Photovoltaic Reliability R&D Toward a Solar-Powered World

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with help from many others
National Renewable Energy Laboratory,
Sandia National Laboratories
SPIE
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NREL/PR-520-46412
• 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 from SPIE
How fast can a world change?
What do we need to do to create a solar-powered world?
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
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

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

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**Without reliability: a Ponzi scheme?** - Bill Marion

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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

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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Years of standards development/field experience
### Building a solar-powered world

#### Defining complementary roles allows more efficient use of resources

<table>
<thead>
<tr>
<th>Social acceptance and utility acceptance of PV</th>
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<tbody>
<tr>
<td>Companies (&amp; investors)</td>
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<tr>
<td>- Development of reliable product</td>
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**Years of standards development/field experience**
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)
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.

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

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

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

Product development
- Identify failure modes
- Understand failure mechanisms
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- Mitigate

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

Diagram:
- Identify serious failure/degradation
  - Model adequacy of mitigation
  - Diagnose failure
  - Mitigate failure
  - Devise test for failure
<table>
<thead>
<tr>
<th>Test</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
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<tbody>
<tr>
<td>Thermal Cycle (°C)</td>
<td>100 cycles -40 to +90</td>
<td>50 cycles -40 to +90</td>
<td>50 cycles -40 to +90</td>
<td>50 cycles -40 to +90</td>
<td>200 cycles -40 to +90</td>
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<tr>
<td>Humidity</td>
<td>70 C, 90%RH, 68 hr</td>
<td>5 cycles 40 C, 90%RH to 23 C</td>
<td>5 cycles 40 C, 90%RH to 23 C</td>
<td>5 cycles 54 C, 90%RH to 23 C</td>
<td>10 cycles 85 C, 85%RH to -40 C</td>
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<tr>
<td>Hot spots</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>3 cells, 100 hrs</td>
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<tr>
<td>Mechanical load</td>
<td>-</td>
<td>100 cycles ± 2400 Pa</td>
<td>100 cycles ± 2400 Pa</td>
<td>10000 cyc. ± 2400 Pa</td>
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<td>Yes</td>
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<td>High pot</td>
<td>&lt; 15 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 2*Vs+1000</td>
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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 MΩm² 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
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.
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?

SunTech raised question of purity of silicon in 2008

QA must be in place before confident predictions can be made
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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Predictive Model Development

Degradation Rates
Real-time Reliability Studies

Field O&M and Failure Data

Failure Statistics
Accelerated Life Tests

Community’s collective data

Process and Design Improvements
New Failure Mode ID and Mitigation

Failure Mechanism ID and Mitigation
Improved ALT and Qual Test Design

Predictive Model

Improved Field O&M methods
Reliability vs Time
Availability vs Time
Field Degradation vs Time
Predictive Model Development

Reliability and availability analysis of a fielded PV system

34th PVSC  Elmer Collins
Systems Approach:

- Understand how each component fits into the system
- The overall reliability of the system is dominated by the least reliable component(s)

Unscheduled maintenance costs

- Inverters: 69%
- System: 21%
- PV: 10%

(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.
Module performance can be good; Some inverters have short lifetimes
Inverters are improving, but still need more work. Limited warranties may be longer. Qualification/performance standards for inverters and BOS are not well defined.

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

About two-thirds of degradation rates are measured as < 1%/yr.
Past success does not guarantee future success.

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

**Qualification Testing of c-Si PV Modules at ASU-PTL**

33rd PVSC, TamizhMani, 2008
Current/recent studies

With highlights of presentations at SPIE this week
Stress tests need to be
- More complete (all stresses)
- More thorough
- More quantitative
- Faster
- Less expensive

Development and application of a UV light source for PV-module testing
Wed. 8:30 am Michael Kohl (7412-2)

Outdoor monitoring and high voltage bias testing of PV modules as necessary test for assuring long-term reliability
Thurs. 3:50 pm Neelkanth Dhere (7412-28)

Accelerated stress testing of hydrocarbon-based encapsulants for medium-concentration CPV applications 34th PVSC Michael Kempe

Application of the NREL test-to-failure protocol for PV modules
Silicon Workshop (Aug 2009) Peter Hacke
Removing Ce from glass may improve performance and decrease cost, but will it affect reliability?

60°C/60% humidity; 2.5 suns UV

Effects of cerium removal from glass on photovoltaic module performance and stability
Thurs. 3:05 pm Michael Kempe (7412-26)
After exposure, thin-film modules show reversible and irreversible changes

Striving for a standard protocol for preconditioning or stabilization of polycrystalline thin-film PV modules

Wed. 9:15 am Joseph del Cueto (7412-3)
Light-soaking and power measurements of thin-film modules
Mon. 9:35 am Karl-Anders Weiss (7409-24)
Degradation and capacitance voltage hysteresis in CdTe devices
Thurs. 10:30 am David Albin (7412-18)
Understanding and mitigating effects of nonuniformities on reliability of thin-film PV
Thurs. 11:40 am Victor Karpov (7412-21)
The effect of metal foil tape degradation on the long-term reliability of PV modules
Thurs. 3:30 pm Rob Sorensen (7412-27)

Change in CdTe cells after annealing
(Albin)
Moisture can degrade TCO

Stability of TCO window layers for thin-film CIGS solar cells upon damp heat exposures
Thurs. 10:55 am Rajalakshmi Sundaramoorthy (7412-19)
Thurs. 11:15 am John Pern (7412-20)

Flexible configuration is especially difficult: harden the cell or the package?

ITO and SnO$_2$ are stable in 85% humidity, 85°C

Pern, 2008
Does concentrated sunlight at cell contain damaging UV dose?

Analysis of transmitted optical spectrum enabling accelerated testing of CPV designs
Wed. 11:35 am David Miller (7407-16)

Are optics durable?

Stress in large-area optics for solar concentrators
Wed. 10:25 am Ralf Leutz (7412-5)
IR image of void in die attach

Reliability testing the die attach of CPV cell assemblies
34th PVSC  Nick Bosco
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 for your attention!

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