Quantifying Reliability –

The Next Step for a Rapidly Maturing PV Industry and China's Role

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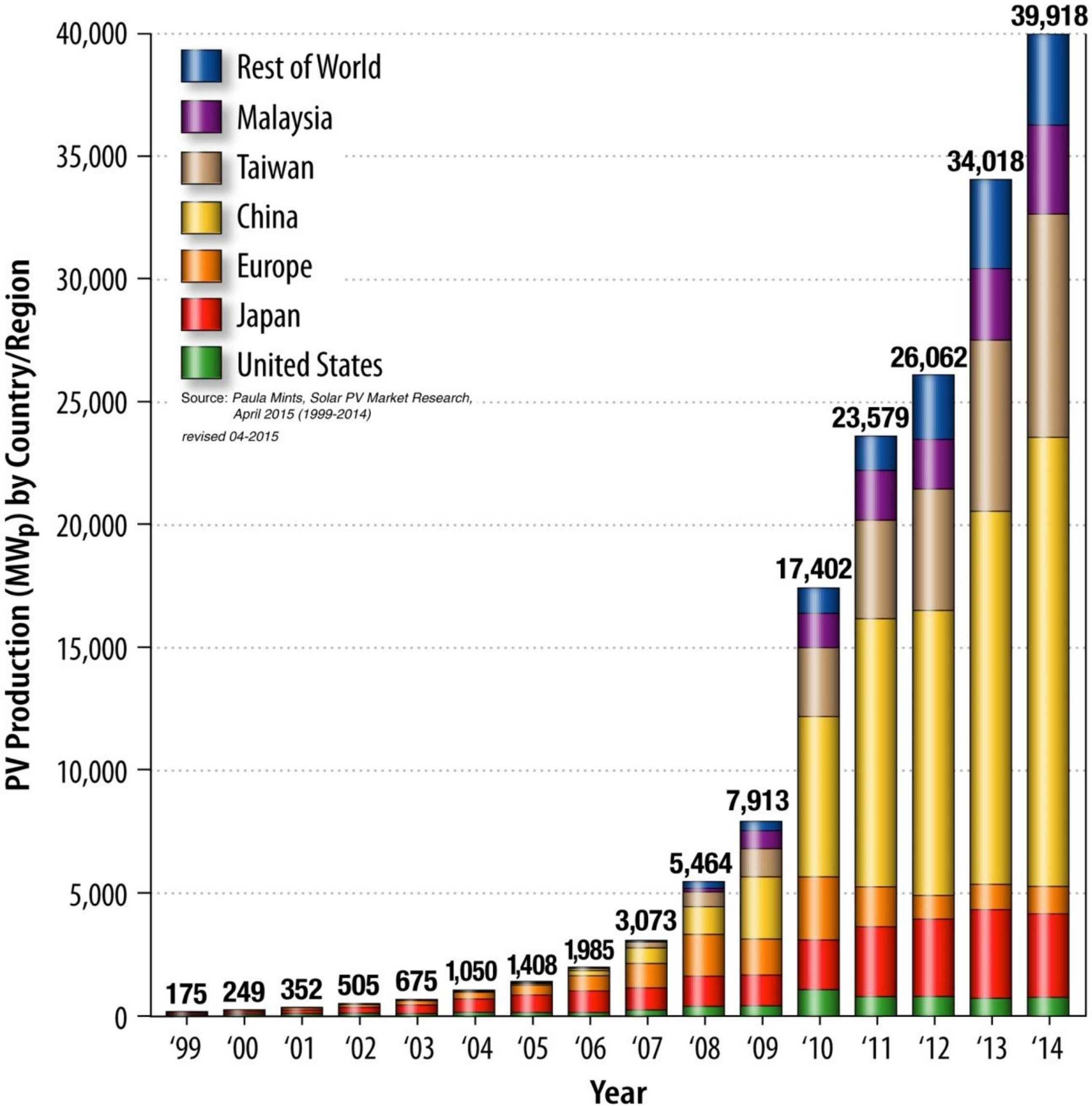
Outline

- Optimizing reliability is necessary part of maturation
- A little history – origin of today's tests
- Need to quantify value of added reliability to see how much more customers will pay
- Challenges and Progress
- What will it take to reach the end goal of being quantitative?

