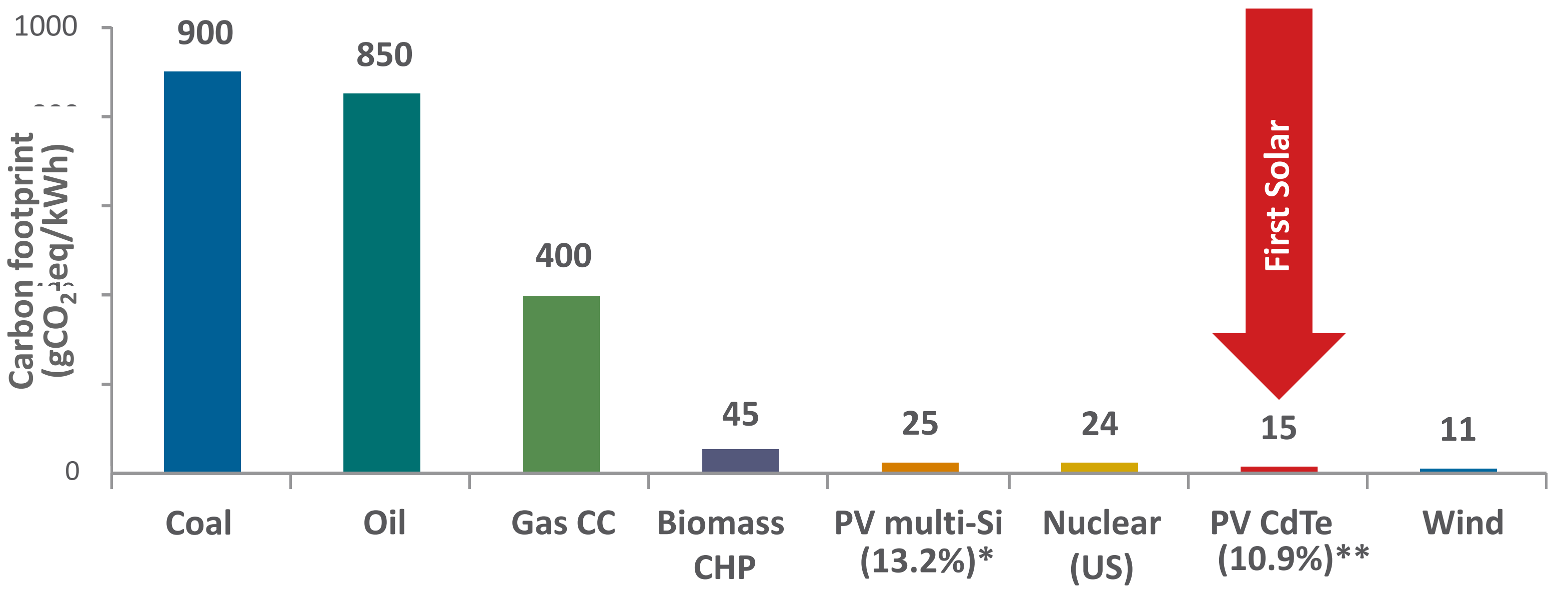
Markus Beck, Pedro Gonzalez, Richard Gruber, Jim Tyler

Our Mission

To create enduring value by enabling a world powered by clean, affordable solar electricity.

Sustainable Environmental Profile

Carbon Footprint is a Fraction of Conventional Sources



Sources: *de Wild-Scholten, M., presented at CrystalClear Final Event in Munich on May 26, 2009. **de Wild-Scholten, M., 'Solar as an environmental product: Thin-film modules – production processes and their environmental assessment,' presented at the Thin Film Industry Forum, Berlin, April, 2009. Both PV technologies use insolation of 1700 kWh/m^2. All other data from ExternE project, 2003; Kim and Dale, 2005; Fthenakis and Kim, 2006: Fthenakis and Alsema, 2006; Fthenakis and Kim, in press.

First Solar's Energy Payback Time (EPBT) < 1 year

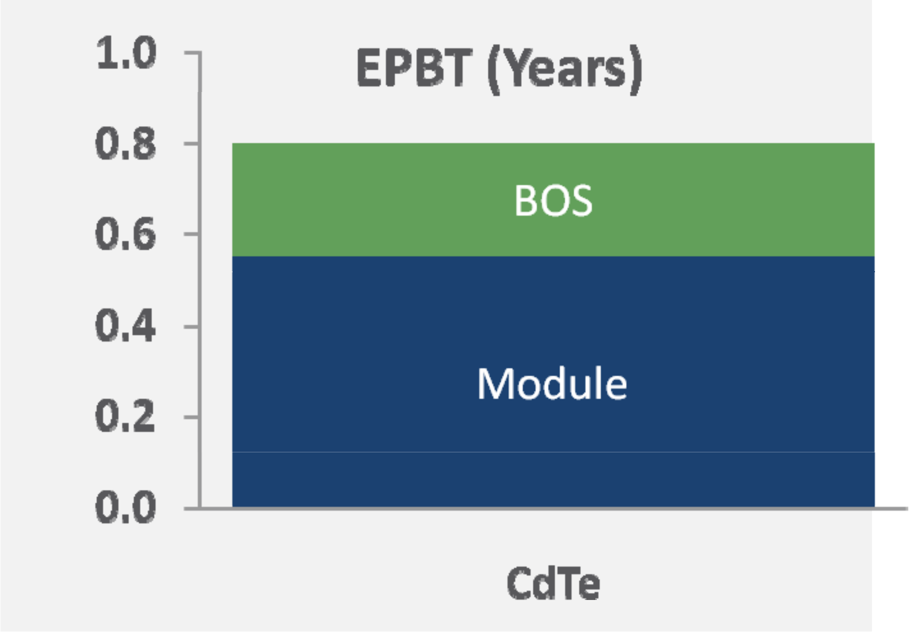
EPBT:

The amount of time
a system must operate to recover
the energy that was required to
fabricate the system

- EPBT = $E_{input}/(E_{output}/yr)$

Objective: Minimize EPBT

- Supports rapid scalability
- <1 year ensures industry growth does not create near term energy deficit

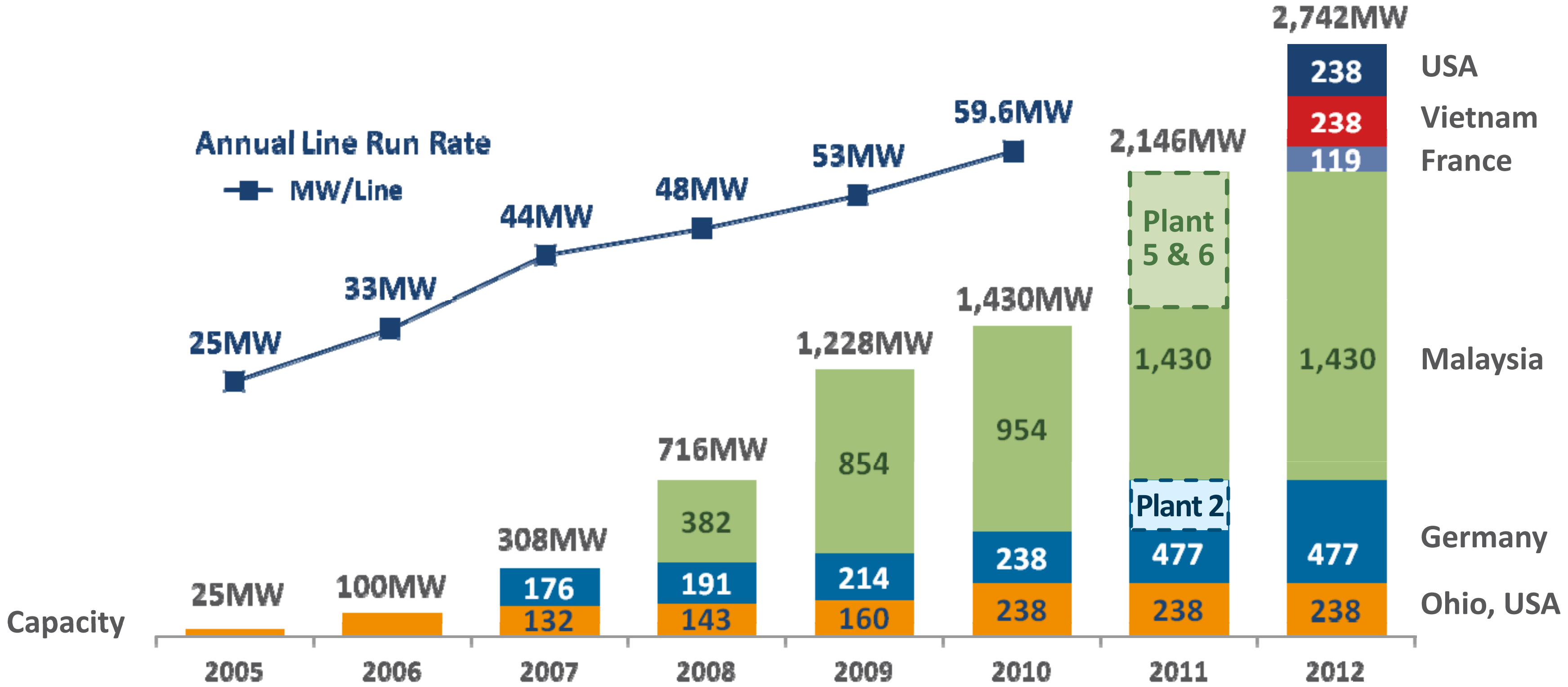


Note: Southern Europe 1700 kWh/m^2/year irradiance.

