Quality Of Goods Installed

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About Us

For companies developing PV products and projects, PVEL is the premier solar panel performance and reliability testing lab.

We provide secure, expert testing and validation services so you can be confident that you're making intelligent decisions based on the most reliable data.

We specialize in 3rd party performance and reliability reports for Bankability, R&D, and manufacturing.

About Us

- State-of-the-Art indoor lab facilities in Berkeley
  - Broad range of specialized capabilities
- Outdoor Research Center in Davis called PV-USA
  - Heavily instrumented, behind the fence, grid connected

About Me

- Co-Founder and CEO of PV Evolution Labs
- Prior to founding PVEL was SunPower Senior Quality and Reliability Engineer
  - Developed and executed quality strategy for global 3rd party solar panel supply
  - Developed and characterized accelerated stress testing and module characterization techniques
- Advisory Board Member to the NREL's International PV Module Quality Assurance Forum

Show of hands

- Module Manufacturer
- Finance
- Developer or EPC
- Other

PV Technology expertise

- High
- Medium
- Low

Survey:

- Solar panels are very reliable, no diligence necessary
- Solar panels are reliable but rigorous diligence is required to avoid quality issues
- Most solar panels will fail within their warranty period and there's nothing you can do
- no idea

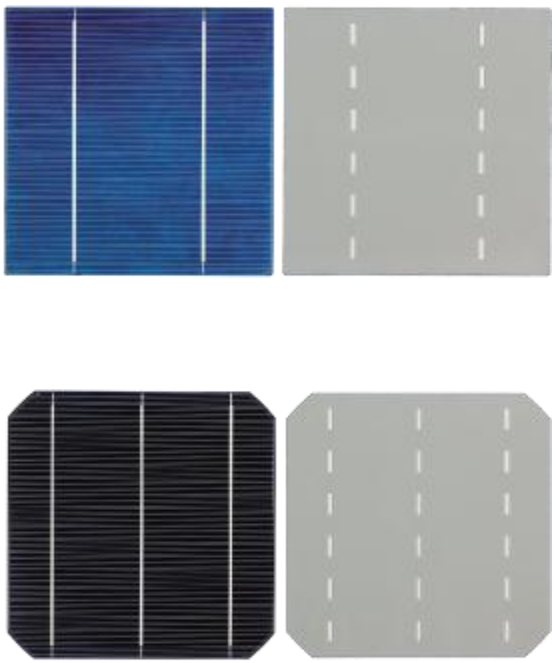
Today

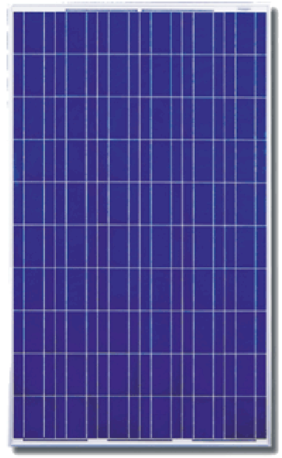
- Please jump in with questions any time
- Objective is an interactive session
- Input, feedback, questions, comments are welcome

Background

- Over 600 solar panel manufacturers globally
- Many technologies
  - Crystalline silicon (mono and poly) – 80 to 90% market share
  - Thin Film – 10 to 20% market share
    - CdTe
    - CIGS / CIS
    - a-Si
  - Novel Technologies
    - Concentrating PV
    - Dye Sensitized
    - Organic PV
    - CTZS cells
- Most of the industry is crystalline silicon so that is what we will focus on today

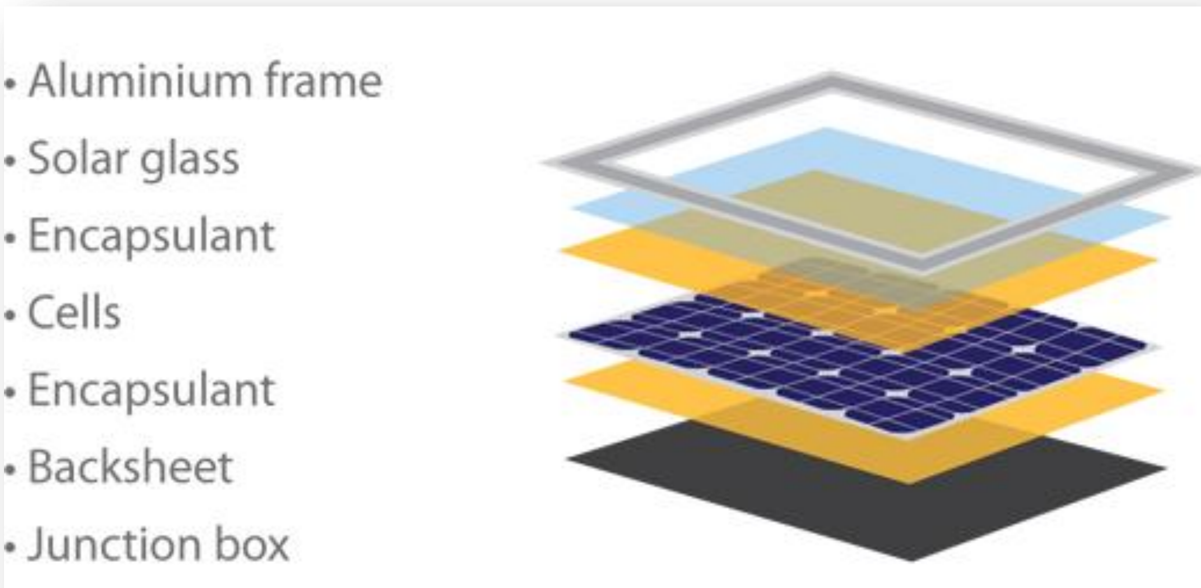
Background





Construction

- Pretty simple, right?



Source: SunGrid Solar

Front

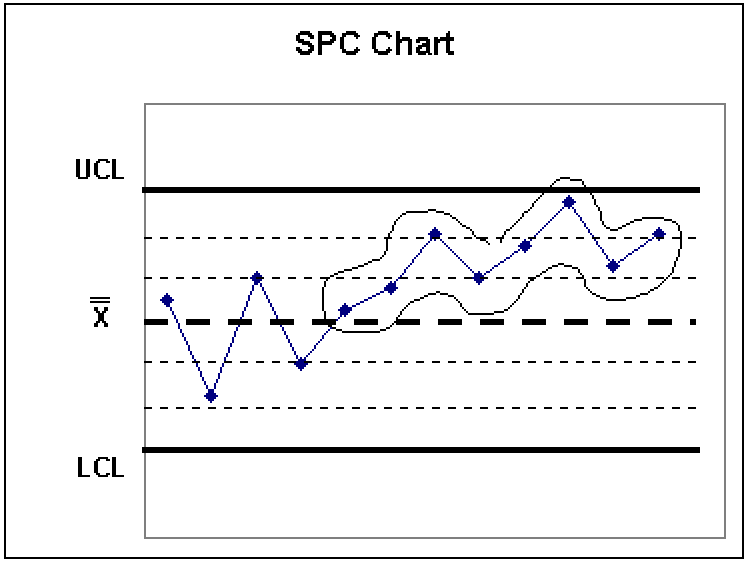
Back

Lots to Control in Manufacturing

Manufacturing Step	Several Concerns (not comprehensive)
Incoming raw material control	Supply deviations happen – sometimes suppliers just change something without notification
Raw material storage	Materials are sensitive to moisture and heat and some have expiration dates
Tabbing: Soldering busbars on solar cells	Solder quality, solder alloy, solder iron pressure, flux, soldering method, cell preheat, cell cracks, residue on cells
Stringing: Soldering multiple cells together	Solder quality, solder alloy, solder iron pressure, flux, soldering method, cell preheat, cell cracks, residue on cells
Glass washing	Water Ph, water quality, speed, complete drying, residue
Layup: Placing glass, encapsulant, cells, backsheet stack together	Foreign materials, residue, alignment, cell cracks,
Lamination	Temperature, temp uniformity, vacuum pressure, cool down, material compatibility
Frame and Jbox attach	Residue, alignment, curing, material compatibility
Final test	Calibration, re-calibration frequency, traceability, temp
Packaging and shipping	Labeling, proper packaging design to avoid cell cracks

Manufacturing

- Tool aging and drift and variation in operators is the cause of most underperformance
- Statistical process control can limit quality issues however it's impossible to capture everything
- Just because something is plotted doesn't mean it's well understood
- Control limits must be well defined
- Rules must be understood by operators



Important to Remember

- Can’t assume quality is a foregone conclusion in this industry yet
- Testing is typically destructive and takes time
  - Some examples:
  - Solder joint pull test
  - X-Ray imaging of solder joints
  - EVA & backsheet peel tests
  - EVA gel content
- Manufacturers have intense downward cost pressure
  - Quality costs money
- At the end of the day everyone is selling the same product

Manufacturing - Stringing

Manufacturing – Visual Cell Inspection

Background

- Typically 60 or 72 solar cells per module
- Roughly 250 Watts per module
  - About 40 volts and 7.5 amps per module
- Systems in the U.S. are typically 600 volts
  - 1,000 volts in EU

- About 65 Gigawatts installed globally – 65 billion watts
- That’s about 260 million solar panels installed as of the end of 2011