Why is "Reliability" a hot topic now?

The industry is growing spectacularly!

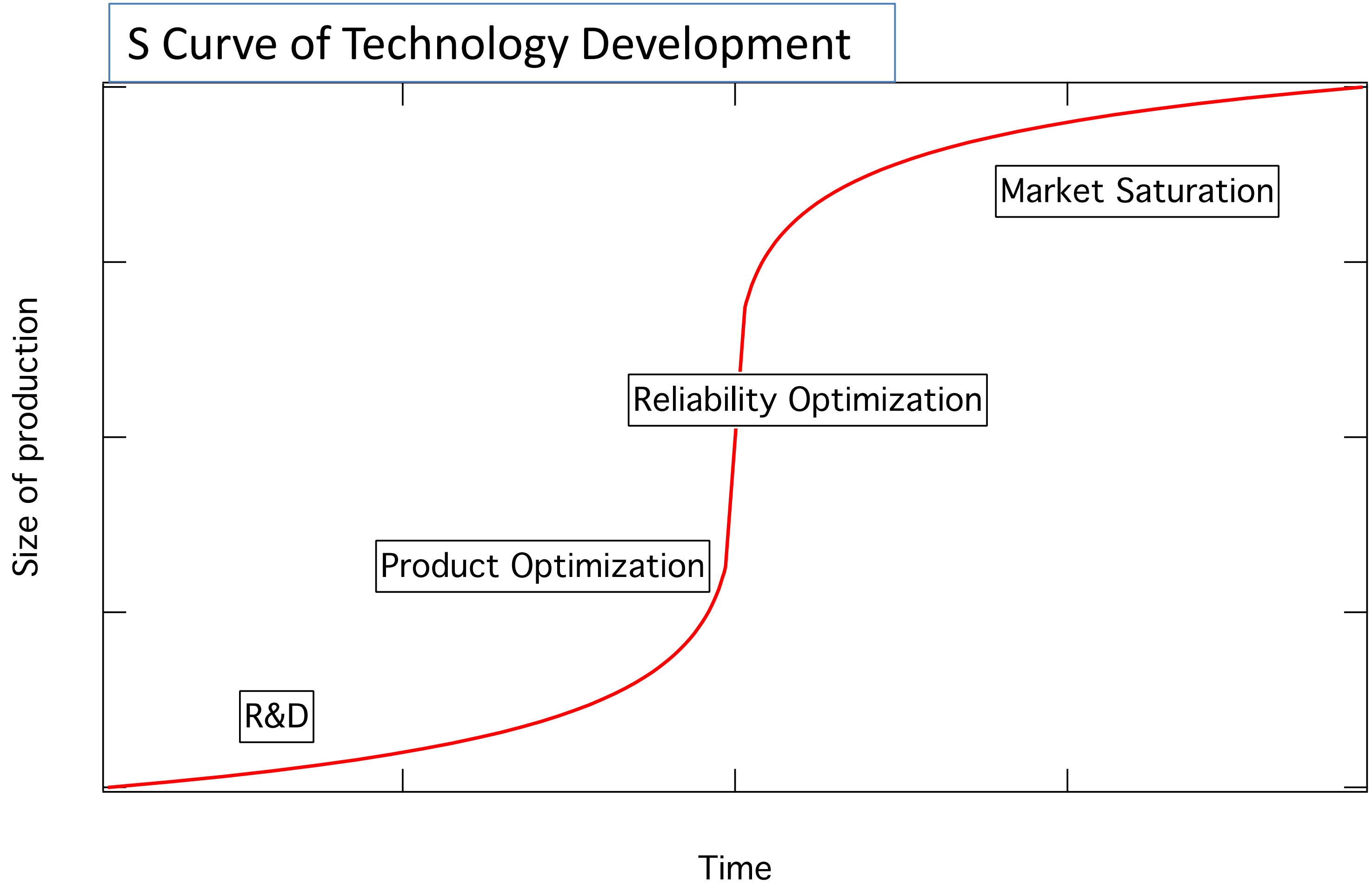


- If the 40 GW/y of 2014 is sustained, and
- If systems stay in the field for 25 years