Source: de Wild-Scholten, M., 'Solar as an environmental product: Thin-film modules – production processes and their environmental assessment,' presented at the Thin Film Industry Forum, Berlin, April, 2009

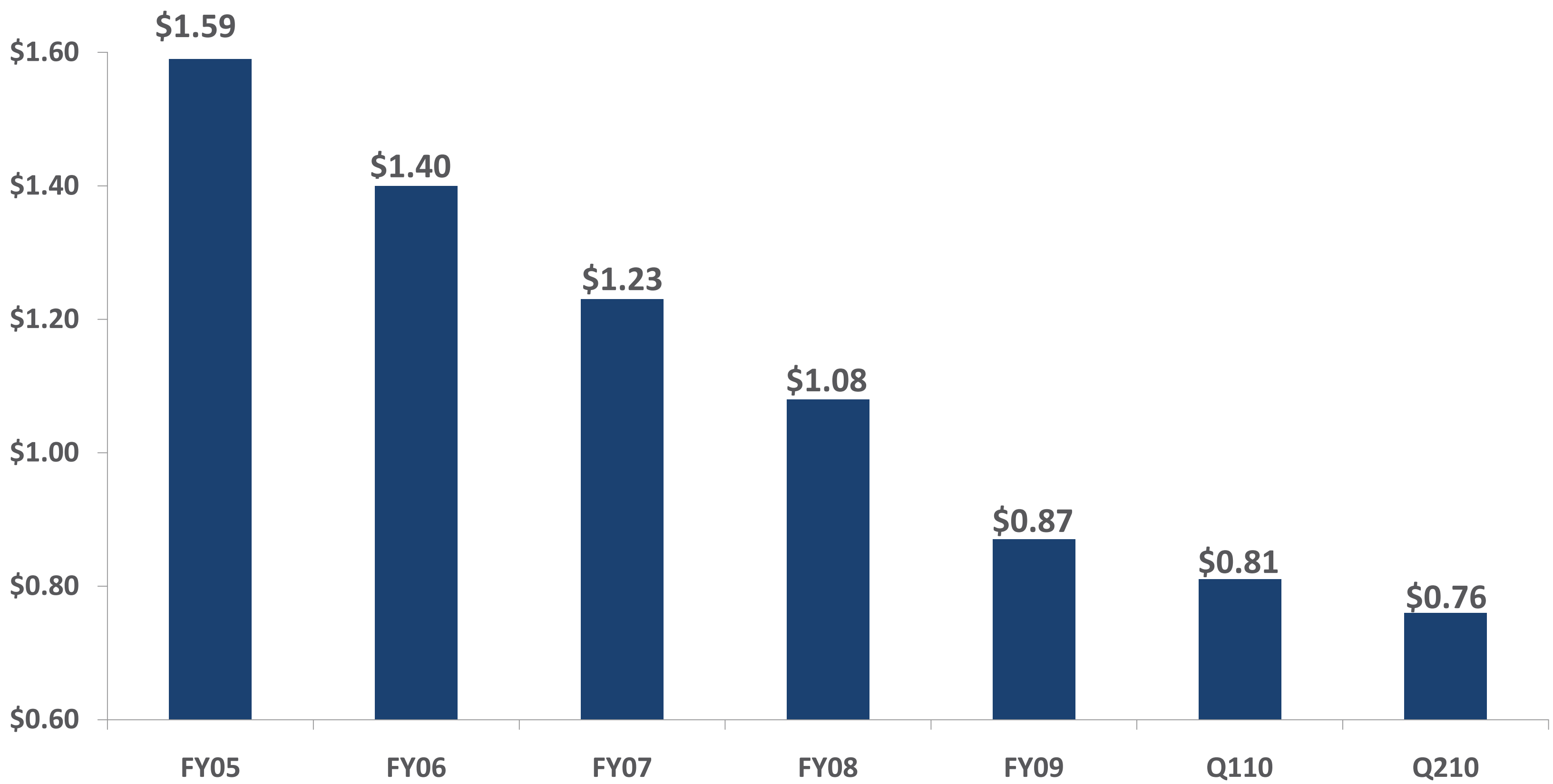
Production Capacity Growth (year-end capacity)

Current and announced capacity grows by 1.3GW (92%) to 2.7GW

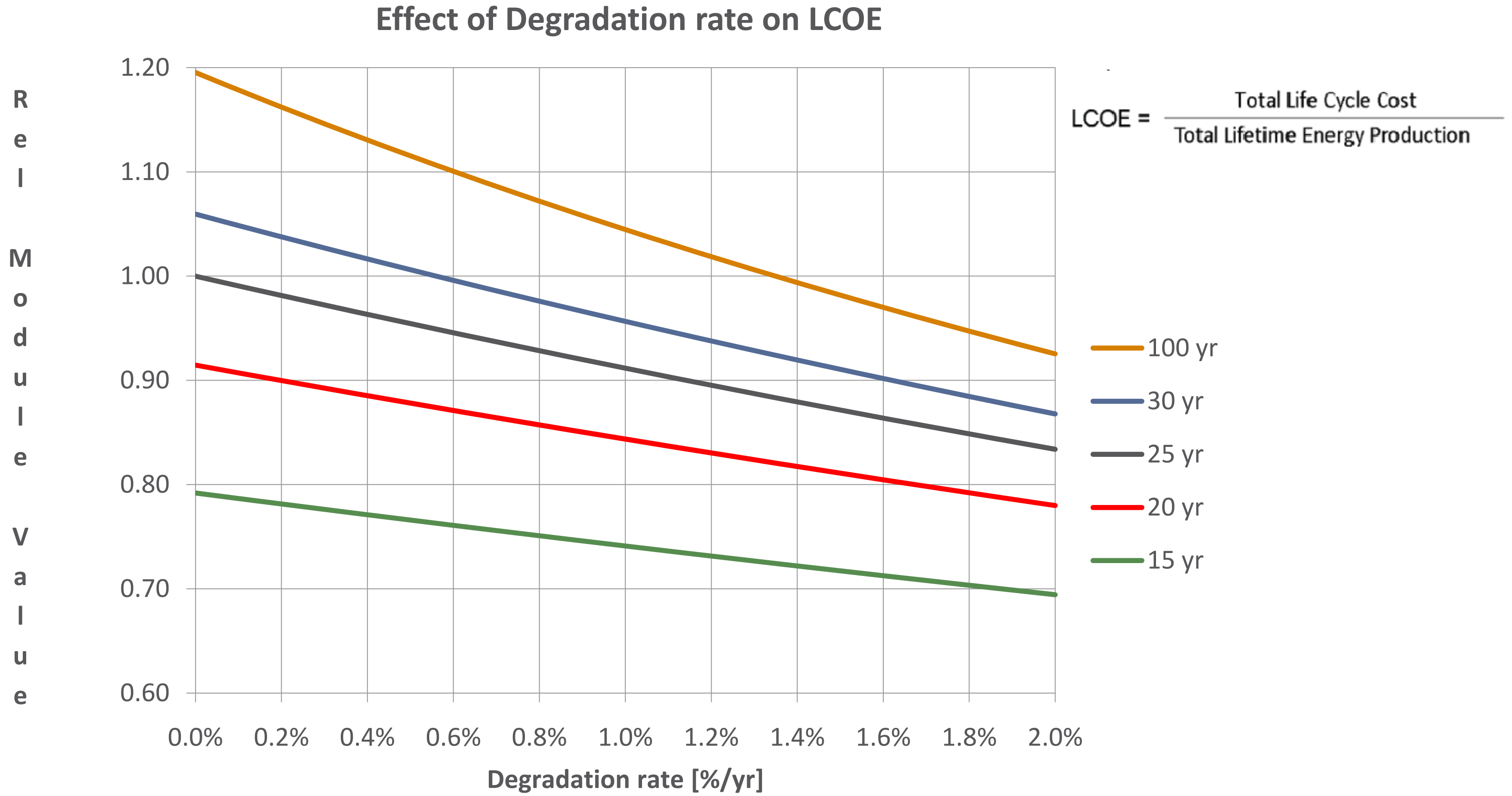


Representation of year-end capacity. 2005 & 2006 based on Q4 06 run rate; 2007 based on Q4 07 run rate; 2008 based on Q4 08 run rate; 2009 based on Q4 09 run rate, 2010-2012 based on Q3 10 run-rate.