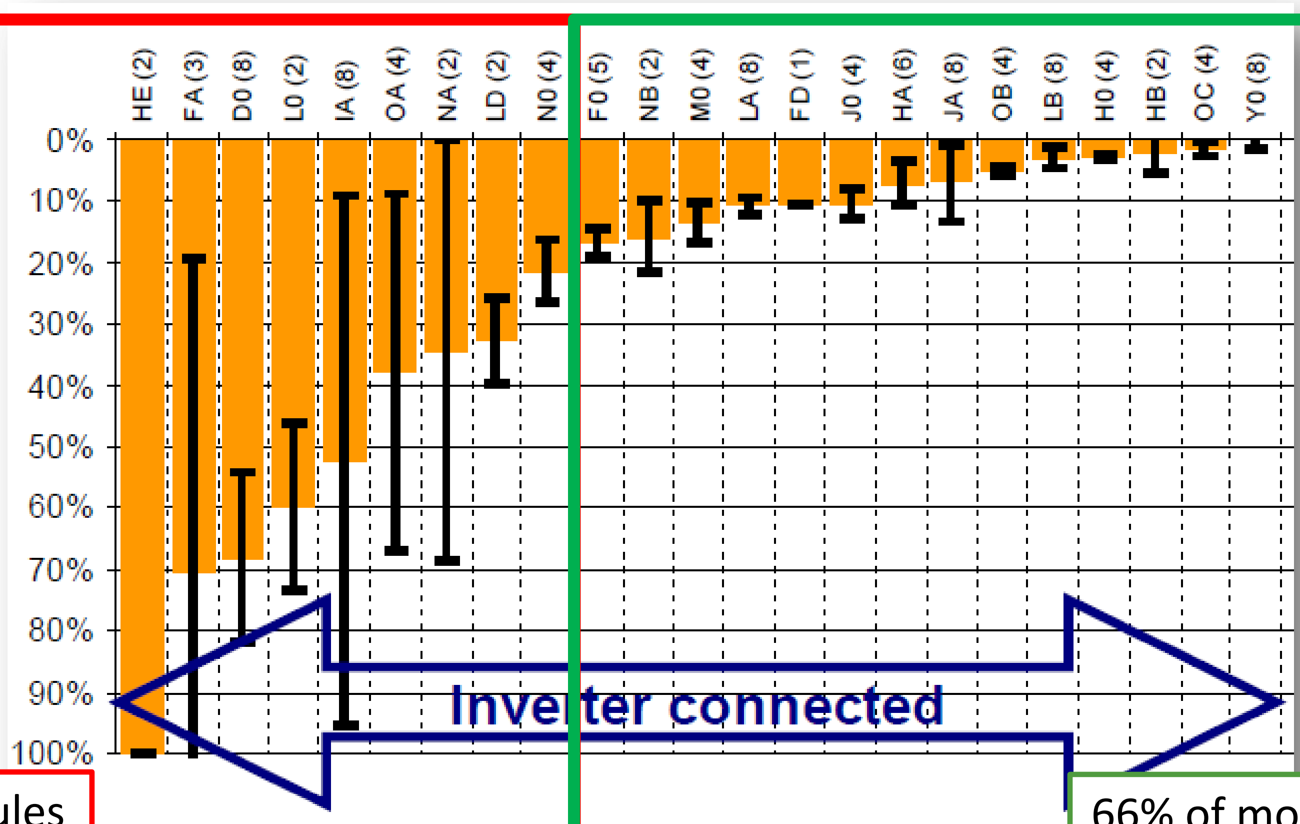
- 1% degradation is 650 MW - long-term performance matters

Some Industry Experience

Test Details	Findings	Source
• 103 modules tested for 18 to 24 years outdoors • 20 different manufacturers evaluated	• Average degradation rate of 1% per year • Catastrophic failure rate of 6.8%	JRC European Commission *Results on next slide*
• 1,900 modules in the field for 3 – 18 years • 8 module types	• Degradation from about 0.5 to over 4% per year • Mismatch losses of another 22% (!)	ASU-PTL *Results in upcoming slides*