→ **25 y X 40 GW/y = 1 TW**

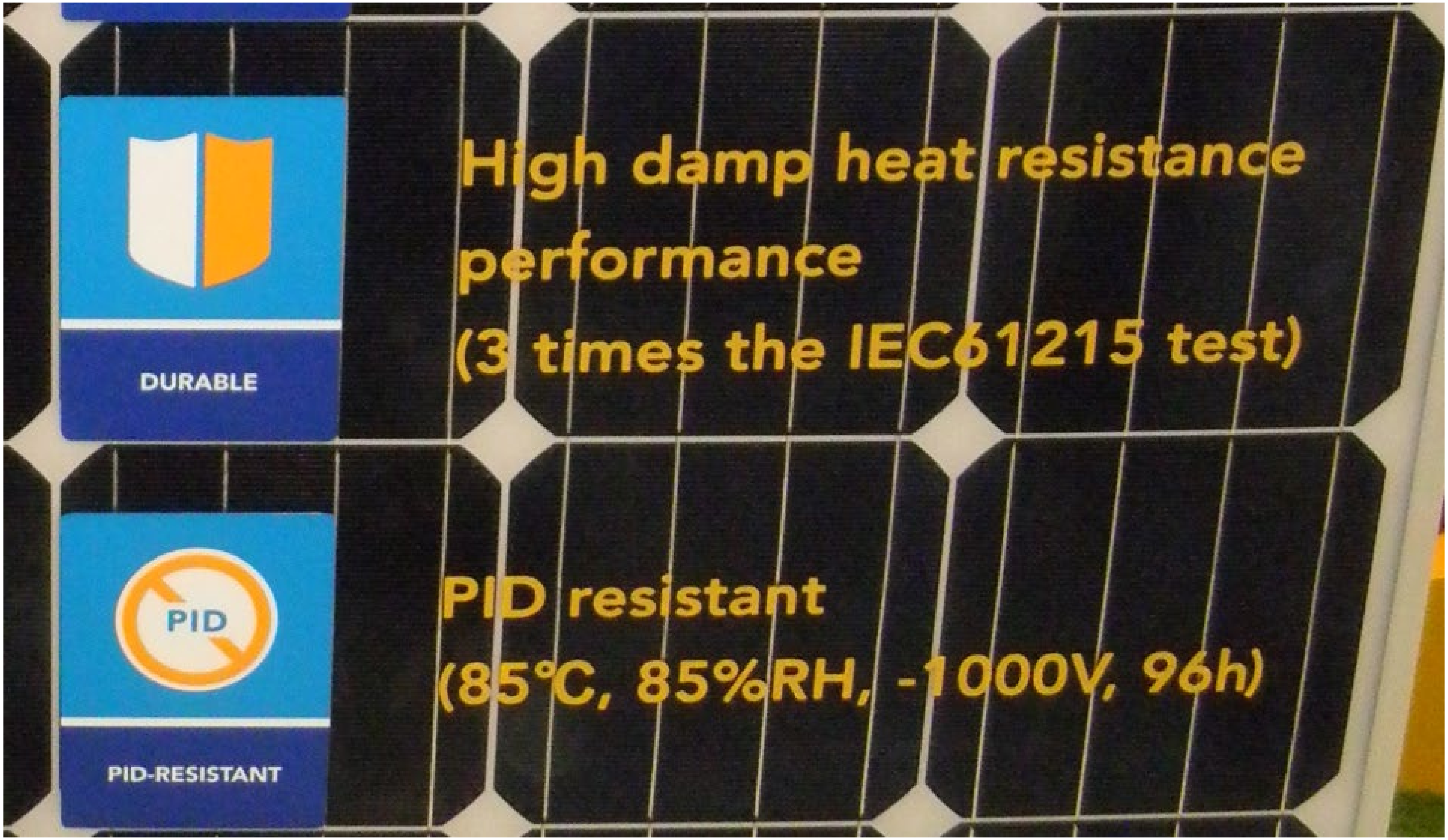
The industry is maturing!