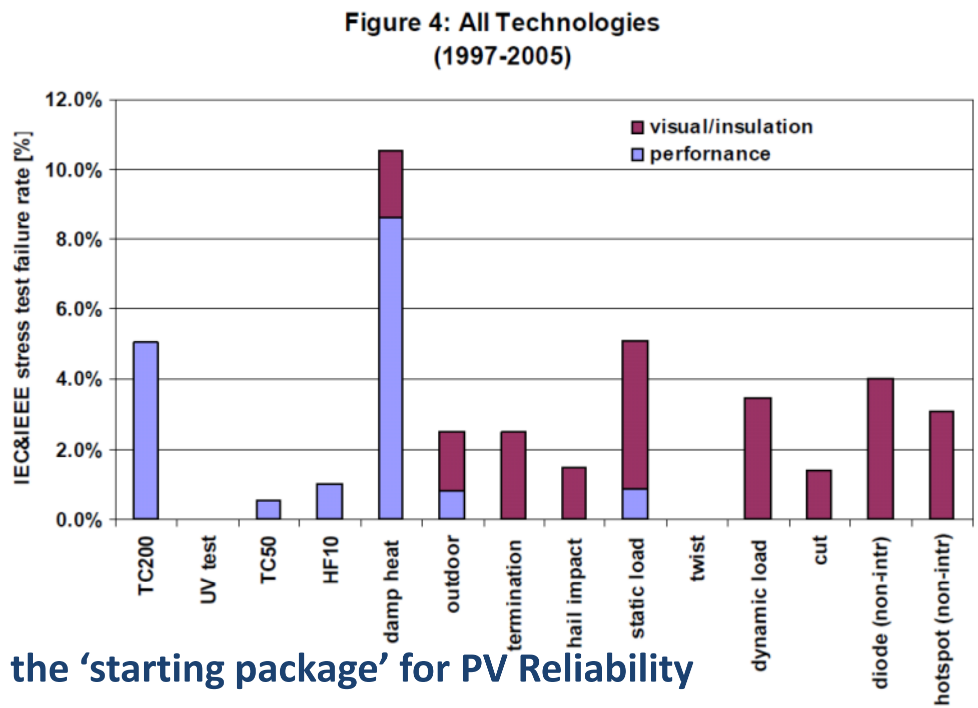
Manufacturing Cost per Watt Trend



Reliability Impact on Module Value



Module Failures from Qualification Testing



- Qualification testing is the 'starting package' for PV Reliability
- Just a screening test for key design flaws/infant mortality
- No correlation to MTBF, long term OD performance, degradation

TamizhMani, et al, "IEC And IEEE Design Qualifications: An Analysis Of Test Results Acquired Over Nine Years", 2008

TF Module Failure Modes

Issue	Description	Tests	References	R&D need
Increase in series resistance after exposure to moisture	Moisture ingress is known to increase the series resistance of ZnO and some other materials commonly used in thin-film modules; this is a special issue for flexible products.	Damp heat	[27, 51] [41]	Development of thin-film products that are not sensitive to moisture or development of a barrier that keeps moisture out of sensitive layers.
Instability of thin-film layers caused by delamination and/or diffusion	Thin-film products usually require many layers; if any of these has poor adhesion, delamination may occur, often breaking the electrical connection between active layers. Also, Cu and other elements are known to diffuse, causing changes in how the cells perform.	Damp heat; temperature cycling	[18, 23, 52-57]	Develop understanding of the diffusion/delamination mechanisms, what affects them, and how to test for instabilities.
Nonuniformities in manufacturing, including scribe-line issues	Nonuniformities can lead to "weak diodes" that may then run hotter than the rest of the module, providing a weak point for degradation. Similarly, many other manufacturing nonuniformities (especially at scribe lines) can lead to reliability problems.	Damp heat; temperature cycling	[23, 58]	Much work is needed to understand what parameters must be carefully controlled during manufacturing and what nonuniformities can be tolerated.

Sarah Kurtz, et al, "Photovoltaic-Reliability R&D toward a Solar-Powered World", Proc. of SPIE 2009

TF Module Failure Modes cont.

	Known and Anticipated Failure Modes & Degradation Mechanisms	Priority/Prob. of Success / Role for Labs (High-Medium-Low)	Diagnostic Technique / Qual Test (e.g., chamber tests, HVTB)	Comment
General	Corrosion leading to loss of grounding	H/H/H		
	Quick connector reliability	H/H/L		
	Improper installation leading to loss of grounding	H/H/L		
	Delamination	H/M/M		This is especially a problem for flexible packages
	Glass breakage	M/H/L		For products using glass
	Bypass diode failure	M/H/L		
	Inverter reliability	M/H/M		
Film Si	See items listed in "General" section			
	Electrochemical corrosion of SnO_2:F	M/M/L	Light soaking; Voltage biased damp heat[2]	
	Initial light degradation (a-Si)	L/L/L	Light soaking	
CdTe	Cell layer integrity – backcontact stability	H/H/H		
	Cell layer integrity – interlayer adhesion and delamination; Electrochemical corrosion of SnO_2:F	L/L/M	Voltage biased damp heat[2]	
	Fill-factor loss (increased series resistance and/or recombination)	H/M/H	Cell + Module Light soaking; Damp Heat	Screen at cell initially; then module
	Busbar failure - mechanical (adhesion) and electrical	H/H/M	IR Camera; Hot/humid vs. damp heat	Thermal stress[3]
	Shunt hot spots at scribe lines before and after stress	H/M/M	IR Camera; Hot/humid vs. damp heat	
	Weak diodes, hot spots, nonuniformities before and after stress	H/M/H	IR Camera; Hot/humid vs. damp heat	
CIS	Cell layer integrity – contact stability	H/H/H		Mo backcontact (all), the front contact is only a problem when the module is assembled from discrete cells
	Cell layer integrity – interlayer adhesion	M/H/M		
	Fill-factor loss (increased series resistance and/or recombination)	H/M/H	Cell + Module Light soaking; Damp Heat	Screen at cell initially; then module
	Busbar failure – mechanical (adhesion) and electrical	M/H/M	IR Camera; Hot/humid vs. damp heat	
	Notable sensitivity of TCO to moisture	H/M/H	Damp heat exposure	
	Moisture ingress failure of package	H/M/H	Hot/humid vs. damp heat	Flexible roofing products
	Cell–to-cell interconnect (discrete cells)	H/M/H	IR Camera; Hot/humid vs. damp heat	Flexible roofing products; this is a problem when discrete devices are interconnected into modules
	Notable sensitivity of TCO to moisture; need to pass damp heat test (non-shingle specific)	H/M/M	Damp heat exposure	
	Shunt hot spots at scribe lines before and after stress	H/M/M	IR Camera; Hot/humid vs. damp heat	
	Weak diodes, hot spots, nonuniformities before and after stress	H/M/H	IR Camera; Hot/humid vs. damp heat	
	Edge shunting	M/H/M		Discrete Cell – Flexible roofing products

Nick Bosco, "Reliability Concerns Associated with PV Technologies", NREL

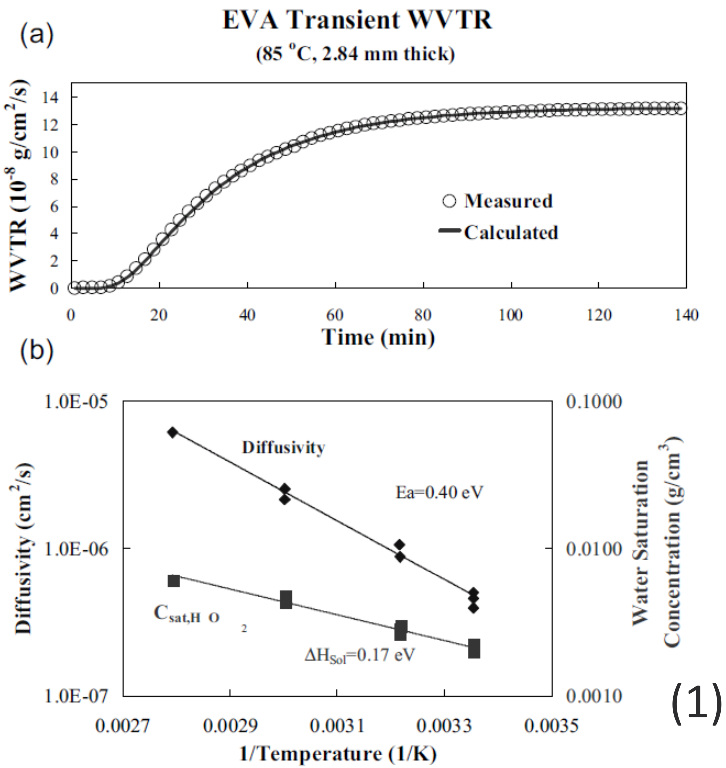
TF Module Failure Modes cont.

