NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Solar PV Reliability Overview

2011 APEX EXPO

Las Vegas, NV

Sarah Kurt

April, 2011

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

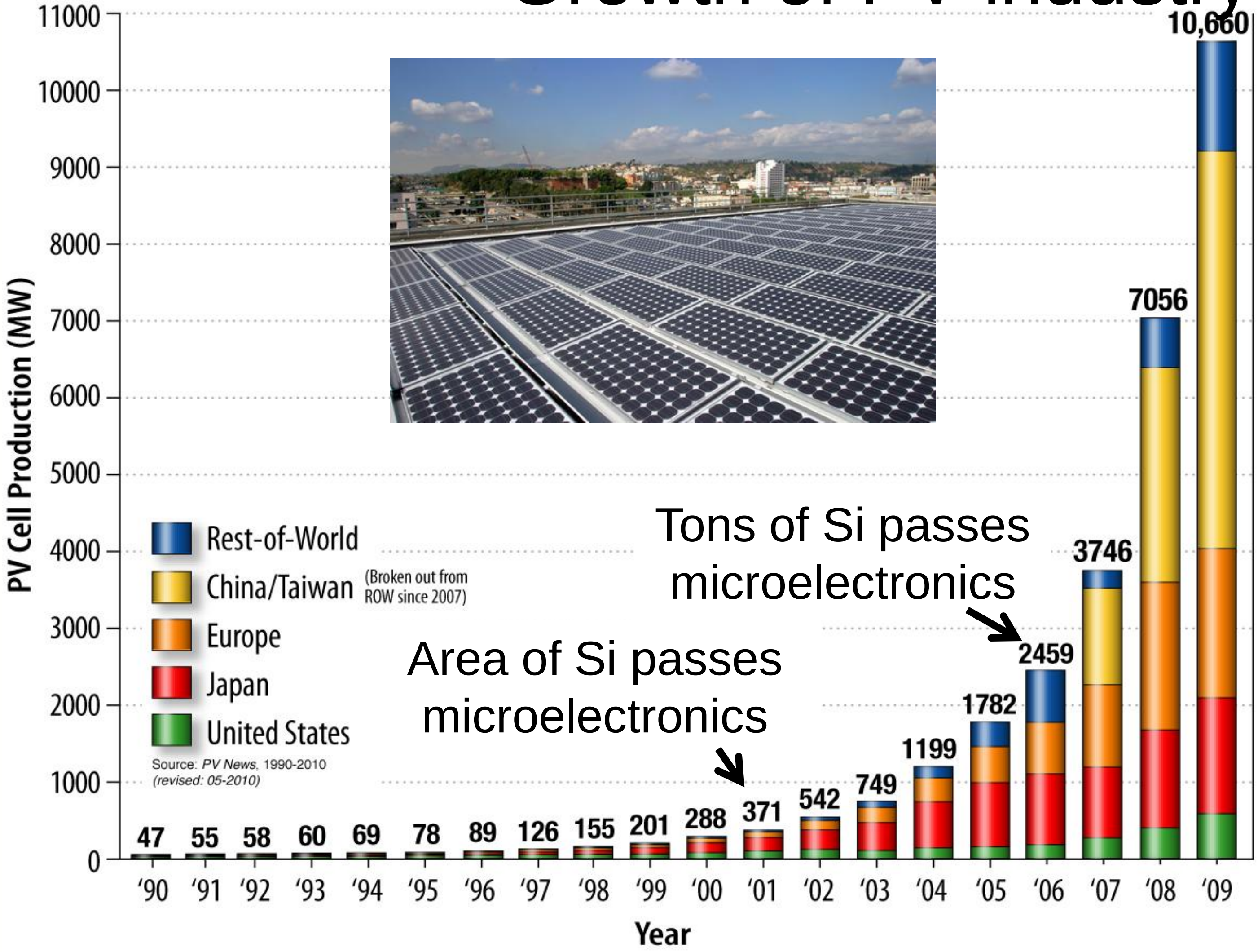
- A vision of a solar-powered world
- Importance of reliability to success of solar
- Working together to establish reliability
- R&D issues related to:
  - Product Development
  - Quality Assurance during Manufacturing
  - Lifetime Predictions
- Current status
- Technology-specific R&D issues
  - Selected highlights

How fast can a world change?

Solar power is within reach

What do we need to do to create a solar-powered world?