JRC EU Commission test Results

103 modules, 20 manufacturers outdoors for about 2 decades



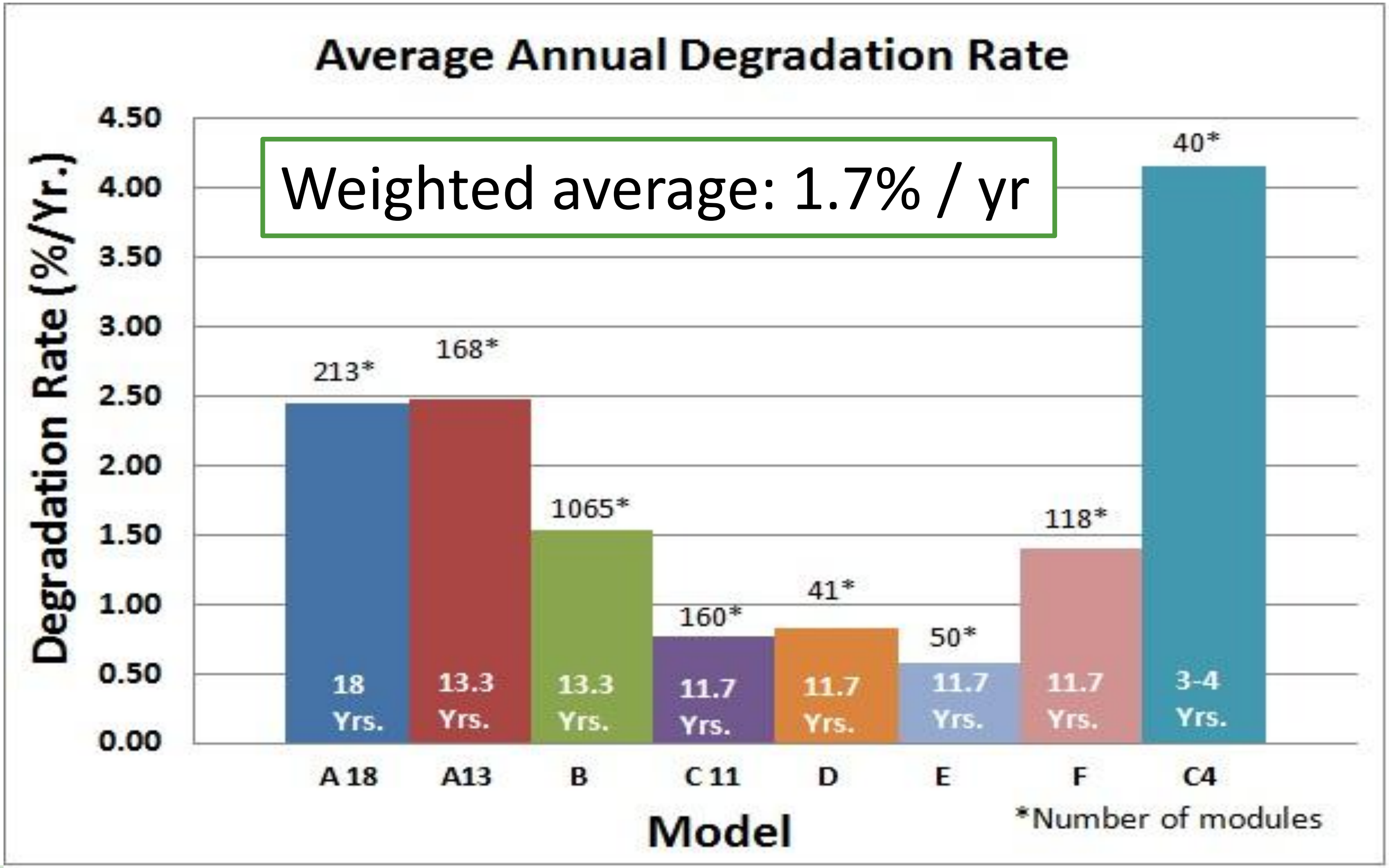
34% of modules

66% of modules

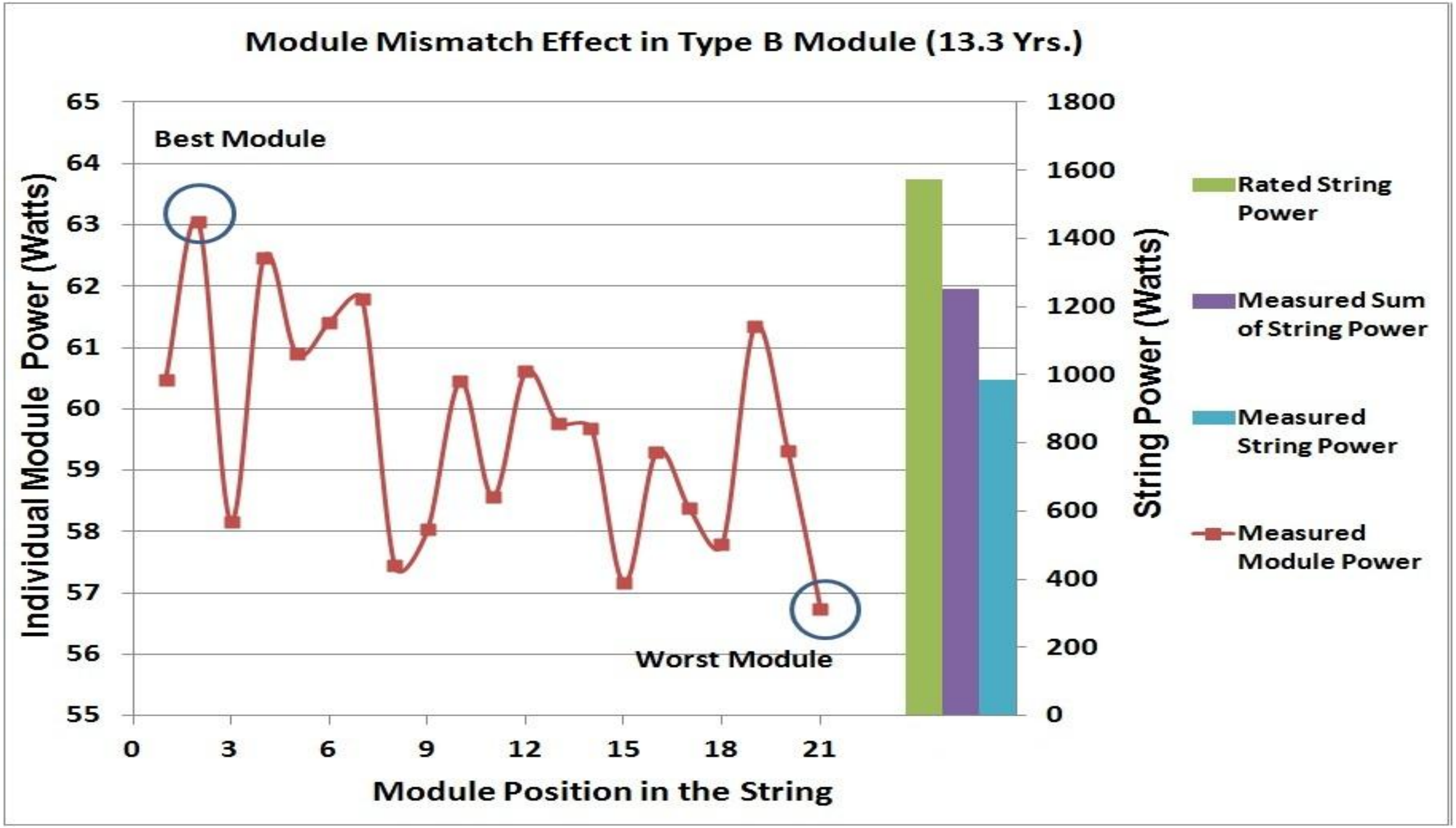
- Degradation greater than warranty allowance
- Degradation within warranty limits

ASU-PTL Test Results

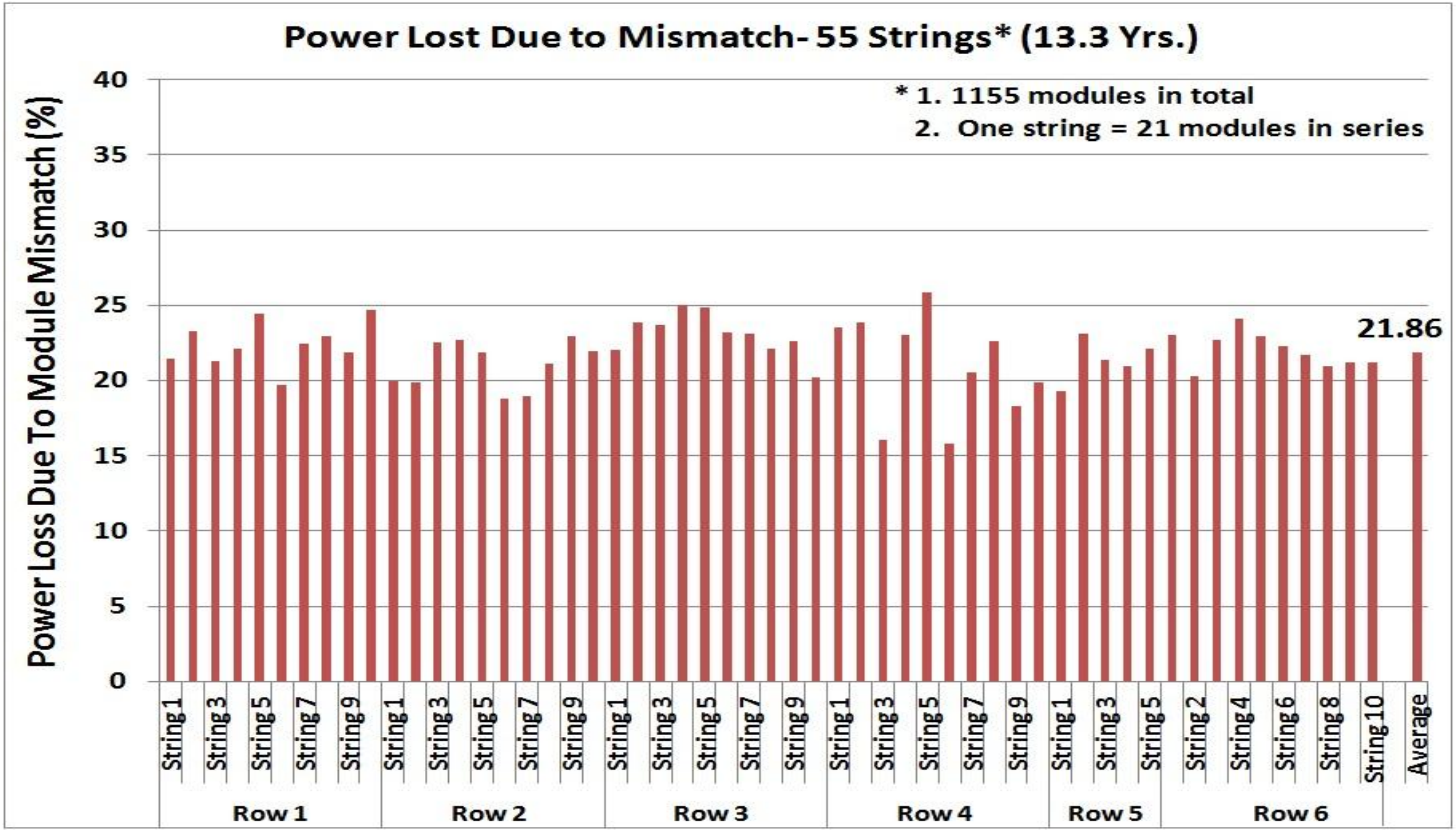
1,900 modules, 8 module types for 3 – 18 years



ASU-PTL Test Results - Mismatch

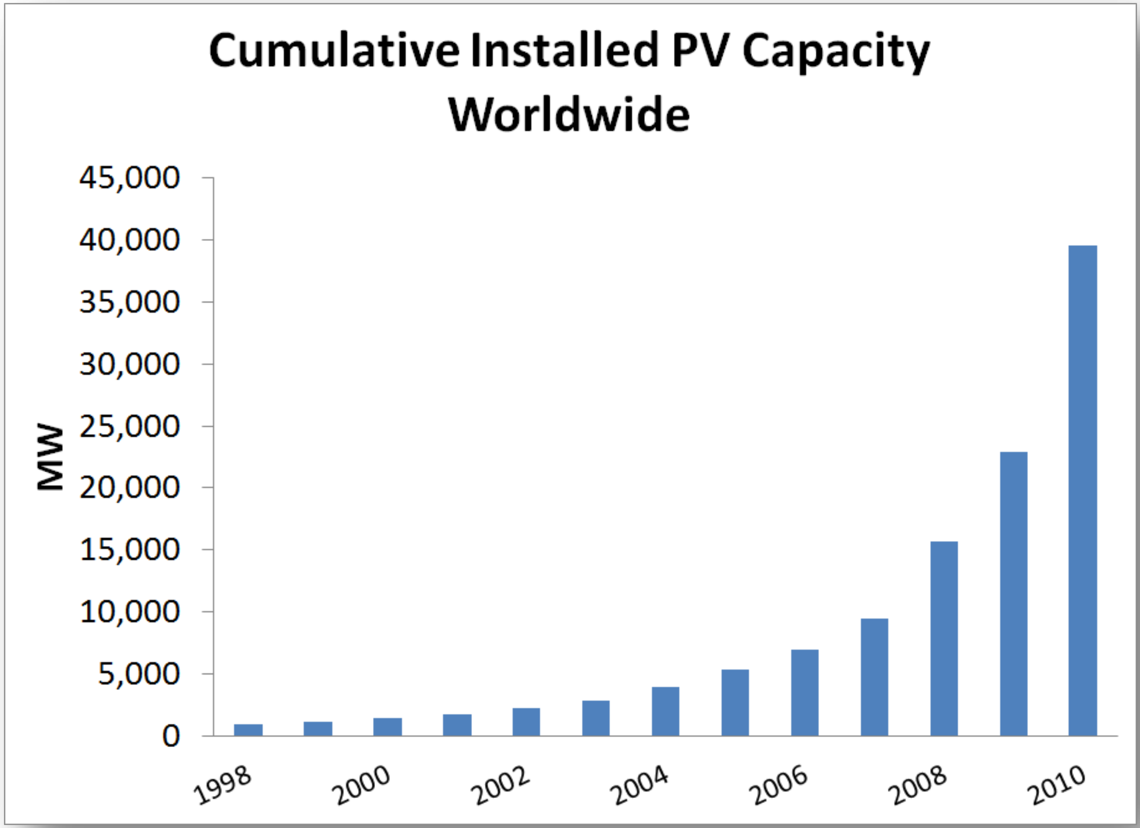


ASU-PTL Test Results - Mismatch



PV Capacity

- < 18% of total installed capacity has been in the field for at least 5 years
- < 5% of total installed capacity has been in the field for at least 10 years
- The next 5 years will likely see a lot of warranty claims



Field experience summary

- Not all modules are created equal
- Most issues are latent – modules look fine out of the box
- There is a lot of risk out there
- Plant degradation is impacted by module degradation and growing mismatch

So what can we do?