Table I. Thin-film failure modes and failure mechanisms

Failure modes	Effect on I–V curve	Possible failure mechanisms
1. Cell degradation		
a. Main junction: increased recombination[24]	Loss in fill factor, I_{sc}, and V_{oc}	Diffusion of dopants, impurities, etc. Electromigration
b. Back barrier; loss of ohmic contact (CdTe)[7,24,25]	Roll-over, cross-over of dark and light I–V, higher R_{ser}	Diffusion of dopants, impurities, etc. Corrosion, oxidation Electromigration
c. Shunting[26–28]	R_{shunt} decreases	Diffusion of metals, impurities, etc.
d. Series: ZnO,[23] Al[29]	R_{ser} increases	Corrosion, diffusion
e. De-adhesion SnO_2 from soda-lime glass[57,59]	I_{sc} decreases and R_{ser} increases	Na ion migration to SnO_2/glass interface
f. De-adhesion of back metal contact	I_{sc} decreases	Lamination stresses
2. Module degradation		
Interconnect degradation		
a. Interconnect resistance; ZnO:Al/Mo or Mo[23]. Al interconnect[49]	R_{ser} increases	Corrosion, electromigration
b. Shunting; Mo across isolation scribe[23]	R_{shunt} decreases	Corrosion, electromigration
Busbar degradation	R_{ser} increases or open curcuit	Corrosion, electromigration
Solder joint	R_{ser} increases or open circuit	Fatigue, coarsening (alloy segragation)
Encapsulation failure		
a. Delamination[36–38]	Loss in fill-factor, I_{sc}, and possible open circuit	Surface contamination, UV degradation, hydrolysis of silane/glass bond, warped glass, 'dinged' glass edges, thermal expansion mismatch
b. Loss of hermetic seal		
c. Glass breakage		
d. Loss of high-potential isolation[50,56,57]		

T Mac Mahonm, "Accelerated Testing and Failure of Thin-film PV Modules" , Progress in PV 2004

Humidity is an important stress factor



(1)

$$k = A_o \, e^{-\frac{E_a}{RT}}$$

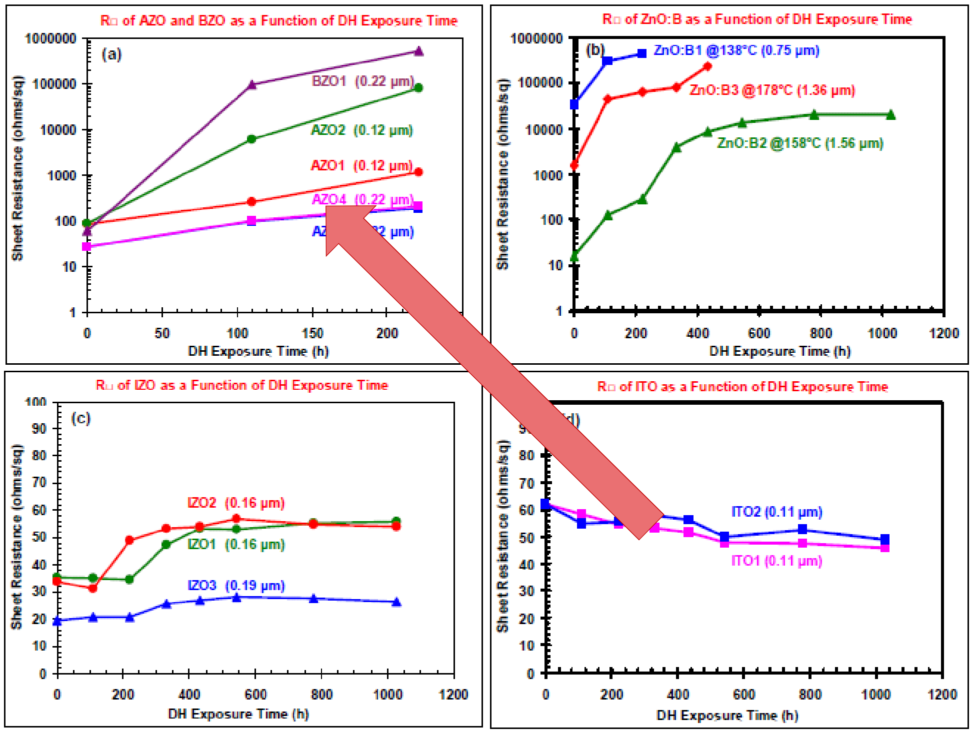
Diffusivity of water follows an Arrhenius model

Choose materials that limit water ingress!

(1) M. Kempe, "Control of Moisture Ingress into Photovoltaic Modules" IEEE PVSC, 2005

(2) D. J. Coyle, H. A. Blaydes, J. E. Pickett et al., "Degradation kinetics of CIGS solar cells," Proceedings of the 2009 34th IEEE Photovoltaic Specialists Conference (PVSC 2009), pp. 001943-7, 2009.

Humidity affects TCO's in different ways



x 10^4 worse

(1)

- **Choose materials that are less sensitive to water**

(1) F.J. Pern, R. Sundaramoorthy, C. DeHart, et al. " Stability of TCO Window Layers for Thin-Film Solar cells", Proc. of SPIE Vol. 7412 74120J-1
(2) Sundaramoorthy, R., et al., "Comparison of Amorphous InZnO and Polycrystalline ZnO:Al Conductive Layers for CIGS Solar Cells," 34th IEEE PVSC, (2009).

Temperature is an important stress factor

- Corrosion of conductive components
- Thermal degradation of polymers
  - Delamination of interfaces
  - Failure of adhesive/pottants
- Diffusivity of water

$$k = A_o \, e^{-\frac{E_a}{RT}}$$

- To find Activation Energy (Ea) we need to go beyond Damp Heat and test at different temperatures

Temperature is an important stress factor

Module Type	Mount	a	b	ΔT (°C)
Glass/cell/glass	Open rack	-3.47	-.0594	3
Glass/cell/glass	Close roof mount	-2.98	-.0471	1
Glass/cell/polymer sheet	Open rack	-3.56	-.0750	3
Glass/cell/polymer sheet	Insulated back	-2.81	-.0455	0
Polymer/thin-film/steel	Open rack	-3.58	-.113	3
22X Linear Concentrator	Tracker	-3.23	-.130	13

$$T_m = E \cdot \left\{ e^{a+b \cdot WS} \right\} + T_a$$

from ambient to module temperature

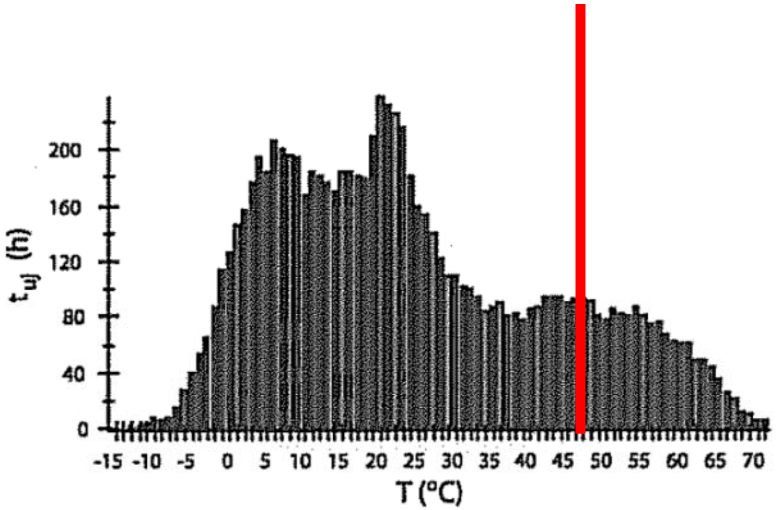
$$T_c = T_m + \frac{E}{E_o} \cdot \Delta T$$

from module to cell (semiconductor) temperature

(1) King et al, “Photovoltaic Array performance model” Sandia SAND2004-3535, 2004

Activation Energy & $T_{equivalent}$

- **$T_{equivalent}$ is the activation energy (Ea)-weighted average temperature for a system**
- **$T_{equivalent}$ is a function of the Activation energy**



$$\Delta P = Ae^{\frac{-E_a}{RT}}\Delta t$$

$$P = \sum_i Ae^{\frac{-E_a}{RT_i}}\Delta t_i = Ae^{\frac{-E_a}{RT_{Equivalent}}}\sum_i \Delta t_i$$

(1) McMahon, "Accelerated Testing and Failure of Thin-Film PV Modules", Prog in PV, 2004

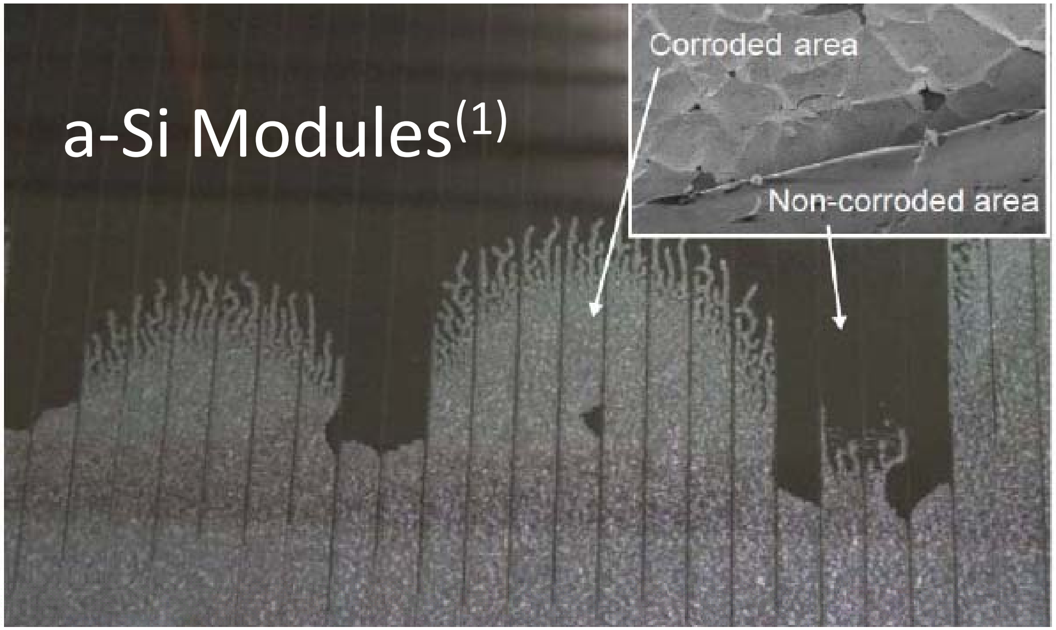
Equivalent Temperature for Different Climatic Zones

