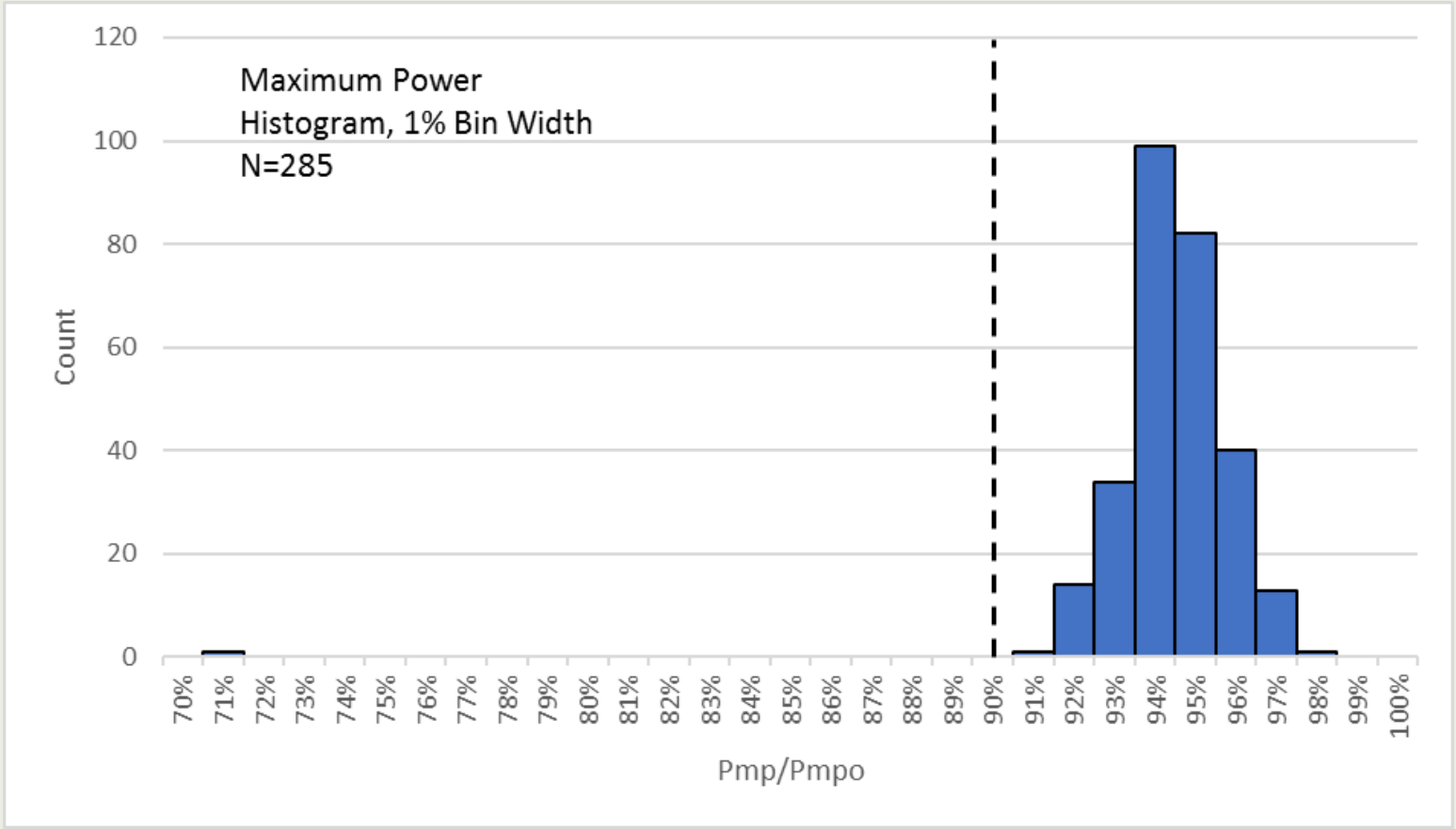




Case Study 7 Success!



8 years old

Conclusions

A Field Testing Protocol Has Beed Developed to Better Assess DC Health

Full Field IR Imaging

- Required Part of Annual O&M
- Although Necessary it is not Sufficient

IV Testing

- Modest Sample Sizes are needed at the module level to determine overall DC health

EL Testing

- Provides root cause answers when cell level defects are present
- Samples can be small if IR and IV are in hand

Expertise is needed to extract meaning information

New Degradation Mechanisms Associated with New Higher Performance Solar Cells