Reliability Optimization is a Key Step Toward Technology Maturity

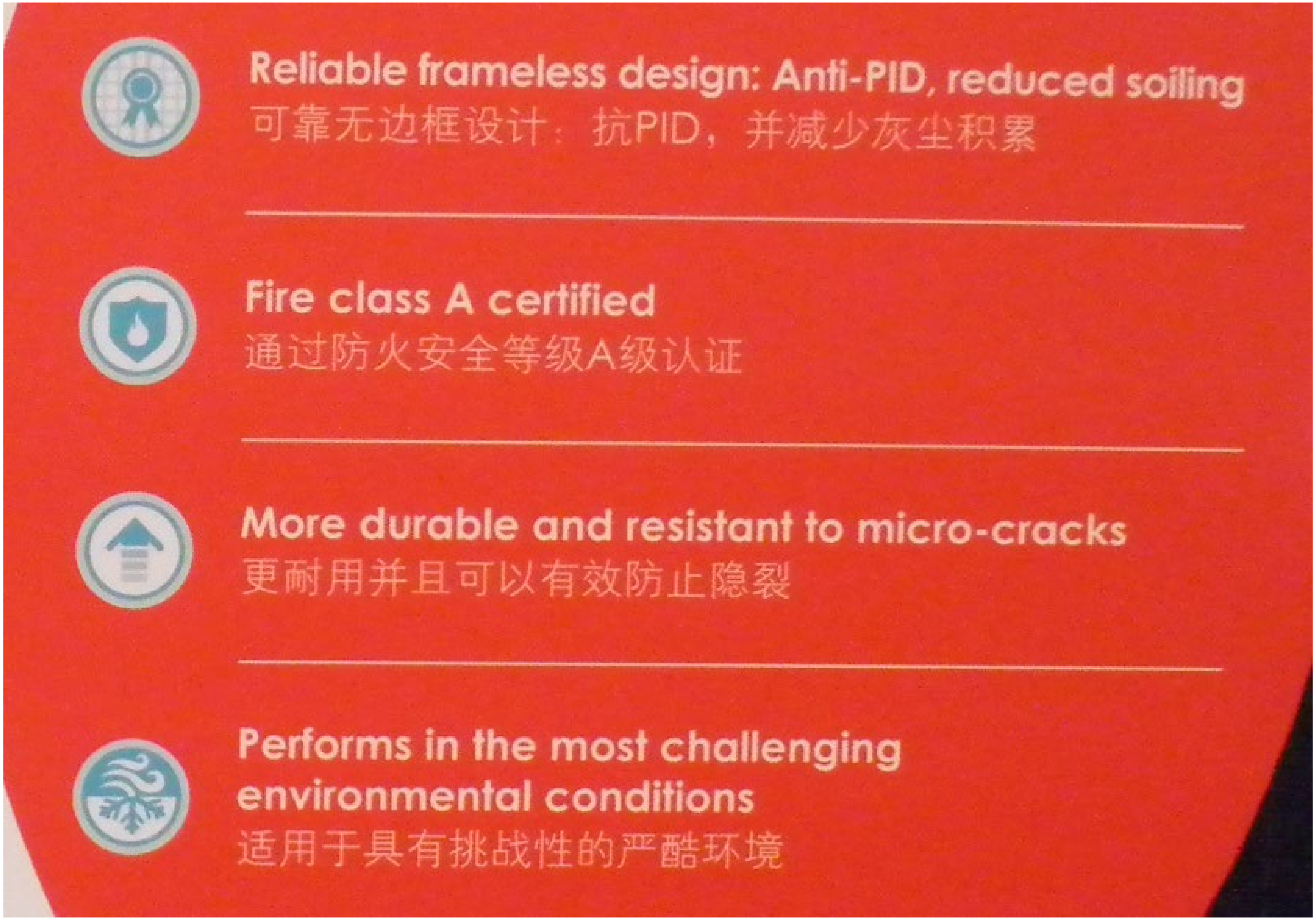


Reliability is key to continued growth and cost reduction

PV module "features" include reliability



PV module “features” include reliability



Historical perspective on PV reliability

- Good success!

Jet Propulsion Lab (JPL) Block Field Experience

In 1970s a series of "Block Buys":

- **A series of PV module buys were used to identify failures.**
  - **JPL prepared test specification**
  - **Companies manufactured modules and modified design to pass tests**
  - **Modules were deployed outdoors**
  - **If there were field failures, tests were modified and the sequence repeated**
- **JPL report found "the major cause of module failure to date was by gun shot".**
  - **Black or blue CZ cells on white background are good targets**
  - **Squares cells on non-white back sheets reduced problem**
- **Many early failures were due to cracked cells:**
  - **Because of module design one cracked cell resulted in total loss of power.**
- **Non glass superstrate modules suffered from significant soiling and delamination, usually due to UV.**

JPL Block Buys led to dramatic improvement

- **One study claimed for 1980s modules (Whipple, 1993):**
- **Pre-Block V: 45% module failure rate**
- **Post-Block V: <0.1% module failure rate**
- **Today, most studies (of c-Si modules) show that module failures are small**