Growth of PV industry

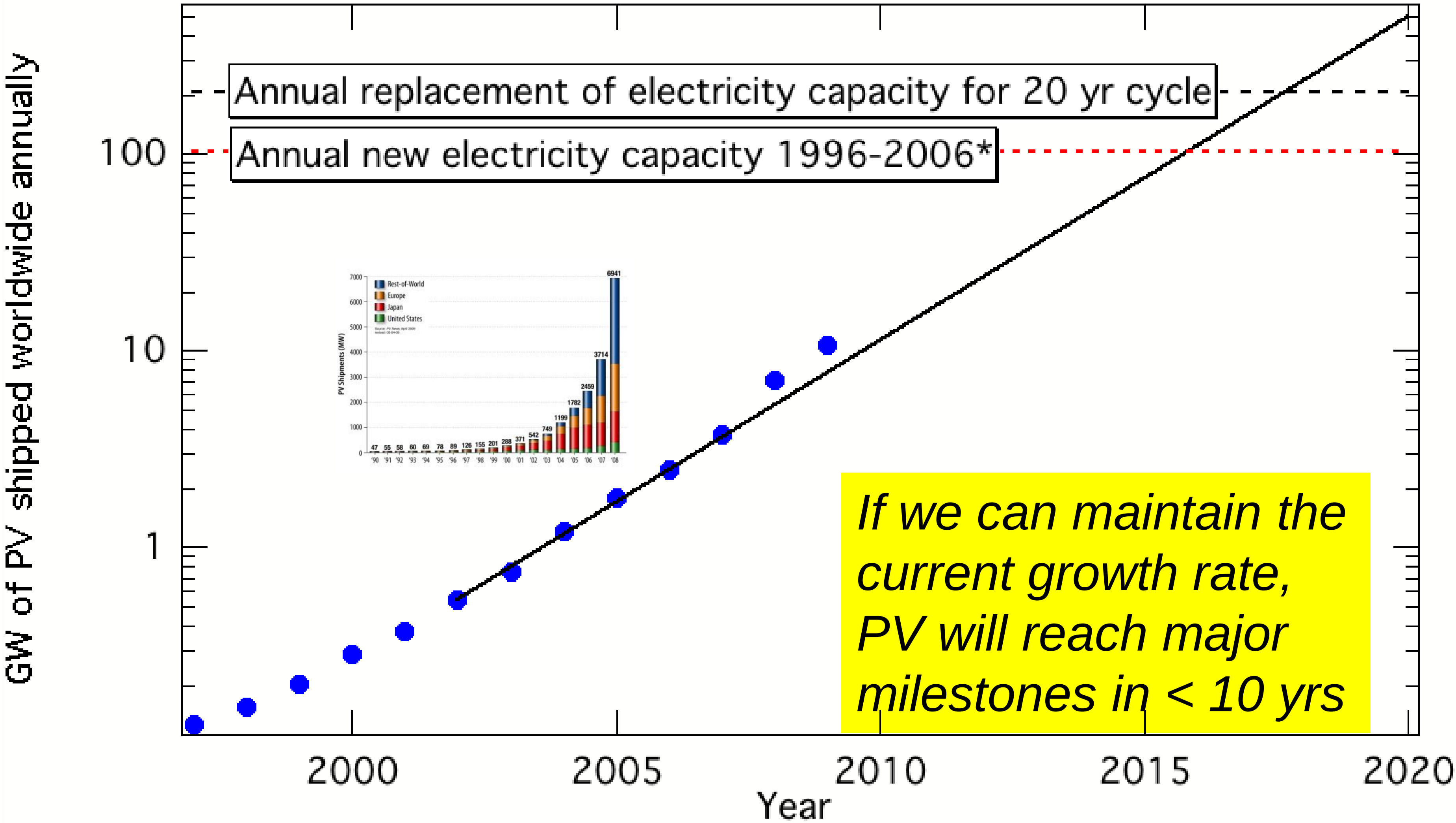


Tons of Si passes microelectronics

Area of Si passes microelectronics

PV shipments have been doubling every two years

Growth of PV industry



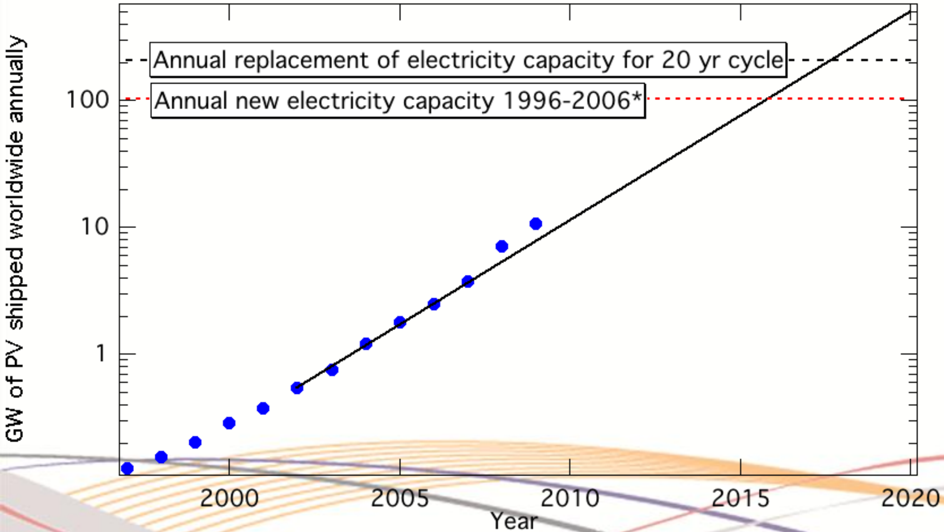
If we can maintain the current growth rate, PV will reach major milestones in < 10 yrs

*www.eia.doe.gov/emeu/international/electricitycapacity.html (4012-2981 GW)/10 yr

Why is reliability important?

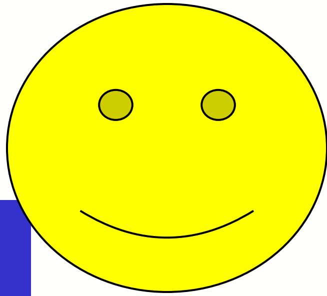
Improved reliability helps to reduce life-cycle cost:
- Longer lifetime
- Slower degradation
- Lower O&M costs

Improved reliability improves customer satisfaction
- Good performance builds customer confidence
- Better confidence inspires investors



*www.eia.doe.gov/emeu/international/electricitycapacity.html (4012-2981 GW)/10 yr

With reliability, this graph leads to a solar-powered world



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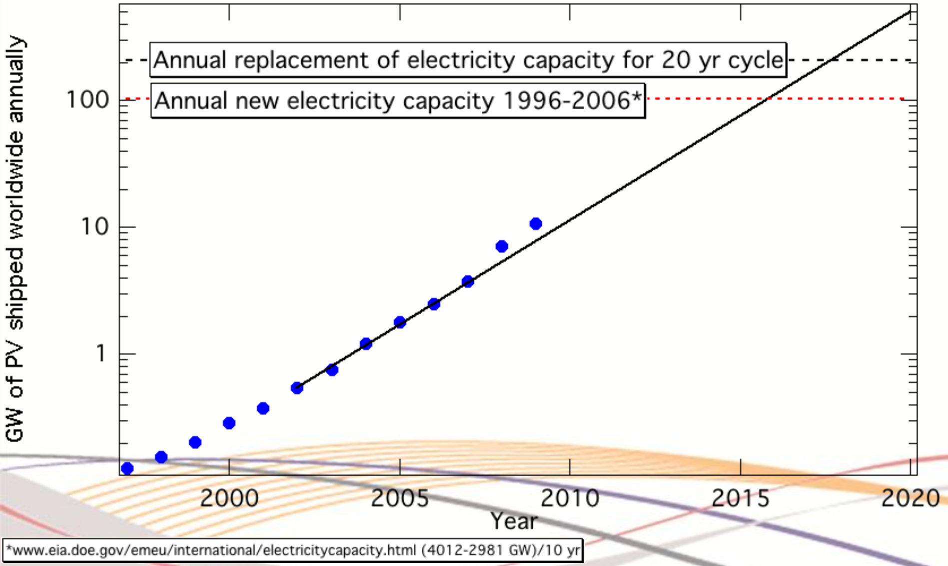

Without reliability: the failures will also grow exponentially

Reliability should be considered by venture capitalists

Venture capitalists funding dot.com look for
- Novel (secret) idea
- Return on investment in a couple of years

Venture capitalists funding PV need to look for
- Good approach (not necessarily novel)
- Excellent implementation
- Plan for enough time to check reliability

Developing a PV product is difficult!!!
The investors must recognize that the potential return on investment is huge, but will take time.
Community should demand public demonstration of reliability before IPO.