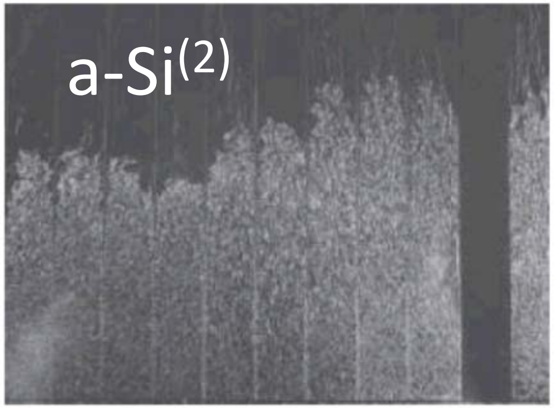
Mount:	Open rack glass-cell-glass		Close roof glass-cell-glass		Open rack glass-cell-polymer		Insulated back		Open rack polymer-cell-steel	
Ea➔ Location🡫	1.1 eV	2 eV	1.1 eV	2 eV	1.1 eV	2 eV	1.1 eV	2 eV	1.1 eV	2 eV
Riyadh	48.4	55.1	61.0	69.5	45.9	52.3	67.1	76.3	44.0	50.3
Kuwait	46.0	53.0	56.0	66.3	43.8	50.3	60.9	73.1	41.7	47.9
Bangkok	41.7	46.5	51.5	58.6	39.8	44.1	56.4	64.4	38.3	42.3
New Delhi	44.8	51.2	56.8	65.2	42.7	48.6	62.7	72.0	41.2	46.9
Seville	39.5	47.1	51.3	60.4	37.4	44.6	57.0	66.7	35.8	43.1
Munich	26.7	35.4	37.2	48.2	24.8	33.0	42.3	54.2	23.3	31.4
Phoenix	47.1	53.9	59.9	68.2	44.6	51.0	66.0	75.0	42.6	48.8
Yuma	43.8	50.2	54.9	63.0	41.6	47.7	60.3	69.2	39.9	45.8
Daytona	37.2	42.9	47.7	55.2	35.0	40.3	52.7	61	33.0	37.9
Miami	37.1	41.9	46.7	53.7	35.0	39.3	51.5	59.3	33.1	36.9

- **We can now answer the question "how long will my module last" for some degradation mechanisms**
- **What comes next? Correlate your lab model with real outdoor data**

Kent Whitfield, "Evaluation Of High-temperature Exposure Of Rack-mounted Photovoltaic Modules", PVSC IEEE 34th

Voltage is an important stress factor





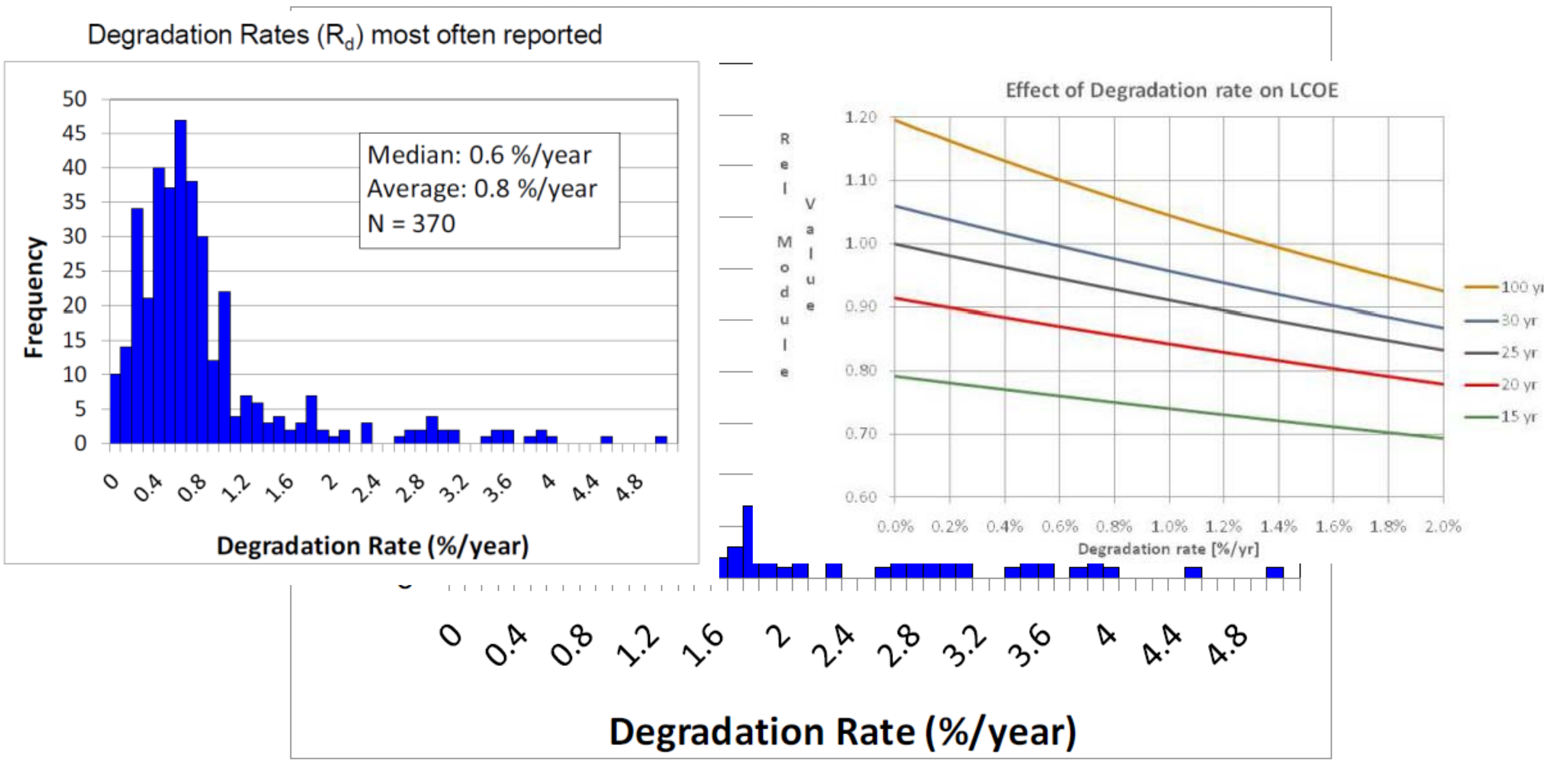
'Bar-graph' delamination

- **There are other stress factors, some of them not in the 'starter package'**

(1) Peter Hackle "Characterization of Multicrystalline Silicon Modules with System Bias Voltage Applied in Damp Heat ", 25th European Photovoltaic Solar Energy Conference and Exhibition. September, 2010
(2) T McMahon, "Accelerated Testing and Failure of Thin-film PV Modules" , Progress in PV 2004
(3) JPL- Mon, Ross (1984): "Predicting electrochemical breakdown in terrestrial photovoltaic modules"

PV System Degradation rates

Degradation Rates (R_d) most often reported



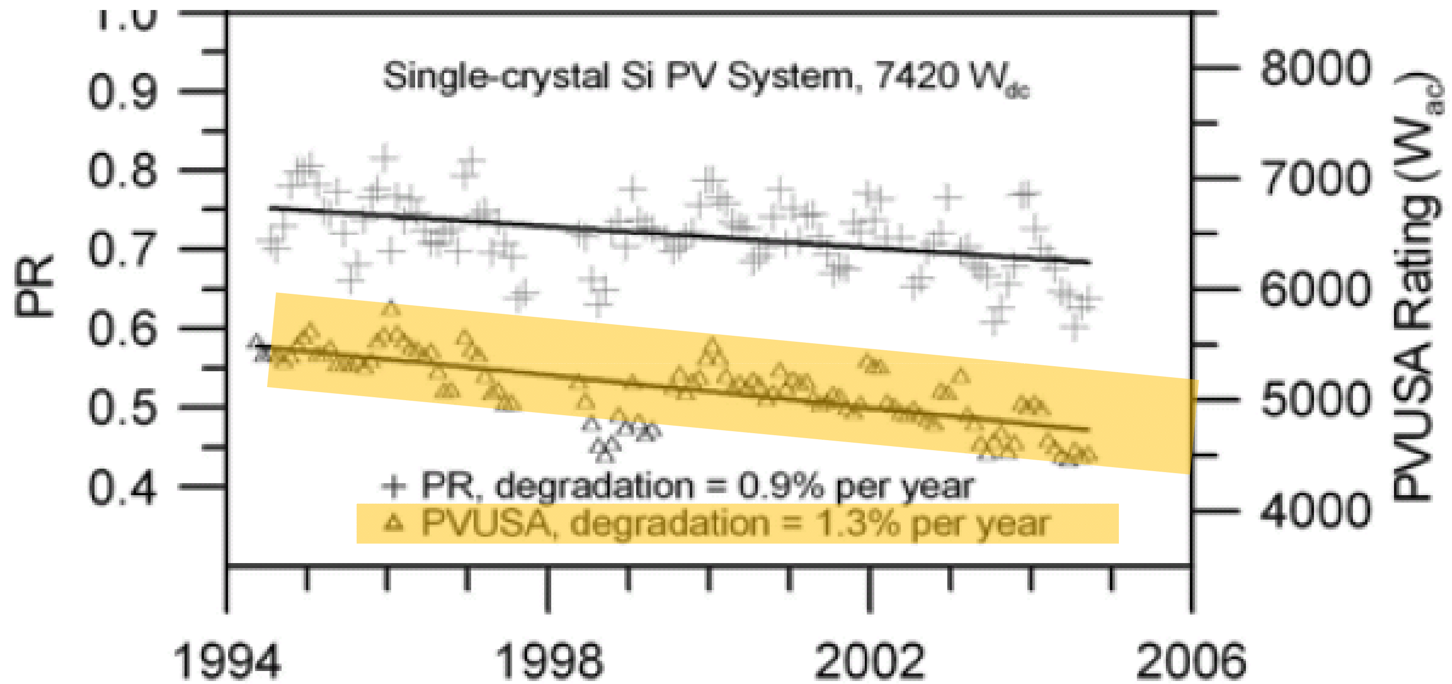
Dirk Jordan (NREL), “Degradation Rates”, Feb-2010