- There are two distinct areas of concern

Design	Manufacturing Stability
Bill of materials	Tool quality and drift
Product design	Material consistency
Manufacturing recipes	Material storage
Quality management system	Training and drift
	Tolerance stack-up

- Is product certification sufficient?

Product Certification

- Today's modules are typically qualified/certified to:
  - IEC 61215 for Crystalline Silicon Modules
  - IEC 61646 for Thin Film Modules
  - IEC 62108 for CPV Modules
  - UL1703 for all modules
- Much of the early development work was performed by the Jet Propulsion Laboratory (JPL) in the mid to late 70s
  - Block I to V buys
  - JPL bought modules, tested them, fielded them, and correlated results
- Block VI planned for 1985 then fell victim to Reagan budget cuts

Product Certification

- Many of the very early failures were due to cracked cells and gun shots
- Non-glass superstrates and early encapuslants suffered from severe browning and delamination
- Early modules had lots of hot spots
- Designs evolved

- Pre-Block V modules suffered from 45% field failure rate
- Post- Block V modules suffered from < 0.1% field failure rate

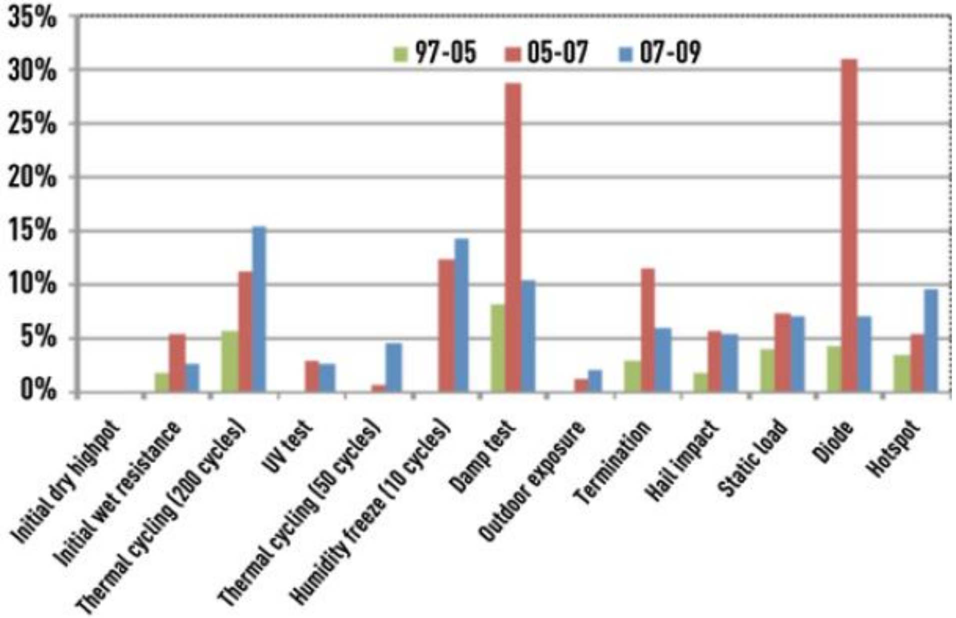
- This JPL work made the PV industry possible

Design – some good news

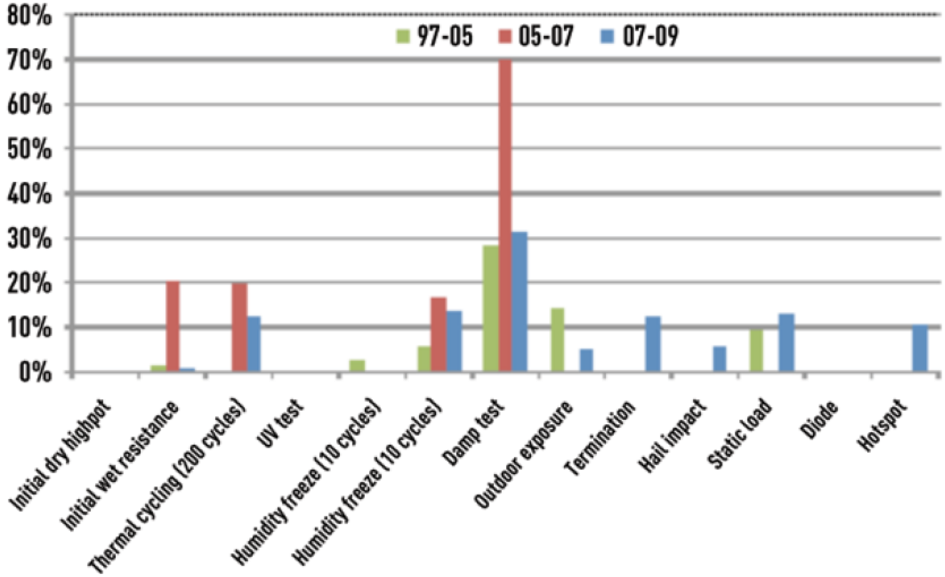
- Certification is weeding out gross design flaws

Certification failure rate, 1997 – 2009:

Crystalline Silicon



Thin-Film



Source: Govindasamy TamizhMani, PV-Tech.org

Is this enough?

- Certification development committees must craft a program that supports an active commercial industry
  - All commercial modules must pass
  - Certification is not a long-term reliability test – it sets a minimum bar

- Product differentiation beyond this is market driven
  - Quality, price, aesthetics, commercial terms, customer support, warranty and guarantees

- Certification is performed on a small number (~10) of samples pre-production
  - This provides no protection against manufacturing variability

Several Recalls

PHOTON: The Photovoltaic Magazine Issue 9 (2011)

Supplier	Year produced	Defect	Effect on performance	What affected?	Resolution
SunPower	2005	Weak cell connectors	10% lower yields	~54,000 200- and 210-WHT-1	Replaced 8,000 with 20W better panels & $86/panel
First Solar[1]	08 – 09	Not specified	Increased first year degradation	~30MW	Resolved 35%
Sanyo	02 – 08	Deteriorated insulation	Electrical shock, delamination	300,000 HIT modules	Inspection & replacement for large-scale customers
Schneider Electric SA	05 – 10	Outgassing in interconnect	Arcing can blow the cover off	250,000 Xantrex inverters	Free on-site repair

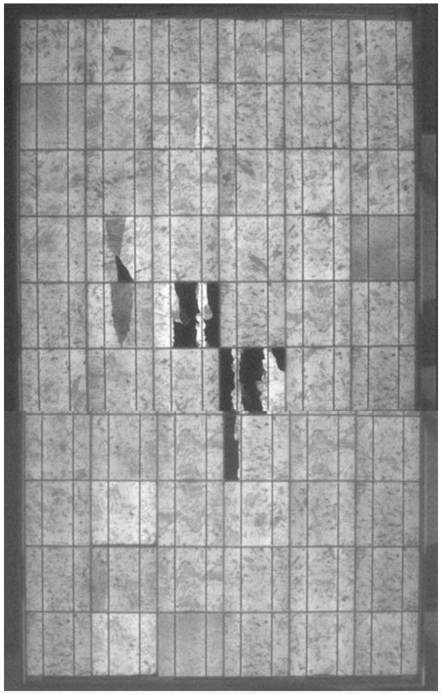
1. ”Manufacturing Excursion” recently increased by an order of magnitude to $250MM

Certification Gaps

- Long-term reliability / durability evaluation
  - Can be site specific – Florida vs. Arizona vs. Ontario
- Evaluation of manufacturing Stability

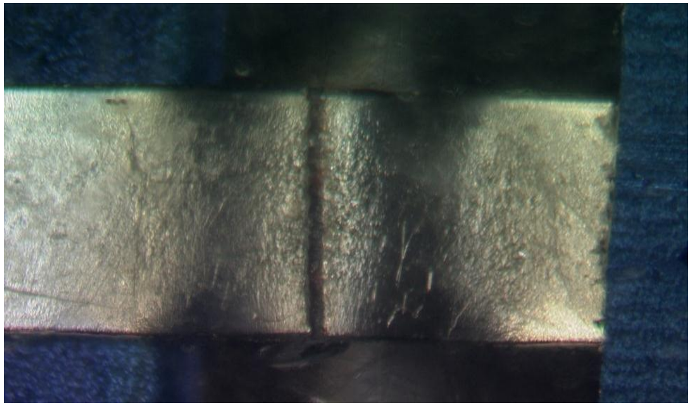
What does a failure look like?