Building a solar-powered world

Years of standards development/field experience

Building a solar-powered world

Universities
-Educate work force
-Original research to extend useful PV-reliability knowledge

National labs
-Build foundation of PV-reliability knowledge through R&D
-Long-term or larger projects

Years of standards development/field experience

Building a solar-powered world

Complementary roles

Companies (& investors)
-Develop reliable products
-Manufacture quality products
-Customer satisfaction

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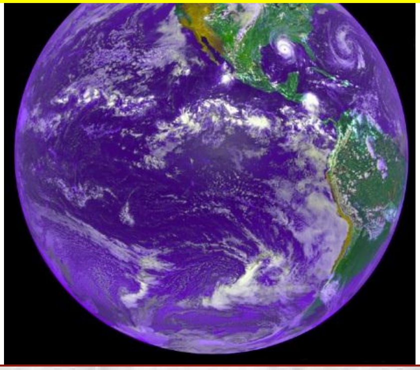
Building a solar-powered world

Solar-powered world



Defining complementary roles allows more efficient use of resources

Social acceptance and utility acceptance of PV

Companies (& investors)
-Development of reliable product
-Manufacturing of quality product
-Customer satisfaction

Universities
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-Original research to extend useful PV-reliability knowledge

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Years of standards development/field experience

What do we mean by reliability?

For a solar-powered world, Reliability means:
the lights go on when the switch is flipped

For today's talk,
Reliability means a PV system working as expected when the sun is shining (with low O&M costs and long life)

Developmental stages

Achieving excellent reliability is a step-by-step process; you can't skip the early steps and expect to be successful with the final steps

QA during product development
-Identify failure modes
-Understand failure mechanisms
-Test for failures
-Mitigate

→

QA during manufacturing
-Test raw and refined materials
-Control process
-Test final products

→

Predict reliability
-Identify useful tests
-Understand all components
-Make predictions

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QA during product development

Reliability should be considered from day 1 forward

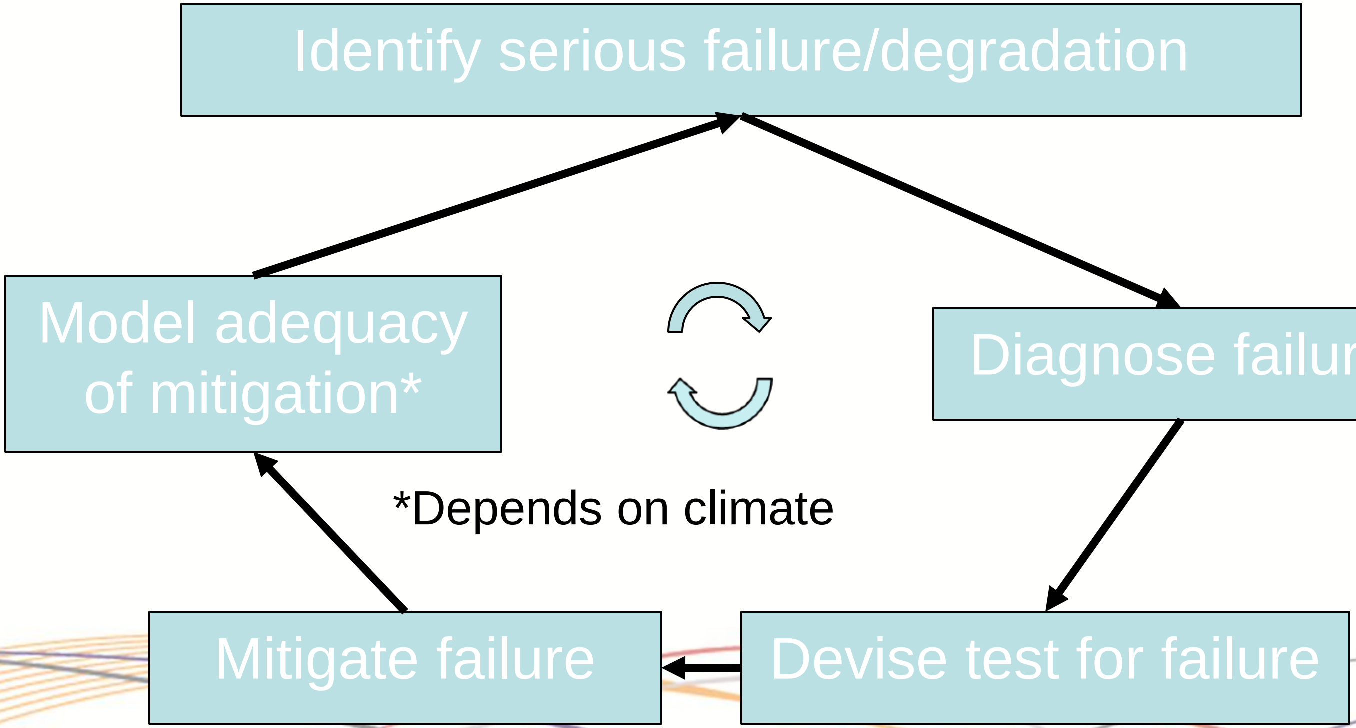
Lots of tools:

-Advanced Product Quality Planning
-Design Failure Modes Effects and Analysis
-Fault Tree Analysis
-Design for Manufacturability
-Design Review Based on Failure Mode (Toyota)

Prototype testing

QA during product development
- -Identify failure modes
- -Understand failure mechanisms
- -Test for failures
- -Mitigate

This cycle has been effective at improving PV module reliability and in developing standard for qualification test; not done yet!