Outdoors Performance Monitoring

- **energy output** — E — **[amount of energy kW-AC]**
- **final PV system yield** — $Y_f = E/P_0$ — **[takes into account system size]**
- **performance ratio** — $PR = Y_f/Y_r$ — **[size + solar radiation]**
- **PTC ratio** — PTC — **[size + solar radiation + temperature/wind]**

IEC 61724 "Photovoltaic system performance monitoring-guidelines for measurement, data exchange, and analysis"

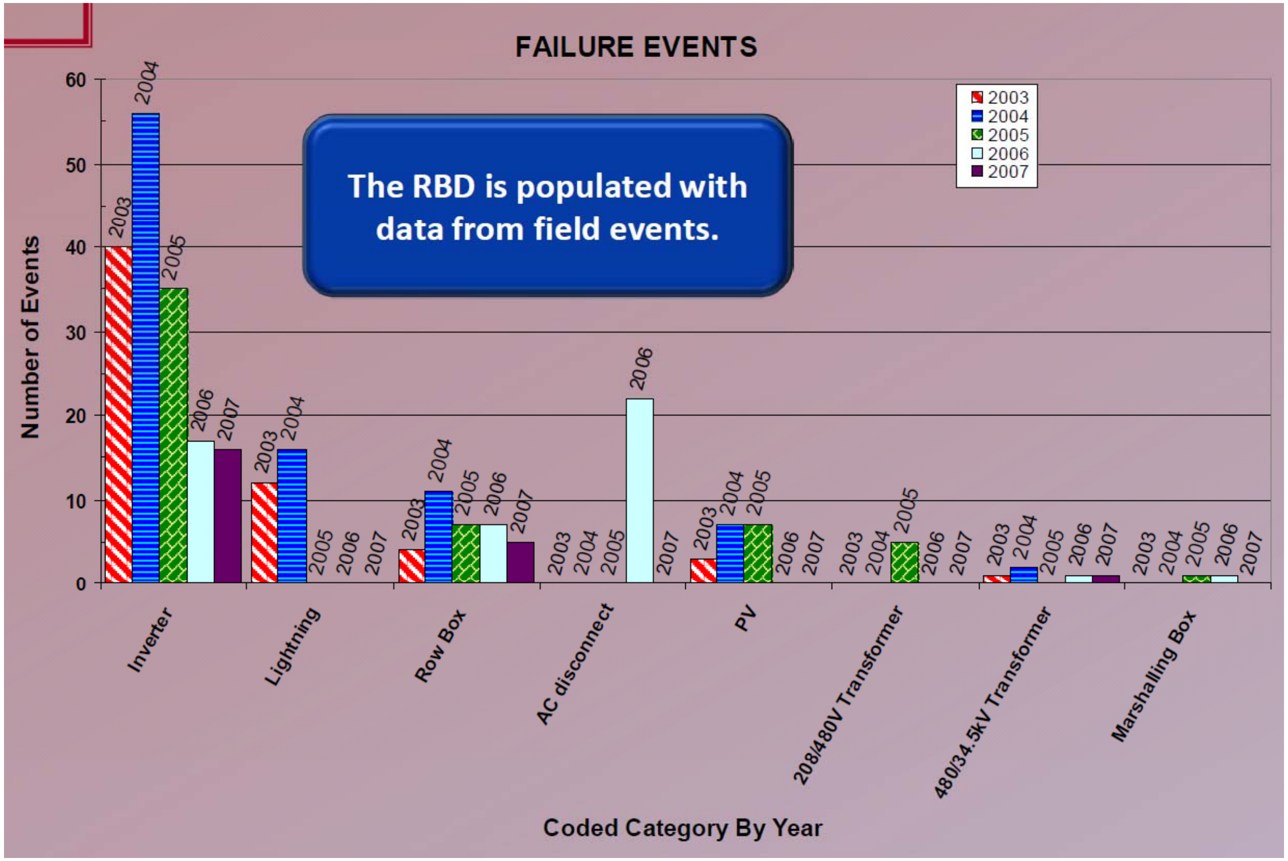
Calculation of PV System Degradation rates



- **The variability on PTC(PVUSA) is lower than PR because it compensates for temperature**
- **+3 years of data is recommended to calculate degradation rates**