Broken Cells



Ground Fault

Broken Interconnects



Corrosion

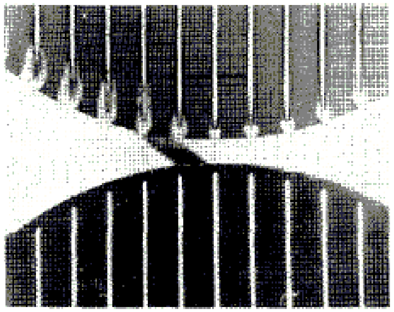


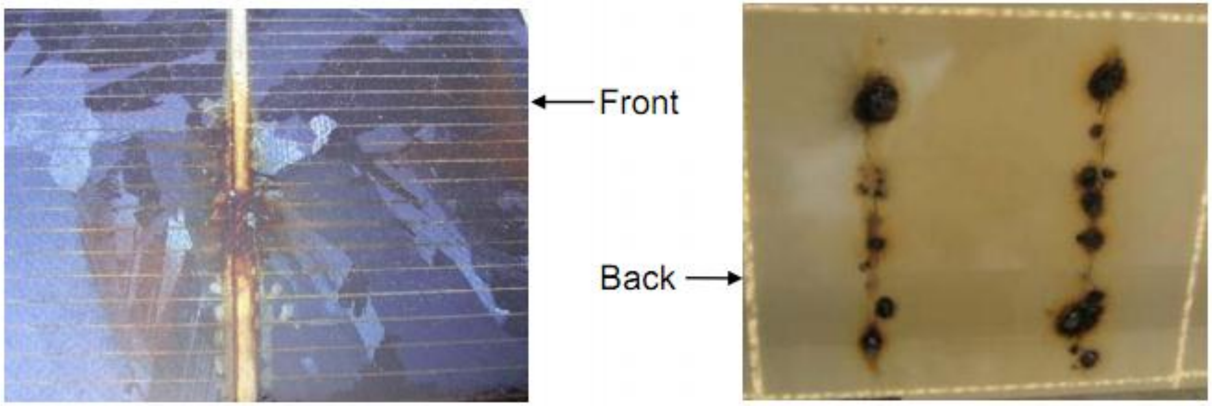
Figure 2. Solar-Cell Electrochemical Corrosion

Delamination

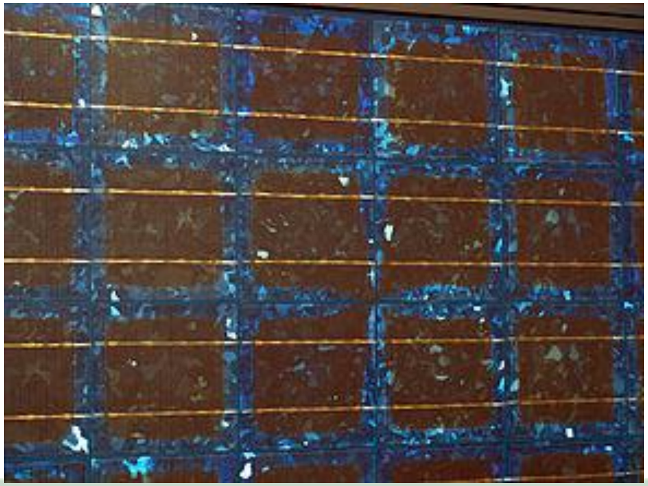
What does a Failure Look Like?

Jbox Arcing

Solder Joint Degradation



Encapsulant Browning



Backsheet Yellowing

Bubbles

Common PV Module Failure Modes

in no particular order, compiled with NREL and Sandia

Quick connector embrittlement (moisture ingress)	Cell/busbar arc to frame
Junction box failure (poor solder joints, arcing, etc.)	Light-induced cell degradation (LID)
Glass fracture	Outgassing of in-laminate materials (Chemical incompatibilities)
Bypass diode failure	Backsheet embrittlement leading to exposed conductor
Cracked cells	Busbar sharp edges, solder peaks, cutting through backsheet leading to exposed conductor
Solder joint degradation	Electrochemical corrosion of busbars or cell metallization
Delamination – Encapsulant, backsheet	Polarization (charge build-up on cell) / Potential Induced Degradation (PID)
Junction Box detach	Corrosion
Optical degradation of encapsulant, backsheet, and superstrate	Ion migration to cell surface or interfaces / Potential Induced Degradation (PID)
Frame tape or frame adhesive failure	Discoloration of frame, JBox, or polymeric materials

Reliability Demonstration Test

Mission Statement

- Provide the industry a **robust** and **comprehensive** test protocol to evaluate long-term PV module aging behavior for a reasonable price in a reasonable amount of time.
  - **Robust**: only a fraction of module types tested will perform well
  - **Comprehensive**: stimulates all failure behaviors witnessed in the field while avoiding non-realistic failures

- Designed with the most current knowledge – protocol evolves with experience

Reliability Demonstration Test

Test	RDT Duration	Certification	Primary Degradation Behaviors Stimulated
Thermal Cycling	600 cycles	200 cycles	Solder joint degradation, cell cracks, Jbox failure, Polymer embrittlement, solder peaks cutting through backsheet
Damp Heat	2,000 hours	1,000 hours	Delamination, Corrosion, polymer embrittlement, discoloration, cell degradation, Jbox failure
Damp Heat w/ +1kV	600 hours	None	In addition to aging behavior above: Ion migration, electrolytic corrosion, polarization
Damp heat w/ -1kV	600 hours	none	

- Details and frequency of module characterization is very important
- All modules sun soaked before testing starts