History of Si module qual. test: JPL (Jet Propulsion Lab) Block buys

Test	I	II	III	IV	V
Year	1975	1976	1977	1978	1981
Thermal Cycle (° C)	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90
Humidity	70 C, 90%RH, 68 hr	5 cycles 40 C, 90%RH to 23 C	5 cycles 40 C, 90%RH to 23 C	5 cycles 54 C, 90%RH to 23 C	10 cycles 85 C, 85%RH to -40 C
Hot spots	-	-	-	-	3 cells, 100 hrs
Mechanical load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cyc. ± 2400 P	10000 cyc. ± 2400 Pa
Hail	-	-	-	9 impacts 3/4" - 45 mph	10 impacts 1" - 52 mph
NOCT	-	-	-	Yes	Yes
High pot	-	< 15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000

JPL Block buys led to dramatic improvements

- One study claimed (Whipple, 1993):
  - Pre-Block V: 45% module failure rate
  - Post-Block V: <0.1% module failure rate

Today's qualification test retains similarities to JPL tests

- IEC 61215 - Crystalline silicon design qualification includes 18 test procedures
  - Thermal cycling - 200 cycles -40° C to +85° C
  - Humidity freeze - 10 cycles +85° C, 85% RH to -40° C
  - Damp heat - 1000 hrs at +85° C, 85% RH
  - Wet leakage current - Wet insulation resistance X area > 40 $M\Omega m^2$ at 500 V or system voltage
  - Requirement is typically to retain 95% of original power production
- IEC 61646 (thin film) and IEC62108 (CPV) are similar

www.iec.ch

Developmental stages

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Product development
- -Identify failure modes
- -Understand failure mechanisms
- -Test for failures
- -Mitigate

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QA during manufacturing
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Predict reliability
- -Identify useful tests
- -Understand all components
- -Understand field failures
- -Make predictions

Silicon modules – R&D needs for QA

Quality assurance during manufacturing
-Test raw and refined materials
-Control process
-Test final products

Suntech raised question of purity of silicon in 2008

Quality assurance – R&D opportunities

- IEC standards do not address periodic retesting (when?)
- What QA tests/controls are needed? (e.g. Si purity, EVA cure)
- How can we keep the cost of the QA low, while keeping confidence high and learning as much as possible?

QA must be in place before confident predictions can be made

Developmental stages

Achieving excellent reliability is a step-by-step process; you can't skip the early steps and expect to be successful with the final steps

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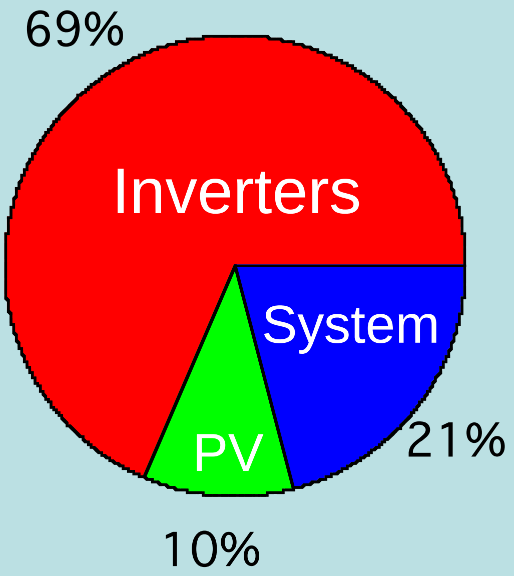
PV Reliability at System Level

Unscheduled maintenance costs



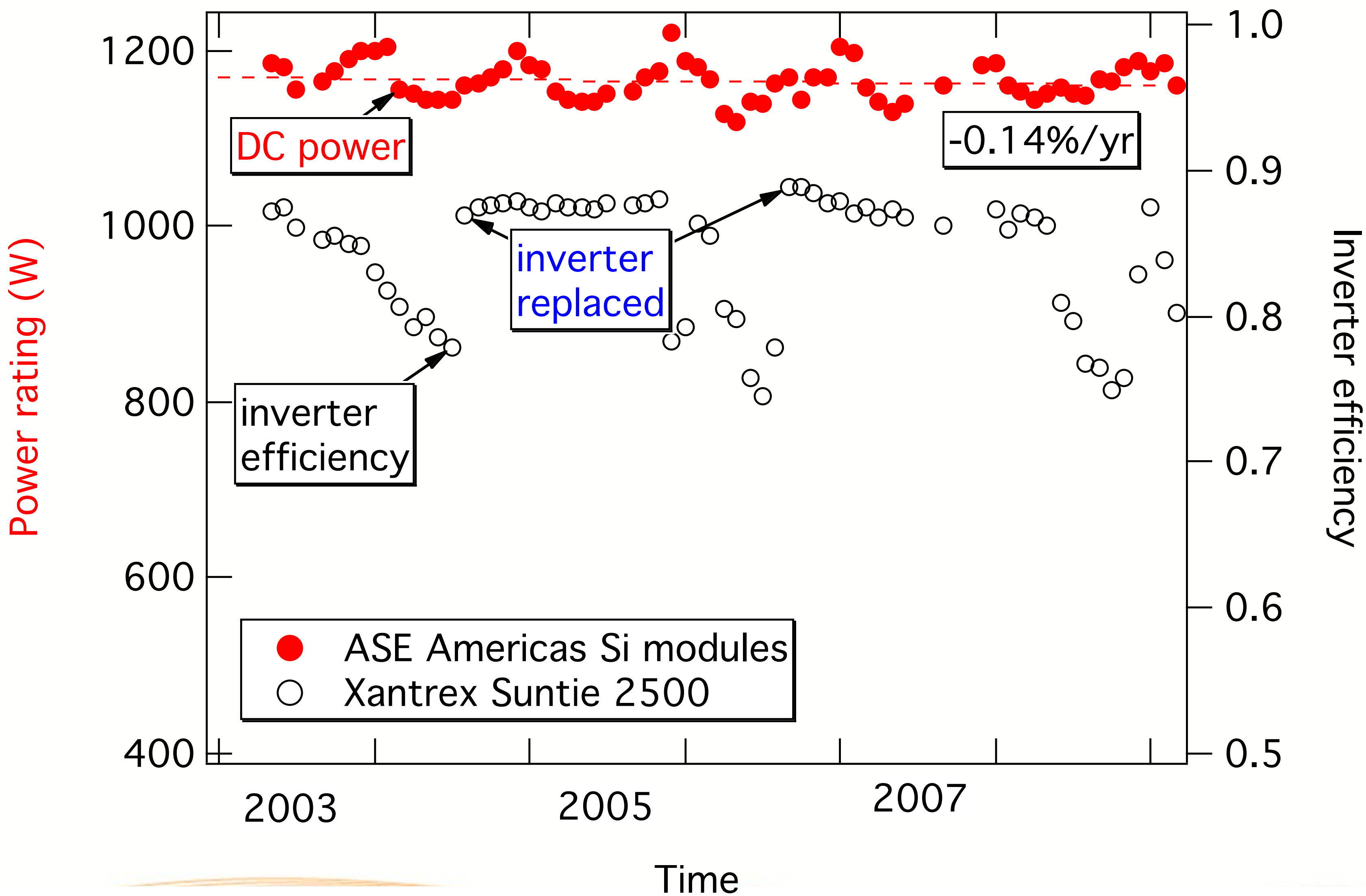
(Prog. PV 2008; **16**:249)