B. Marion, et al, "Performance Parameters for Grid-Connected PV Systems", 30th IEEE PVSC, 2005

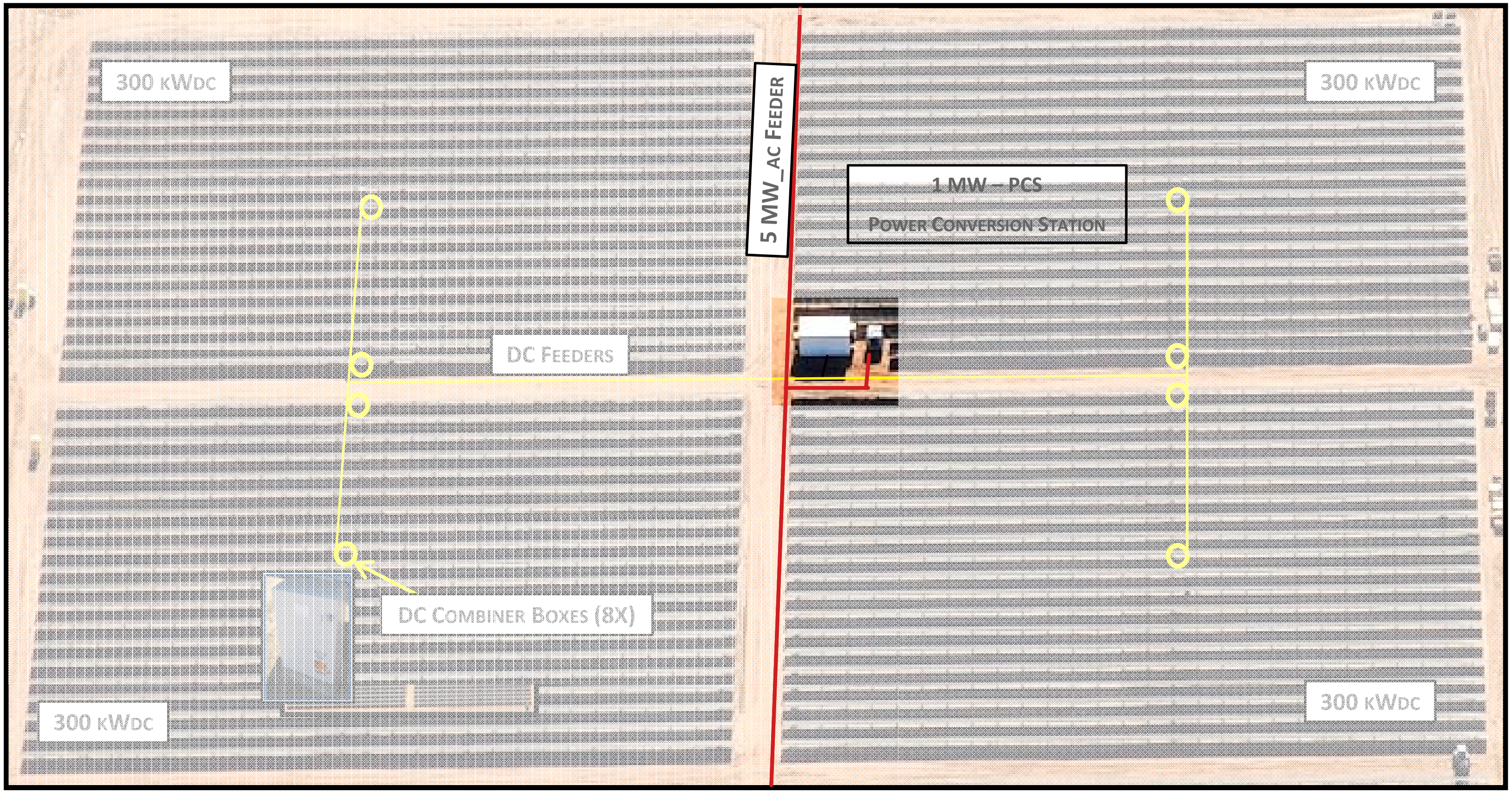
PV System Failure Events



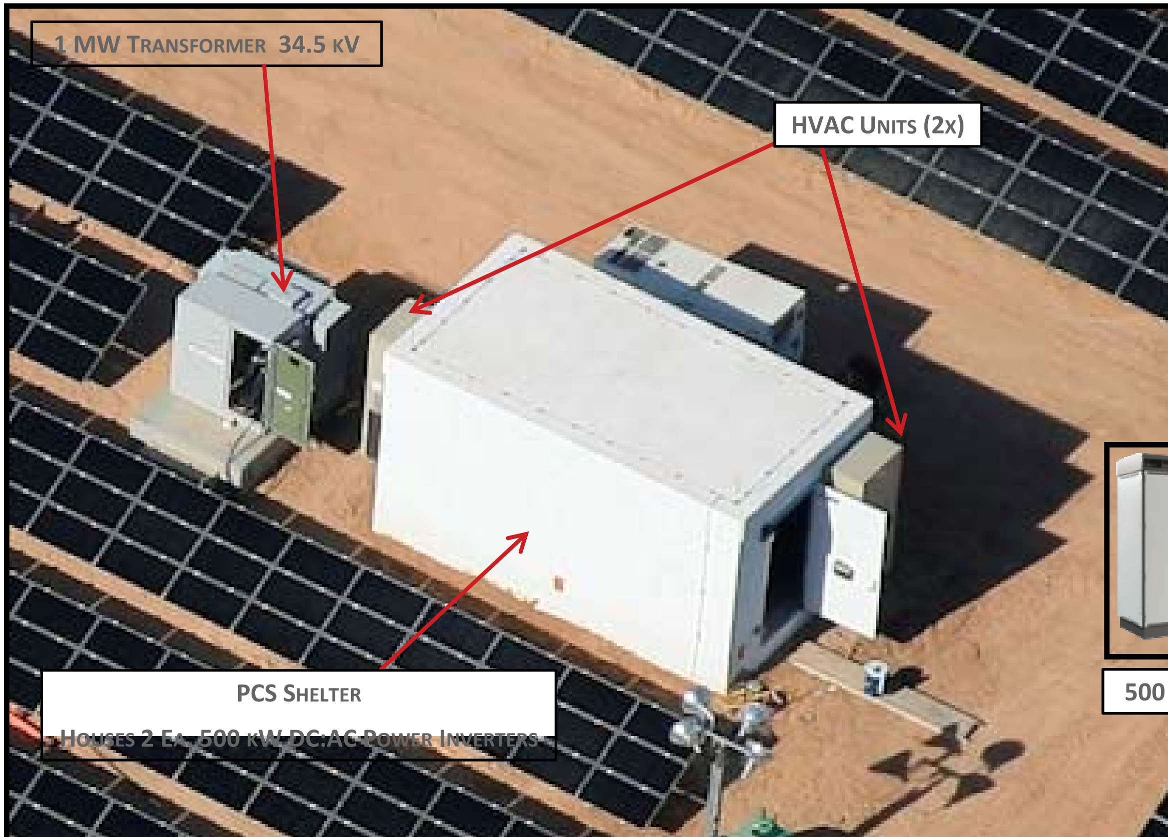
M Quintana, J. Granata, et al. "Sandia'sPV Reliability Program", NREL PV Reliability Conference 2010. Sandia Poster

21 MW Photovoltaic Power Plant: 21 x 1 MW Arrays

1 MWAC ARRAY (1.2 MWDC)

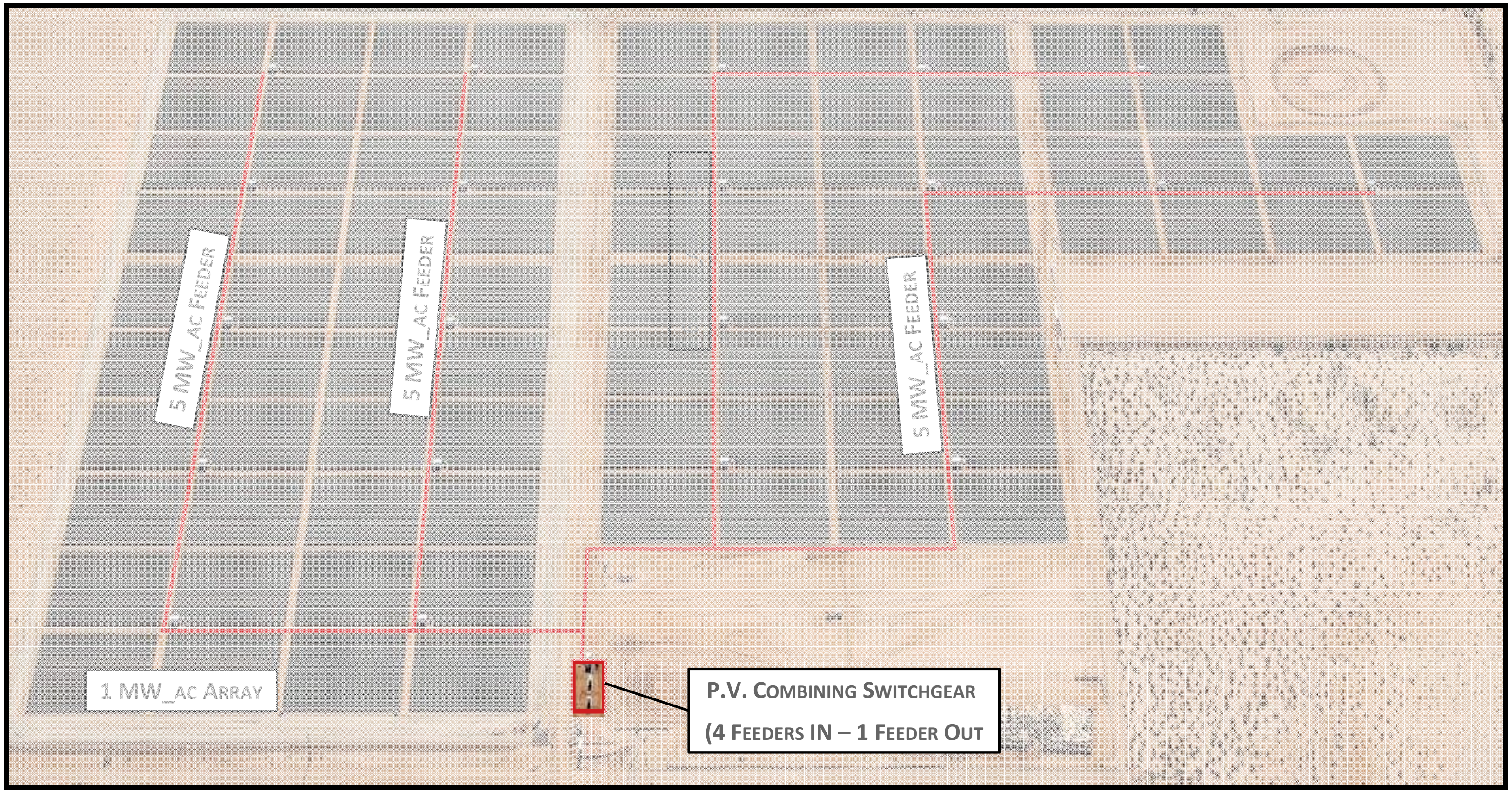


1 MW PCS (Power Conversion Station)



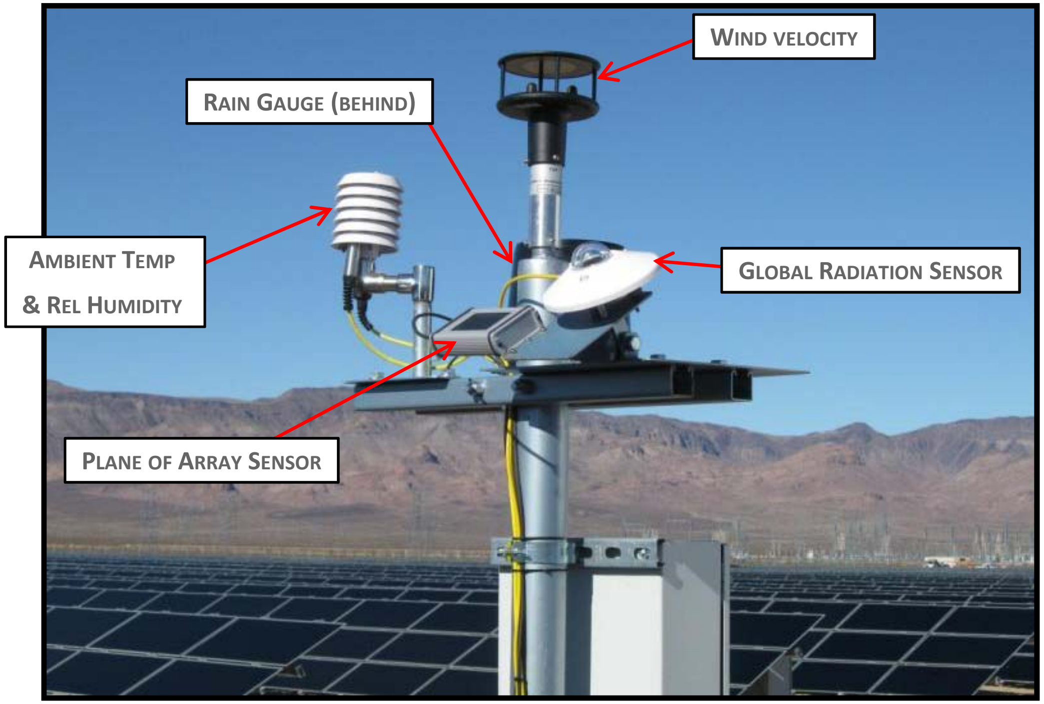
500 kW Inverter

21 MW Photovoltaic Power Plant: 21 x 1 MW Arrays



21 MW PVCS (PHOTO VOLTAIC COMBINING SWITCHGEAR)

METEOROLOGICAL STATION (2 EA.)