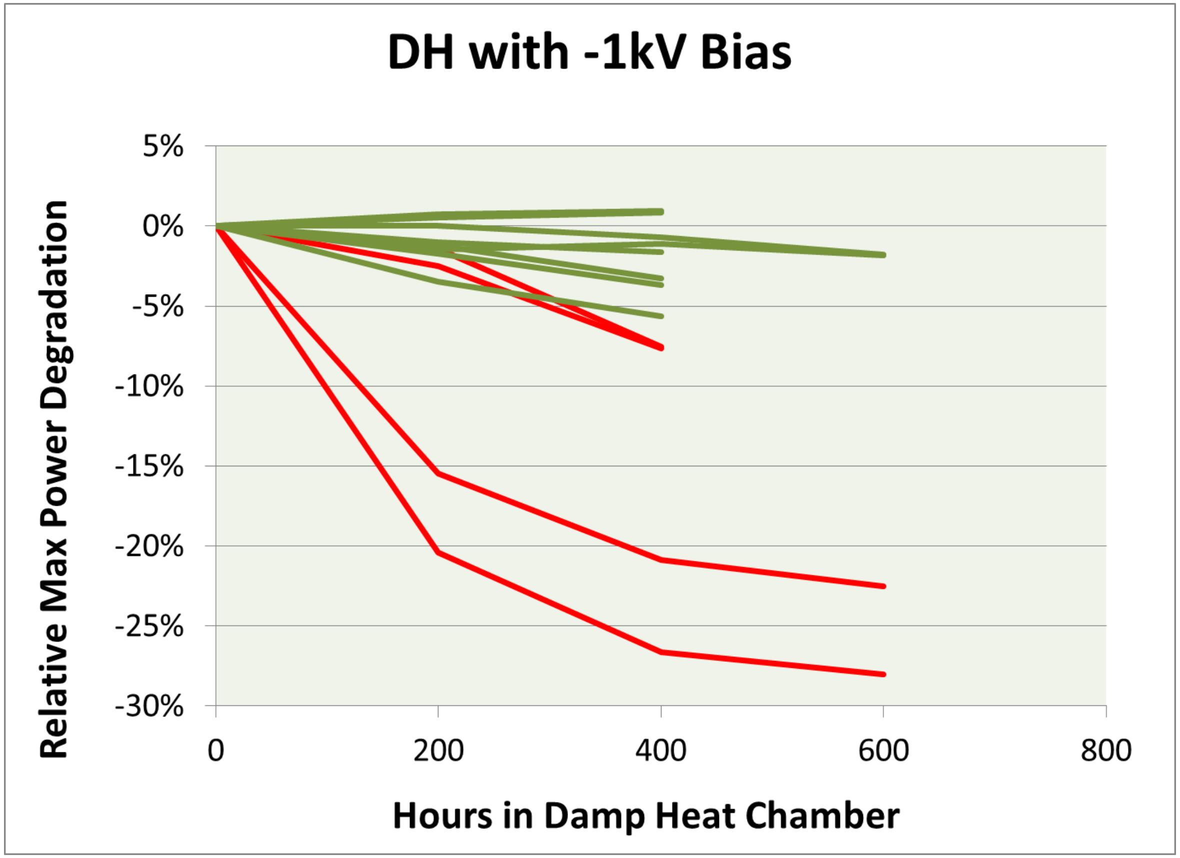
Reliability Demonstration Test

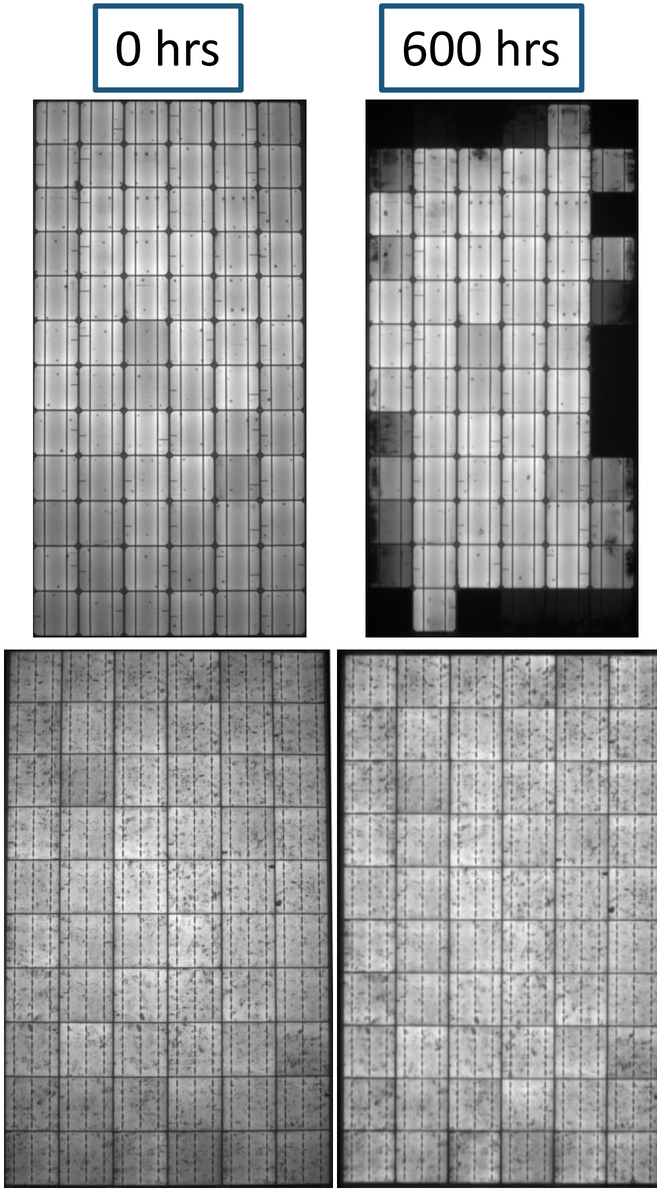
Test	RDT Duration	Certification	Primary Degradation Behaviors Stimulated
Humidify Freeze	30 cycles	10 cycles	Solder joint degradation, cell cracks, Jbox failure, Polymer embrittlement, delamination, cell degradation
1. Mechanical Load 2. Thermal Cycling 3. Humidity Freeze	1. 1,000 cycles 2. 50 cycles 3. 10 cycles	Static mechanical load	Cell cracks leading to performance loss, solder joint degradation, delamination, frame fatigue
UV Exposure	90 kWh	15 kWh	Discoloration, embrittlement, cell degradation, delamination

- Details and frequency of module characterization is very important
- All modules sun soaked before testing starts

PID Test Performed at PVEL

Competitor Cells: Top EL images
Canadian Solar: Bottom EL images





Now that we know how to evaluate PV modules for robust design how can we ensure that the products are being manufactured consistently and that my power plant won’t be impacted by manufacturing defects?

Manufacturing Stability

- The U.S. military developed a statistical method of screening batches of products that exhibit defects
- AQL (acceptable quality level), initially developed for checking batches of bullets, checks the max percent defective

Lot Size	General Inspection Levels		
	I	II	III
2 to 8	A	A	B
9 to 15	A	B	C
16 to 25	B	C	D
26 to 50	C	D	E
51 to 90	C	E	F
91 to 150	D	F	G
151 to 280	E	G	H
285 to 500	F	H	J
501 to 1200	G	J	K
1201 to 3200	H	K	L
3201 to 10000	J	L	M
10001 to 35000	K	M	N
35001 to 150000	L	N	P
150001 to 500000	M	P	Q
500001 and over	N	Q	R

Manufacturing Stability

Acceptance Quality Levels (Normal Inspection)																							
Sample Size Code Letter	Sample Size	0		0.1		0.15		0.25		0.4		0.65		1		1.5		2.5		4		6.5	
		Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re
A	2																					0	1
B	3																			0	1		
C	5																	0	1				
D	8															0	1					1	2
E	13													0	1					1	2	2	3
F	20											0	1					1	2	2	3	3	4
G	32									0	1					1	2	2	3	3	4	5	6
H	50							0	1					1	2	2	3	3	4	5	6	7	8
J	80					0	1					1	2	2	3	3	4	5	6	7	8	10	11
K	125			0	1					1	2	2	3	3	4	5	6	7	8	10	11	14	15
L	200	0	1					1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22
M	315					1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22		
N	500			1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22				
P	800	1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22						
Q	1250	2	3	3	4	5	6	7	8	10	11	14	15	21	22								
R	2000	3	4	5	6	7	8	10	11	14	15	21	22										

Project Development Example

- 20 MW project
- 80,000 modules

- AQL says you have to test 500 panels to screen for defects (!)
- Testing is destructive and not cheap
- 500 samples is fine for bullets but solar panels are expensive
- This is not a reasonable amount of modules to test

- So how can you protect your investment against underperforming products?

Latent Defect Screening

- AQL allows for some number of failures in testing
- By fixing the allowable number of failures to zero we can greatly decrease the necessary sample size

- *Latent Defect Screening* is designed to evaluate stability of manufacturing process

	Test designed to Evaluate	Timing	Sample Size
IEC/UL	Design/Materials	Pre-production	About 10 panels
Latent Defect Screening	Process	Lot-by-Lot	Statistically Significant

Latent Defect Screening

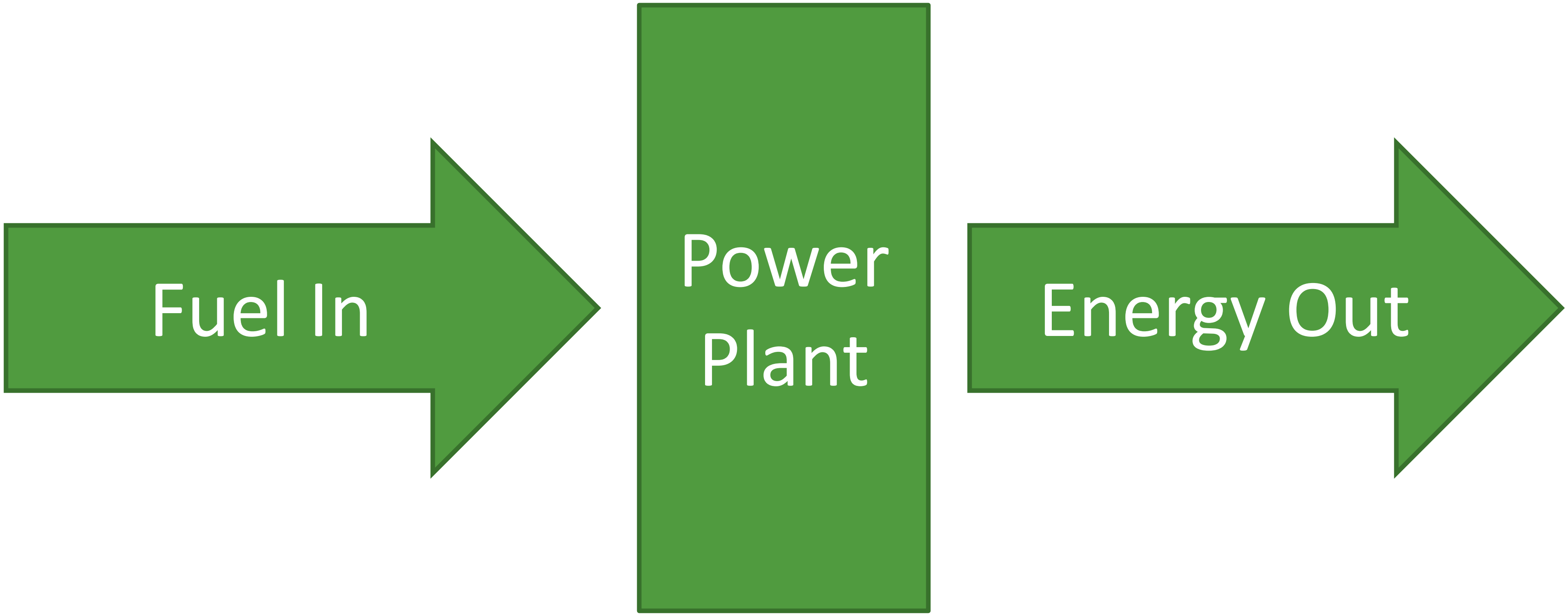
- If you test 34 modules you can be 75% confident that less than 4% of the modules may exhibit a defect
- You can gain substantial confidence for under a penny per watt

F_{max}	Max percent defective in population
N	Population size
A	Confidence Level
C	Number of defects identified in sample

N	α	F_{max} (C=0)										
		0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	6.0%	7.0%	8.0%	9.0%	10.0%
80,000	70%	240	120	60	40	29	23	19	17	14	13	11
80,000	75%	276	138	69	46	34	27	22	19	17	15	13
80,000	80%	320	160	80	53	39	31	26	22	19	17	15
80,000	85%	378	189	94	62	46	37	31	26	23	20	18
80,000	90%	458	229	114	76	56	45	37	32	28	24	22
80,000	95%	595	298	148	98	73	58	48	41	36	32	28

Now that I know how to ensure my reliable modules are being manufacturing consistently how can I monitor their performance in the field with minimal uncertainty?