Studies of c-Si systems typically show few module failures;

Inverters typically dominate O&M cost

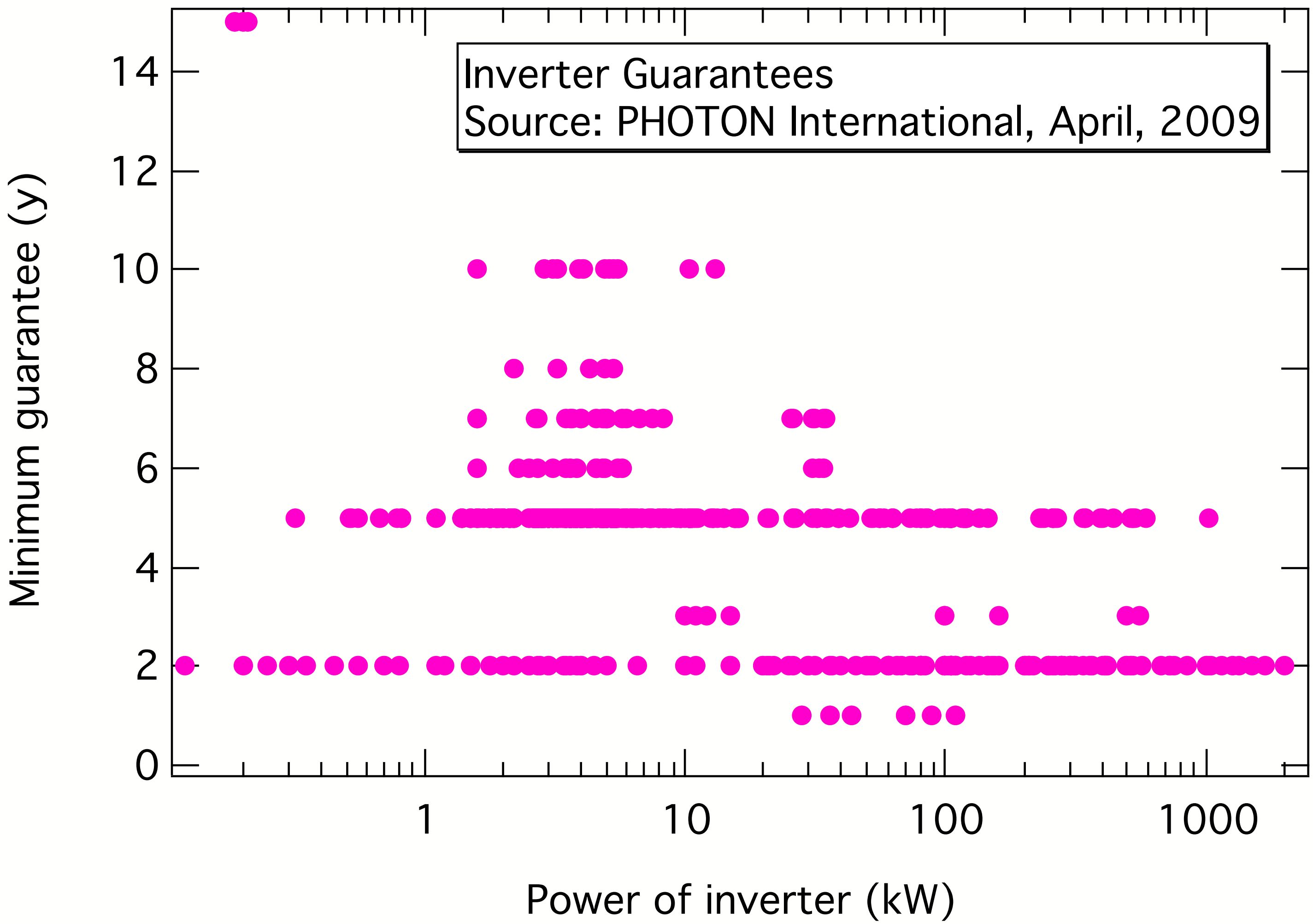
Reliable Si modules are demonstrated, but not guaranteed

Example of PV System Data



Module performance can be good; Some inverters have short lifetimes

Inverters are improving, but still need longer life



Limited warranties may be longer

Qualification/performance standards for inverters and BOS are not commonly used

Inverters suffer from early failures in the field, temperature-related failures, & mismatch between PV voltage & inverter window.

Documented degradation rates

Manufacturer	Module Type	Exposure (years)	Degradation Rate (% per year)	Measured at System Level?	Ref.
ARCO Solar	ASI 16-2300 (x-Si)	23	-0.4	N	2
ARCO Solar	M-75 (x-Si)	11	-0.4	N	3
[not given]	[not given] (a-Si)	4	-1.5	Y	4
Eurosolare	M-SI 36 MS (poly-Si)	11	-0.4	Y	5
AEG	PQ40 (poly-Si)	12	-5.0	N	6
BP Solar	BP555 (x-Si)	1	+0.2	N	7
Siemens Solar	SM50H (x-Si)	1	+0.2	N	7
Atersa	A60 (x-Si)	1	-0.8	N	7
Isofoton	I110 (x-Si)	1	-0.8	N	7
Kyocera	KC70 (poly-Si)	1	-0.2	N	7
Atersa	APX90 (poly-Si)	1	-0.3	N	7
Photowatt	PW750 (poly-Si)	1	-1.1	N	7
BP Solar	MSX64 (poly-Si)	1	0.0	N	7
Shell Solar	RSM70 (poly-Si)	1	-0.3	N	7
Würth Solar	WS11007 (CIS)	1	-2.9	N	7
USSC	SHR-17 (a-Si)	6	-1.0	Y	8
Siemens Solar	M55 (x-Si)	10	-1.2	Y	9
[not given]	[not given] (CdTe)	8	-1.3	Y	9
Siemens Solar	M10 (x-Si)	5	-0.9	N	10
Siemens Solar	Pro 1 JF (x-Si)	5	-0.8	N	10
Solarex	MSX10 (poly-Si)	5	-0.7	N	10
Solarex	MSX20 (poly-Si)	5	-0.5	N	10

Table 1. PV module degradation rates published within the past five years.