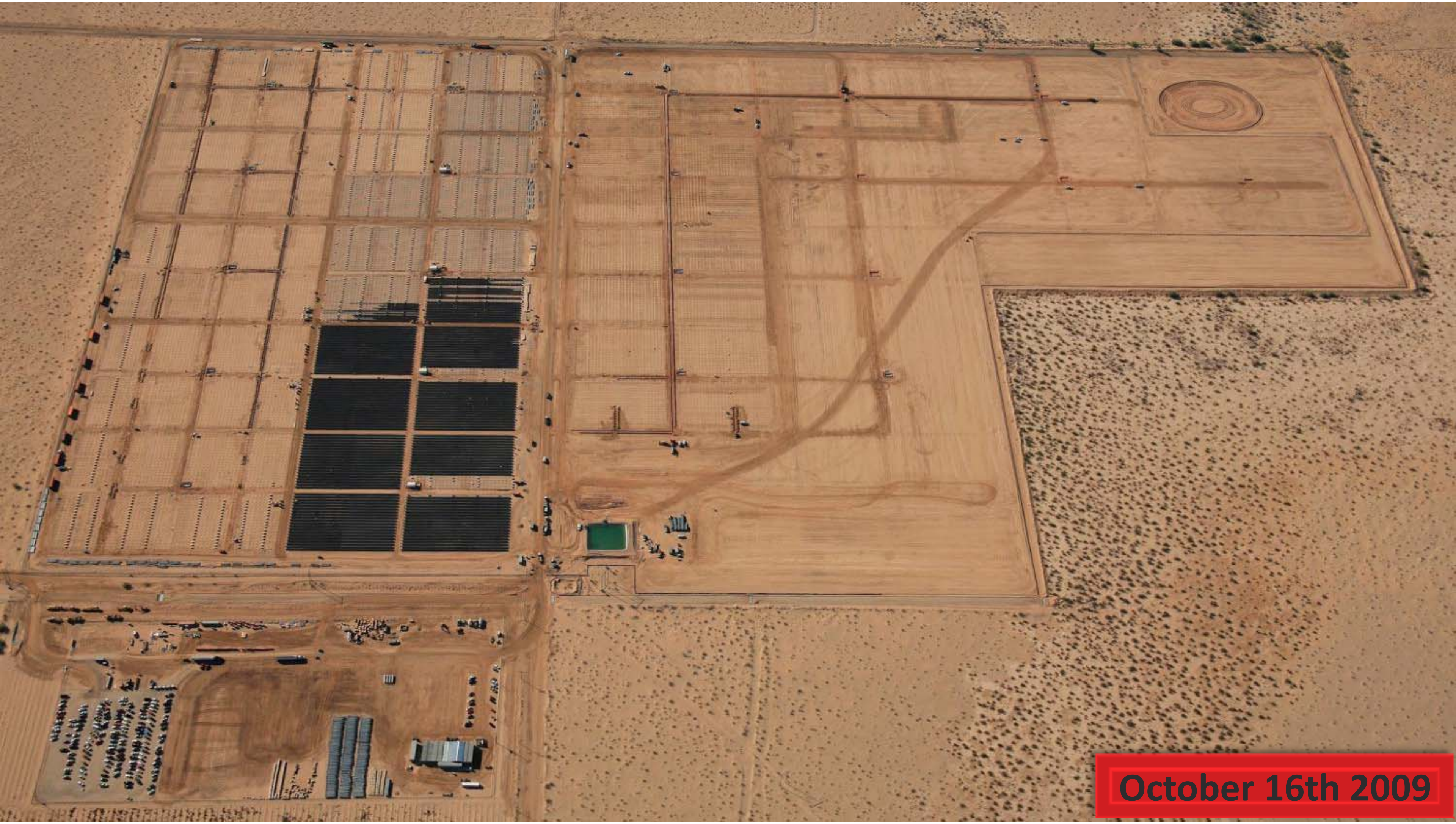


- **Irradiance, Temperature & WindSpeed needed to calculate PR's & PTC's**
- **Correlate your lab model with real outdoor data**


September 25th 2009


October 2nd 2009


October 9th 2009


October 16th 2009


October 23rd 2009


November 3rd 2009


November 13th 2009


November 20th 2009


November 27th 2009

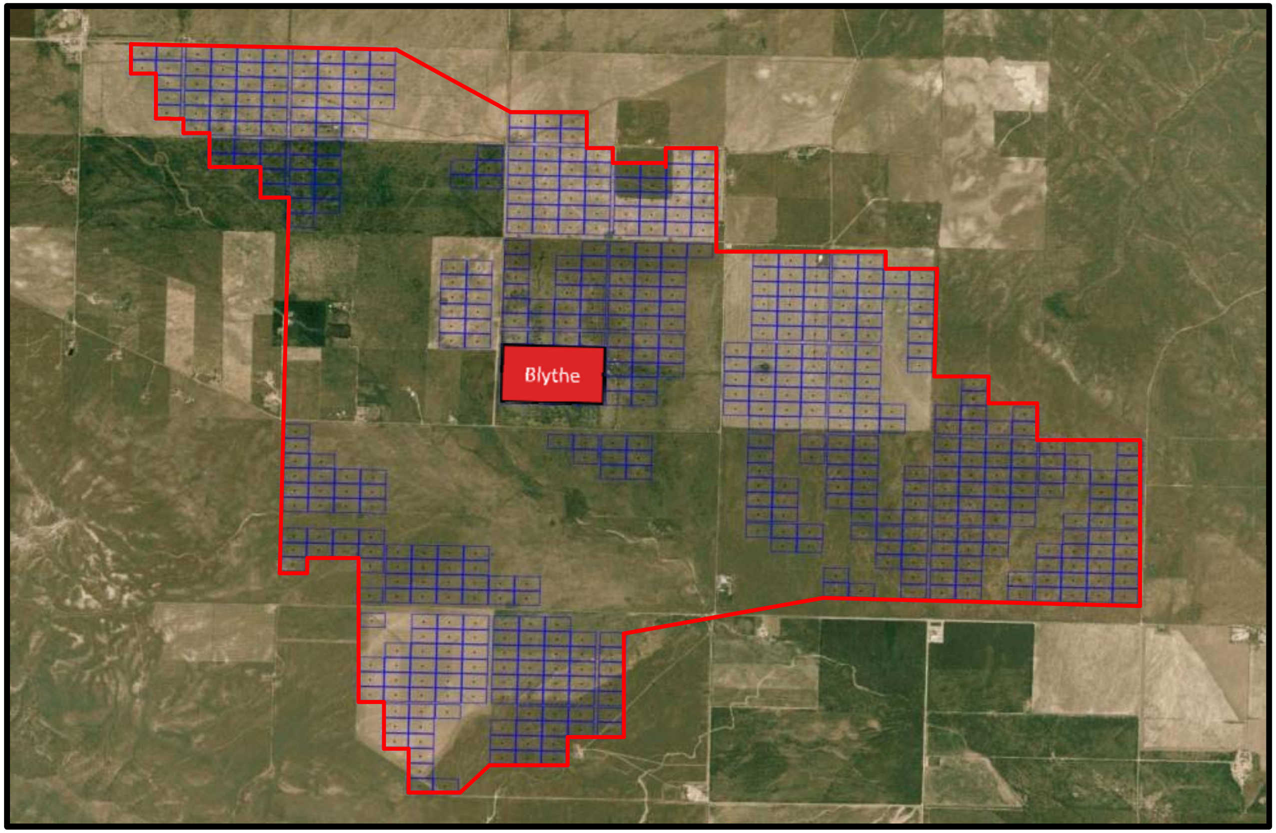
Environmental and Local Benefits

The project will power over 6,000 local homes

The project will avoid emissions of 12,000 metric tons of CO_2 – the equivalent of taking over 2,200 cars off the road.

Utility-Scale Projects in Southwestern U.S. – 2.0 GW AC

From Blythe To Topaz



Summary

- Module reliability is a driver for cost
- Module reliability does not dominate system reliability
- Module reliability enables affordable PV electricity
- Key module stress factors
  1. Humidity
  2. Temperature
- What's needed
  - fundamental understanding of degradation mechanisms
  - correlation to real outdoor performance data
- First Solar enabling statistics at utility scale

thank you

Our Mission

To create enduring value by enabling a world powered by clean, affordable solar electricity.