Power conversion efficiency



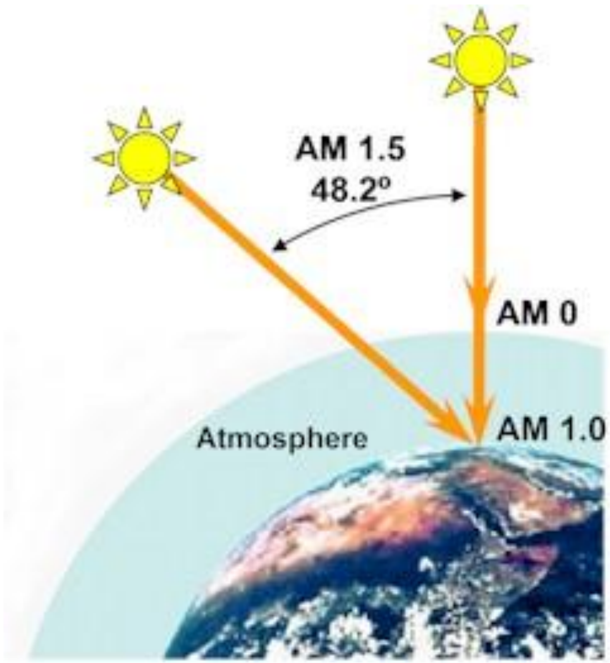
- To determine power conversion efficiency you must know fuel in and energy out with minimal uncertainty

PV System Performance Measurement

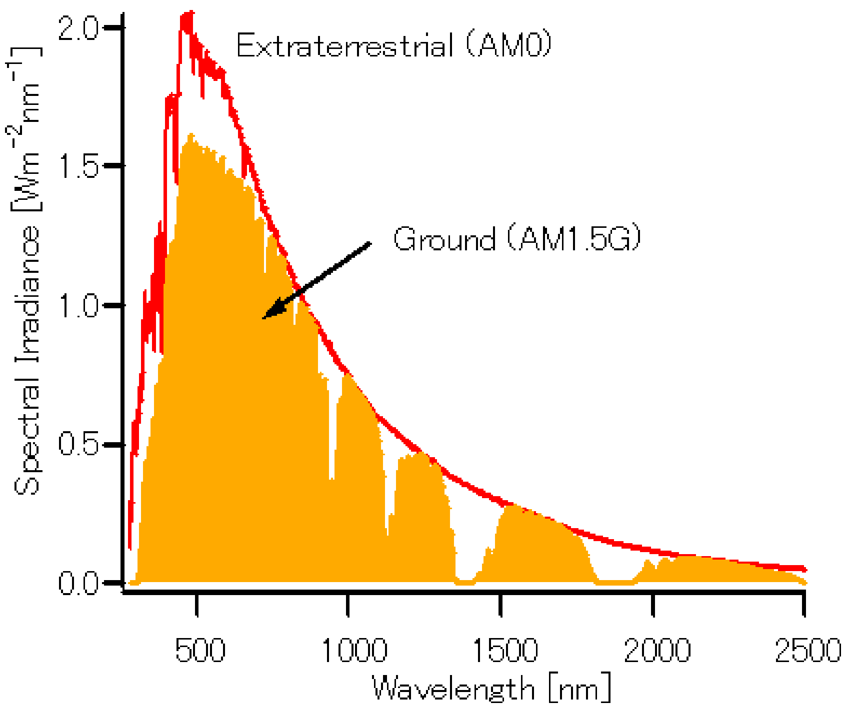
- Investors often seek performance (or production) guarantees to protect themselves against underperformance
- The EPC firm or module manufacturer can be expected to guarantee the performance of their product but not the weather
- In order to determine if your panels are operating as expected you must know the incoming fuel
  - Which is different than the total incident sunlight

PV System Performance Measurement

- PV modules are rated under AM1.5 spectral conditions
- The sunlight spectrum is impacted by
  - The thickness of atmosphere the light has to travel through and
  - local aerosols and particulates



Source: Eye Lighting



PV System Performance Measurement

- PV modules have a characteristic spectral response that varies by technology
- They will have different output under red light versus under blue light even if the incident power is equivalent
  - Since blue light has more energy per photon fewer photons are required to provide the same number of watts
- “Useable” fuel in does not equal total fuel in

PV System Performance Measurement

- Thermopile pyranometers have been used to quantify sunlight for many years
  - Weather stations for airports
  - Agriculture
  - Etc.
- They are designed to measure the total amount of incident energy with broad angular response
- A black disk heats up when under illumination
- Thermocouples mounted to the back of the black disk measure the disk temperature

Source: NREL

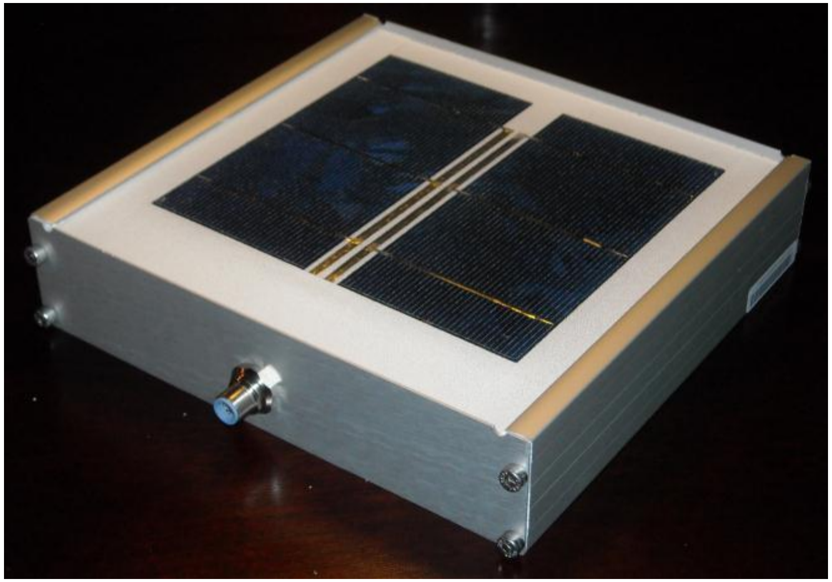
PV System Performance Measurement

- Pyranometers will provide a total incident energy measurement – not a measurement of fuel in for the PV power plant
- Their output must be normalized when used for PV power plant conversion efficiency measurement
- Angle of incidence response also varies a lot from PV modules

PV System Performance Measurement

- Solar reference cells built with the same materials as the PV modules in the field are much more suitable devices for this measurement
- Spectral and angular response mimics the panels in the field
- No normalization necessary because of the device's matching sensitivity

Suntech reference cell
Built and calibrated by
PV Evolution Labs



Solar Reference Cells - Certificate

ISO 17025 Calibration Certificate provided with each cell

PV EVOLUTION LABS
ADVANCING SOLAR

A2LA ACCREDITED

Photovoltaic Reference Cell Calibration Certificate

A2LA Calibration Certificate Number	PVEL Calibration Number
3252.02	5

Calibration By:
PV Evolution Labs
1360 5th St.
Berkeley, California 94710-1311
(415) 320-PVEL

Calibration For:
[redacted]

Equipment ID	Manufacturer	Model	Due Date
44364A	Stanford Research	SR630	01/25/12
44360A	Stanford Research	SR830	08/03/12
58717	Stanford Research	SR830	08/03/12
12105	Newport Corporation	818-UV-L	05/17/12
12113	Newport Corporation	818-UV-L	05/17/12
1193467	Keithley	2400	06/02/12
1155016	Spectral Evolution	SR-500	05/23/12

Approved by: Rajeev Singh
Name: Rajeev Singh, PhD
Title: CTO

Date: January 16, 2012

Certificate Version	Certificate Date	Page Number
V1.1	December 8, 2011	1 of 2

Certificate data may not be reproduced, except in full, without written authorization from PV Evolution Labs.

Page 1

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ADVANCING SOLAR

A2LA Calibration Certificate Number	PVEL Calibration Number
3252.02	5

Device Under Test - Calibration Data

C_0 (V)	α_{rc} (1/°C)	V_{oc} (V)	β_{oc} (V/°C)	Spectral Mismatch Factor M	Diode Factor n
0.0870	0.000352	0.6232	-0.001876	1.0134	1.098
± 0.0014	± 0.000010	± 0.0033	± 0.000003	± 0.0041	± 0.027

- Expanded uncertainties are at the 95% confidence level as defined by the ISO/IEC Guide 98-3:2008 Guide to the Expression of Uncertainty of Measurement (GUM:1995).
- All measurements and uncertainties are traceable to a National Metrology Institute (NIST, CNRC) and the International System of Units (SI).