31st IEEE PVSC p.2085 (2006)

Manufacturer	Module Type	Exposure (years)	Degradation Rate (% per year)	No. of Modules
BP Solar	BP 585F (x-Si)	7	-0.30	2
BP Solar	BP 270F (x-Si)	8	-0.32	2
Kyocera	KC40 (poly-Si)	4.5	-0.91	2
Solarex	SX40U (poly-Si)	5.6	-0.01	2
Siemens	PC-4-JF (x-Si)	9.5	-0.51	1
Photowatt	PWX500 (poly-Si)	6	-0.13	1
Sanyo	H124 (a-Si/x-Si HIT)	2.6	-1.59	1
ECD Sovonix	[none] (a-Si) †	12	-1.17	1
Solarex	SA5 (a-Si)	12	-0.69	1
Uni-Solar	UPM-880 (a-Si)	12	-0.62	2
APS	EP55 (a-Si)	9.5	-1.62	2
Solarex	MST-22ES (a-Si)	6	-0.86	1
Uni-Solar	US-32 (a-Si)	8.5	-0.39	1
EPV	EPV40 (a-Si) †	6.5	-1.40	2
BP Solarex	MST-50 MV (a-Si)	4	-2.47	2
Siemens	ST40 (CIS) †	7	-1.63	1
Solar Cells Inc.	[none] (CdTe) †	10	-1.84	1

Table 2. PV module degradation rates obtained from monthly PTC regressions of PERT I-V data. Module types marked with a '†' indicate non-production prototypes that are not indicative of current products.

Summary of some studies on PV module field degradation around the

Vazquez, Prog. in PV (2008)

Location	Test duration	Module Tech.	Degradation rate (%/year)
Perth (Australia) *Temperate climate*	16–19 months	c-Si	0·5–2·7
		p-Si	1·0–2·9
		a-Si	18·8
		CIS	12·6
Mesa, Arizona (USA) *Desert climate*	2·4–4 years	c-Si	0·4
	2·4–2·7 years	p-Si	0·53
	2·7–6·7 years	a-Si	1·16 (6·7year) to 3·52 (2·7year)
Trinidad, California (USA) *Cool coastal climate*	11 years	c-Si	0·4
Hamamatsu (Japan) *Temperate climate*	10 years	c-Si	0·62
Golden, Colorado (USA) *Mountain continental climate*	8 years	c-Si	0·75
Ispra (Italy) *Temperate climate*	22 years	p-Si	0·3 (Silicone)
		c-Si	0·67 (EVA)
Lugano (Switzeland) *Temperate climate*	20 years	c-Si	0·53
Negev desert (Israel) *Desert climate*	3·4 years	p-Si	1·3

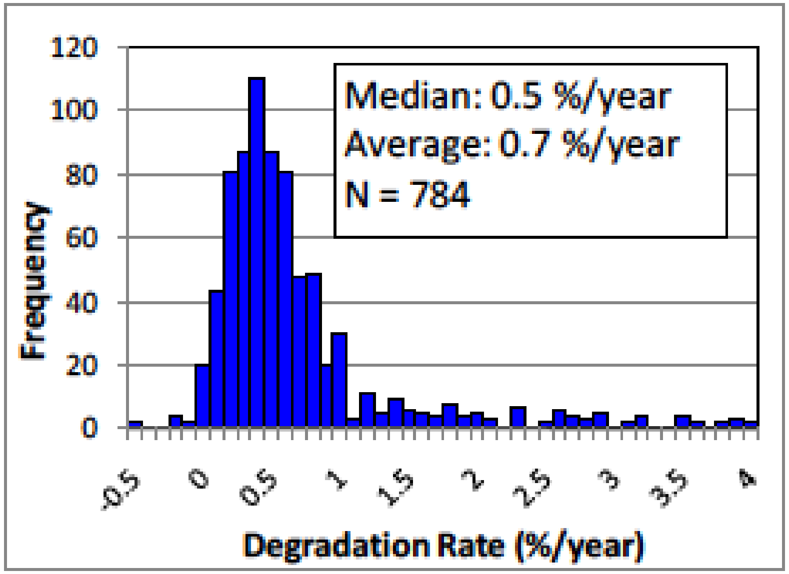
About two-thirds of degradation rates are measured as < 1%/yr

Reliability R&D

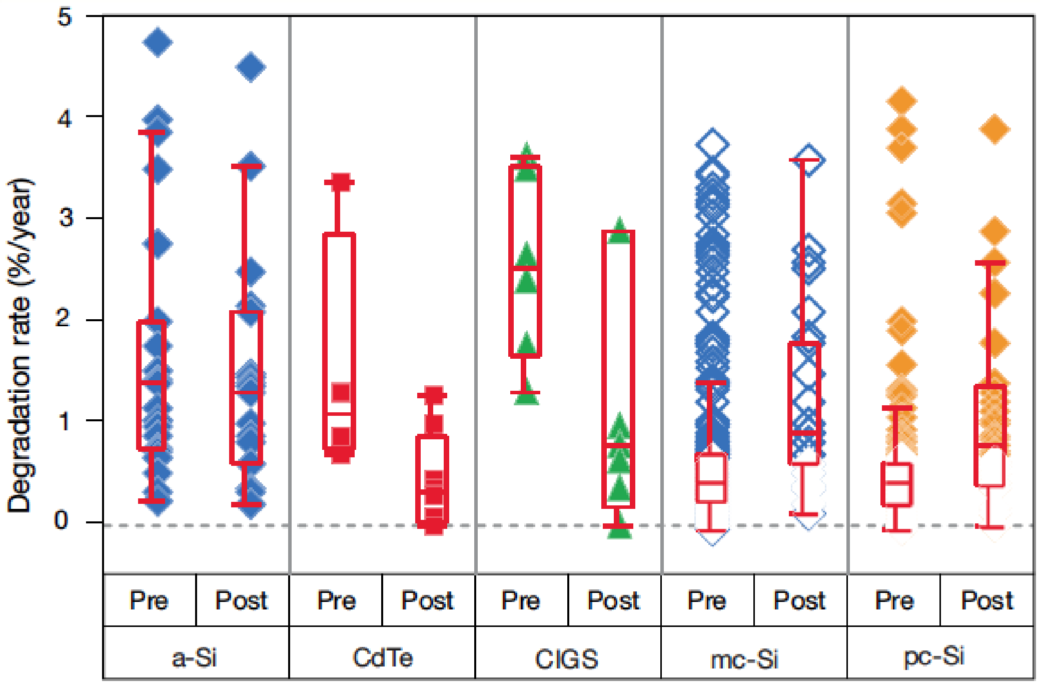
Current/recent studies

Compilation of degradation rates

- What: Compiled degradation rate data from NREL and the literature
- Why: Paint the big picture of how PV is performing



Installation Pre: before 2000   Post: after 2000



Conclusions:

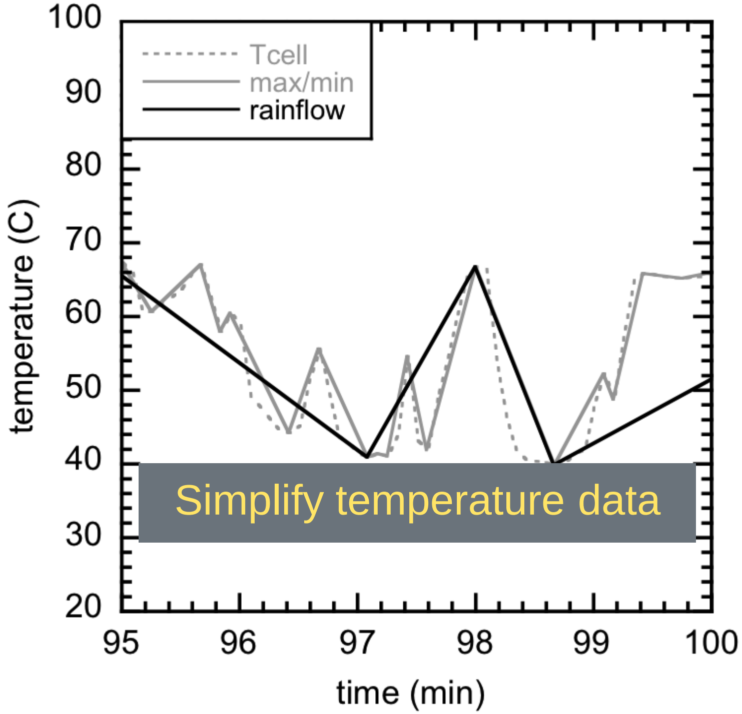
- ***Literature data shows < 1% degradation/yr for most PV***
- ***CdTe & CIGS modules installed after 2000 show improved stability.***

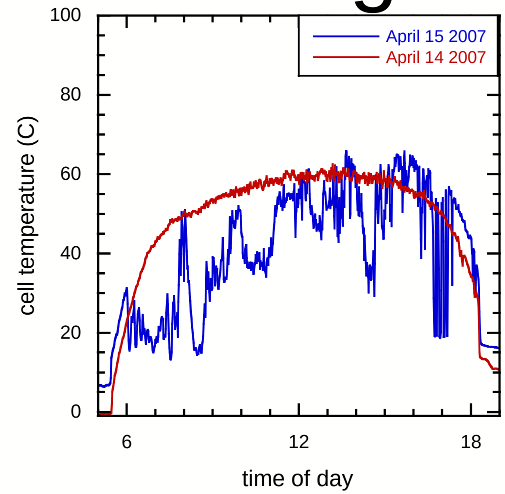
Dirk Jordan: Solar Pro, Dec. 2010

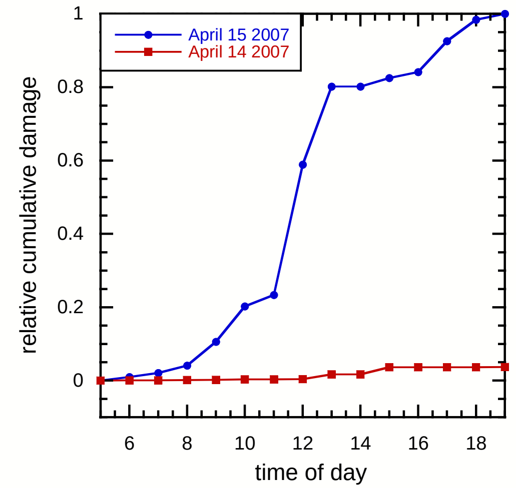
Model to correlate weather with damage

What: Quantify relationship between weather-induced damage and accelerated thermal cycling test