Device Under Test - Information

Serial Number	Manufacturer	Material	Cell Area (cm²)	Configuration	Temperature Sensor
[redacted]			116.13	ESTI-Sensor	p-Si Half-cell

Test Methods:
- I-V: ASTM E948-09 - Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
- QE: ASTM E1021-06 - Standard Test Method for Spectral Responsivity Measurements of Photovoltaic Devices

Standard Reporting Conditions (SRC):
- Total irradiance: 1000 W/m²
- Spectrum: AM1.5-G (ASTM G173/IEC 60904-3 Edition 2)
- Temperature: 25.0 °C

Secondary Reference Device:
- Device ID: PVM 698
- Active material: c-Si
- Window material: BK7 Schott Glass
- Certification: National Renewable Energy Laboratory (NREL)
  A2LA Accreditation Certificate Number 1239.02
  ISO tracking number: 1653
- Certified short-circuit current (I_{sc}) under SRC (95% confidence level): 131.7 mA ± 1.7
- Calibration due date: August 15, 2012

Solar Simulator:
- Spectrum: PV Evolution Labs filename PVEL_94083A_06-01-11.xlsx
- Total irradiance: 1000 W/m² based on I_{sc} of the above Secondary Reference Device

Calibration Procedures:
- I-V: PV Evolution Labs document PVEL1024-E948
- QE: PV Evolution Labs document PVEL1025-E1021

Environmental Conditions During Calibration:
- Temperature: 25 °C ± 1
- Relative Humidity: 42 % ± 2

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Ref cell vs. Pyranometer

	Reference cell	Thermopile pyranometer
Spectral response	Can be made to closely match solar panel	Broadband response needs to be corrected
Angle of incidence	Can be made to match solar panel	Response to all angles
Temperature response	Temperature response is similar to PV system	Are designed to minimize sensitivity to temperature. Can be problematic in cold climates
Time response	< milliseconds; matched to PV response	Up to 30 seconds; Can be problematic for measuring PV performance
Other issues		Emission to cold sky and transients in ambient temperature affect output
International standards for calibration	IEC 60904	ISO 9847, ISO 9845, ISO 9846

Question for discussion

- Can reliability demonstration testing and/or latent defect screening and/or the use of reference cells impact financing terms?
  - Interest rates?
  - Debt service coverage ratio?

PVEL Services

- Reliability & Performance Testing
- PV Module Latent Defect Screening
- Ongoing Degradation Testing
- Supplier Qualification
- Solar Reference Cells
- Warranty Support
- PAN Files
- PV-EPI[1]

In Partnership with

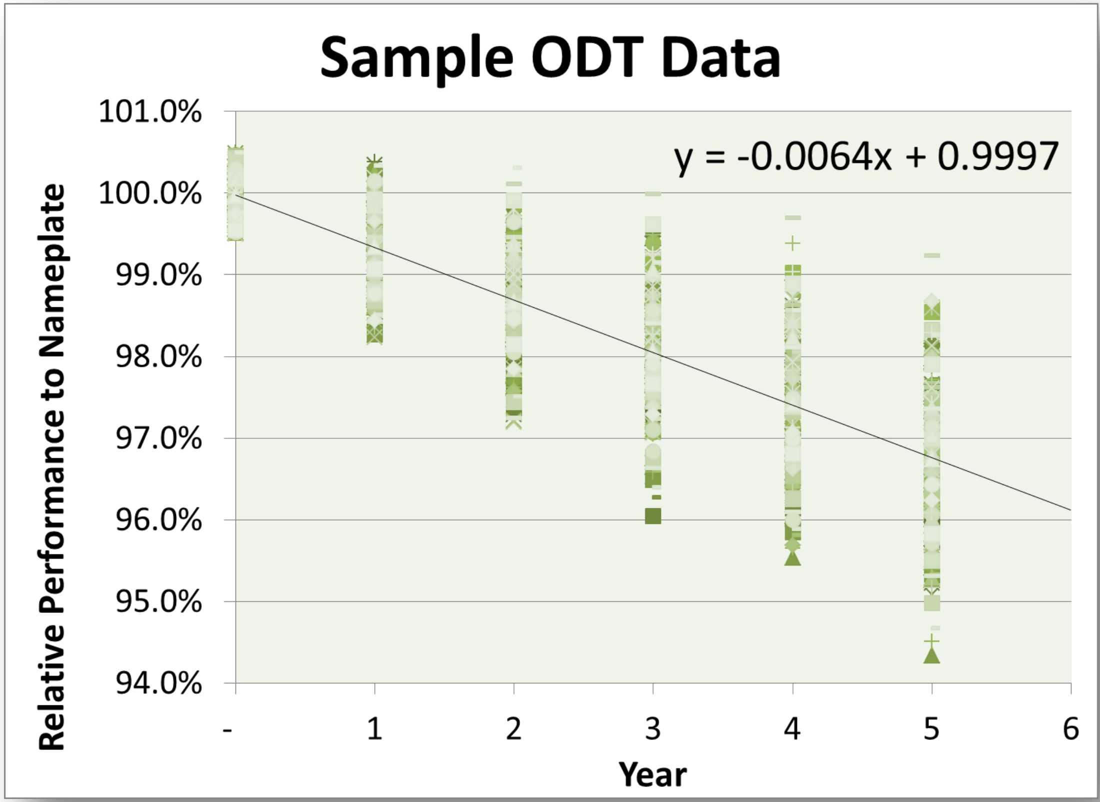
BLACK & VEATCH

1. Energy Performance Index

Ongoing Degradation Testing

- Annual non-destructive laboratory testing PV modules
- Most accurate method to determine actual degradation rates

1. Clean and flash test in Class AAA Pasan 3b tester, most accurate flash tester available
2. If within spec repackage and ship back to the site for reinstallation
3. If outside of spec determine cause



PV-Energy Performance Index

- PV-EPI is the first public report on different module's energy yield
- Multiple 5kW systems deployed at PV-USA
- DC Performance Ratio released publicly on quarterly basis

	Module Manufacturer	DC Performance Ratio*	Rank
System 1	Company 1	87.5% - 88.5%	1
System 2	Company 2	87.5% - 88.5%	1
System 3	Company 3	86.5% - 87.5%	2
System 4	Company 4	86.5% - 87.5%	2
System 5	Company 5	85.5% - 86.5%	3
System 6	Anonymous	84.5% - 85.5%	4
System 7	Anonymous	84.5% - 85.5%	4
System 8	Anonymous	83.5% - 84.5%	5
System 9	Anonymous	83.5% - 84.5%	5
System 10	Anonymous	83.5% - 84.5%	5

*PR range indicates measurement uncertainty.

PAN Files

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- PVSyst is the industry standard modeling software
  - Each module has a PAN file that outlines panel characteristics
  - Typical PAN files have missing or incorrect data leading to conservative projections by several % – money left on the table

- 3rd party PAN file creation and validation
  - Service offered in partnership with Black & Veatch
- B&V performs IE work on 70% of large scale PV projects in North America – B&V PAN file is valuable

- 3rd party report includes:
  - Light Induced Degradation (LID) evaluation
  - Temperature coefficients

PAN Files

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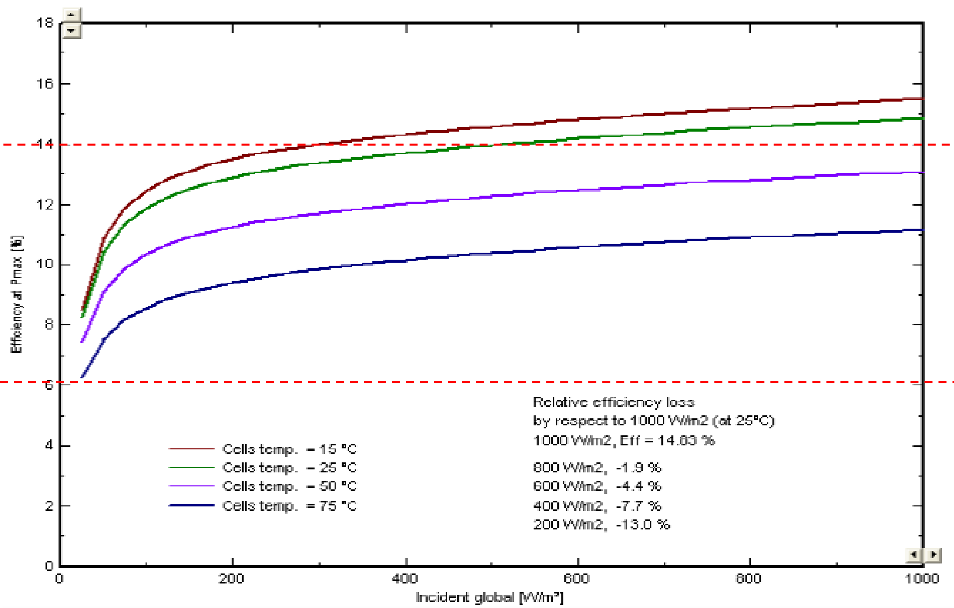
- Module characteristics at non-deal conditions impact projected energy yield by several percent
- Energy projections are central to developer's buying decisions

Efficiency vs. irradiance for different temperatures

Typical PAN file



PVEL / Black & Veatch PAN file