Why: Predict lifetime associated with thermal fatigue

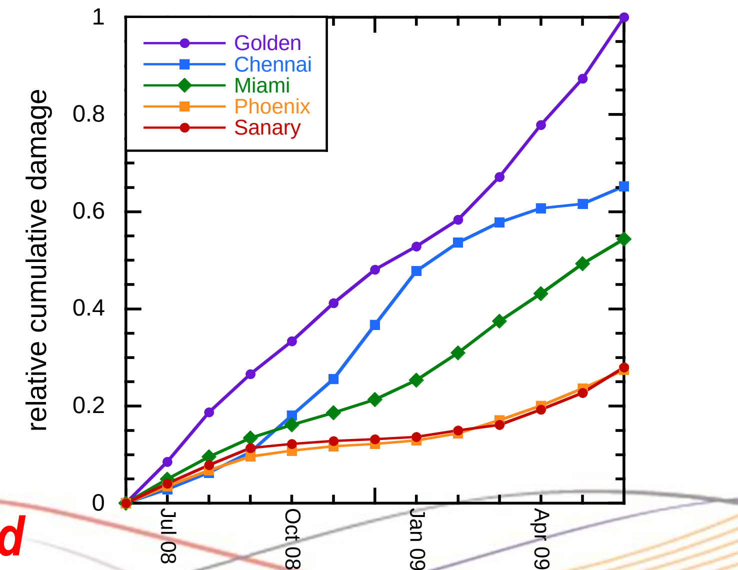






Partly cloudy day causes more damage than clear day

Nick Bosco
PVSC, 2009
CPV6, 2010

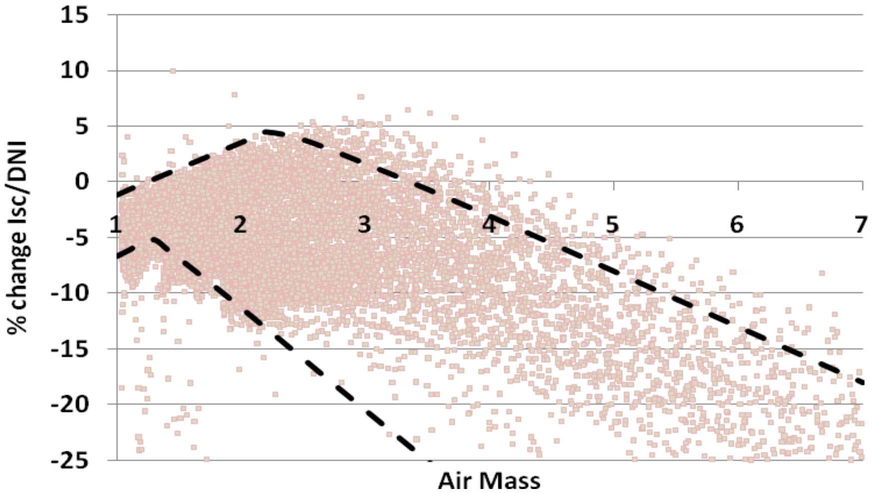


Conclusion: Rainflow algorithm provides method for quantifying damage for any weather; Need to validate and assess accuracy, then put into standard

CPV Module Performance Measurements

What: Measure I-V curves of 7 CPV modules every 5 min

Why: Provide data for the community to use for standards development and failure identification



Spectral effects are correlated with air mass.

Two-axis tracker at NREL with CPV modules from Boeing, Concentrix, GreenVolts, Arima, and Opel.

***Conclusions** (these have been presented at conferences and to standards committee):*

- ***Correlating Isc/DNI with air mass is most useful way to present data***
- ***Low moisture days can affect Isc/DNI by up to 10%***
- ***Temperature can affect Isc significantly***

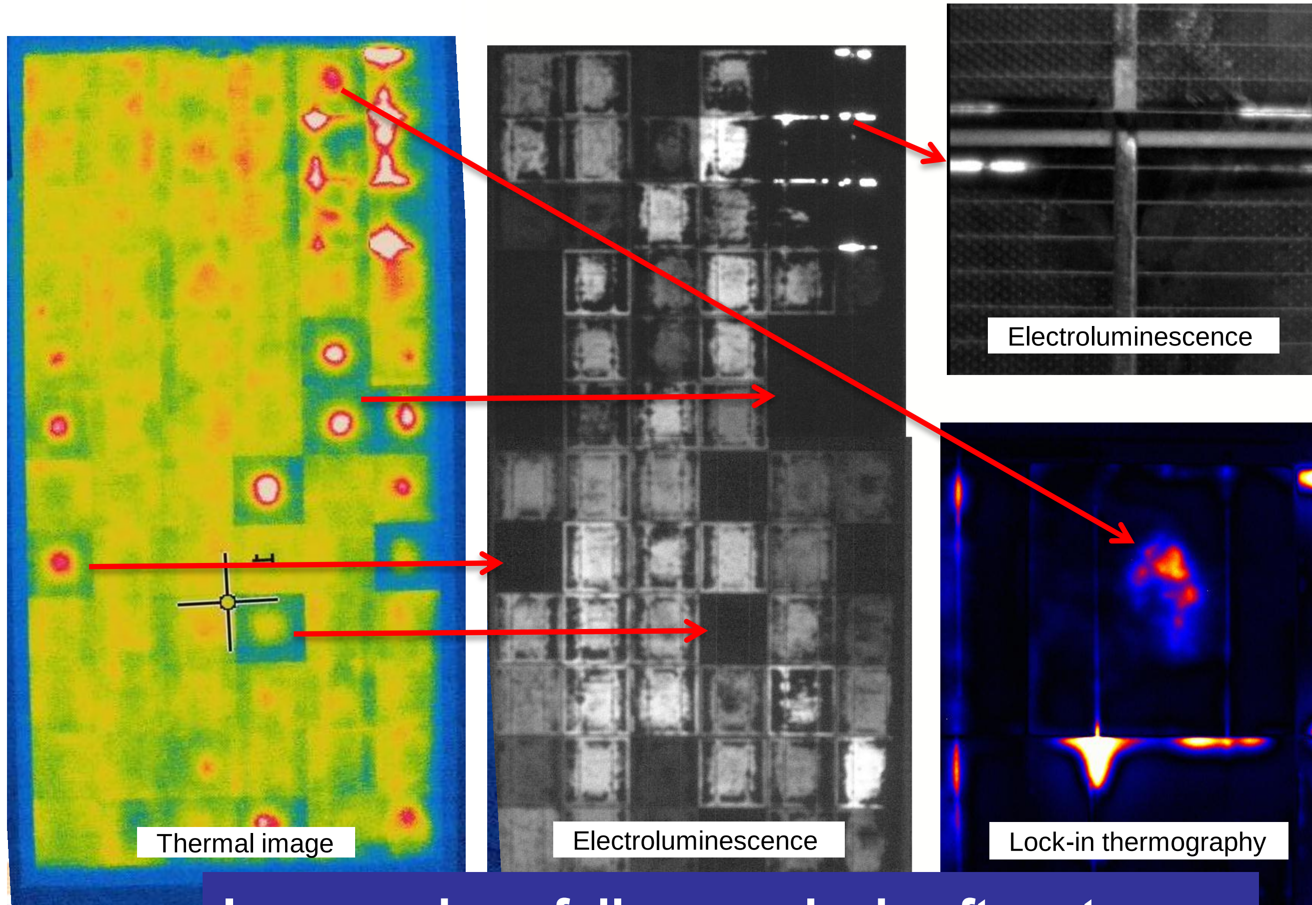
Matt Muller
CPV6, 2010

Demonstration of failure mechanism

- What: Measured leakage current and associated degradation as a function of the module construction
- Why: Elucidate cause of failure associated with high system voltages

Conclusion: Diffusion of Na through glass and into silicon cells appears to be cause of degradation

Peter Hacke
PVSC, 2010
EuPVSEC, 2010



Images show failure analysis after stress

Summary

- Solar is growing rapidly; could become a significant source of electricity within 10 yrs
- Excellent performance of silicon modules has been demonstrated in the field; but new products may repeat old mistakes
- Inverters currently dominate system failures
- Many R&D needs are best met by community working together
- *Need to ensure reliability to build foundation for a solar-powered world*

Planet powered by renewable energy By year 2100 or before?

Thank you to:
Nick Bosco
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