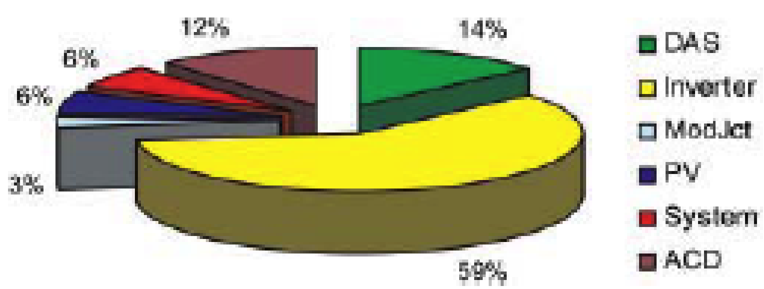


Figure 8. Unscheduled maintenance costs by category

Prog. PV 2008; 16:249

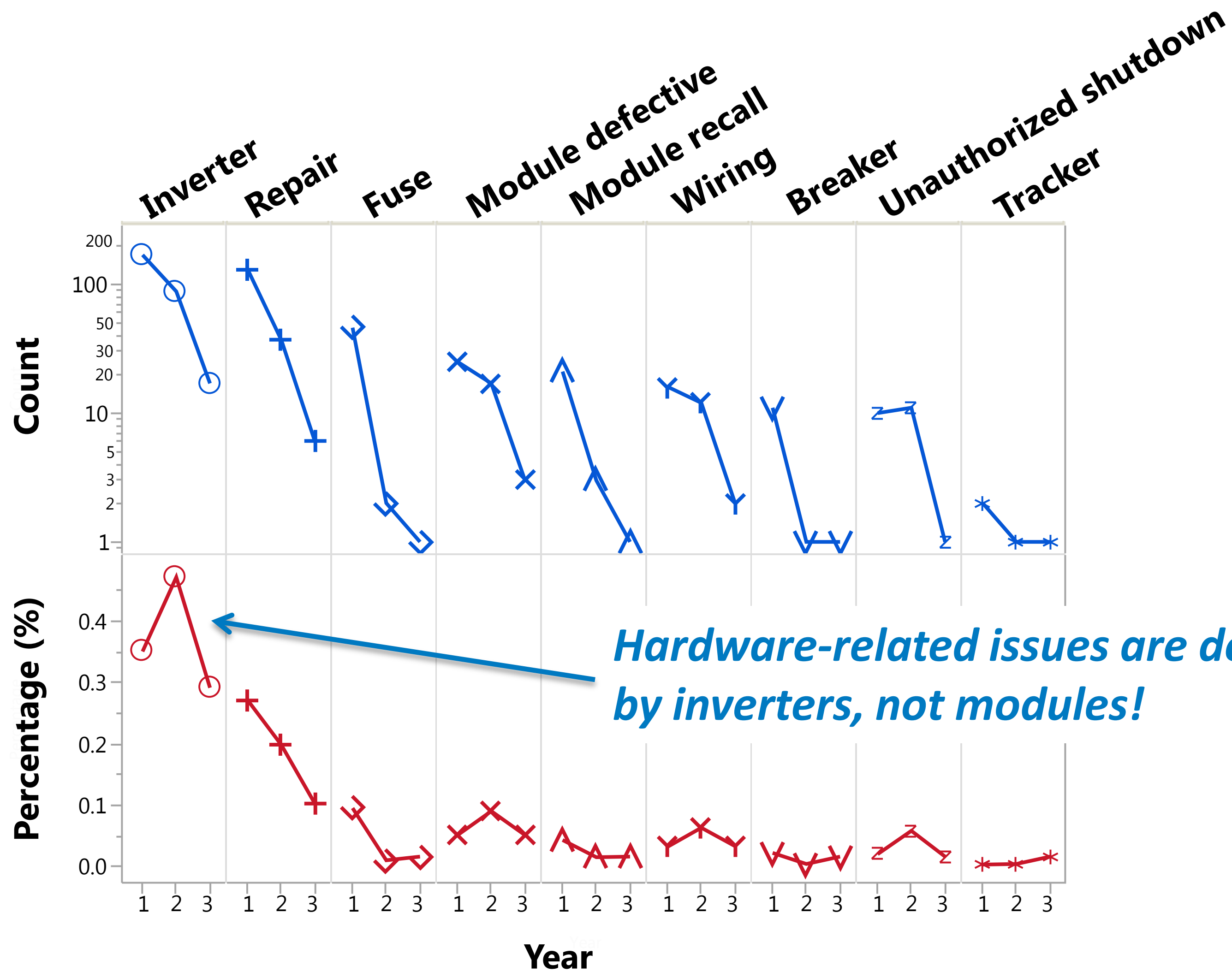
Similar efforts in Europe also contributed

What were the tests that fixed the problems?

Modules were required to pass a test, then the test was modified to reflect field experience

Test	Block I	Block II	Block III	Block IV	Block V
Thermal Cycles	100 -40 to +90C	50 -40 to +90C	50 -40 to +90C	50 -40 to +90C	200 -40 to + 90C
Humidity	70C,90% 68 hrs	5 cycles 40 C, 90%RH to -23 C	5 cycles 40 C, 90%RH to -23 C	5 cycles 54C, 90%RH to -23 C	10 cycles 85C, 85%RH to -40C
Hot Spot (intrusive)					3 cells 100 hrs
Mechanical Load		100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 ± 2400 Pa	10000 ± 2400 Pa
Hail				9 impacts ¾" –45 mph	10 impacts 1" – 52 mph
High Pot		<15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000

Analysis of 50,000 systems - Hardware-related Issues



Hardware-related issues are dominated by inverters, not modules!

Jordan, et al., 2014

Historical perspective on PV reliability

- Good success,

But, still more work to do!

Deficiencies of current qualification tests

- **Don't identify all problems**
  - Cracked cells
  - Potential induced degradation
  - Damage caused to bypass diodes during manufacturing by electrostatic discharge
- **Don't require random sampling**
  - IEC 61215 can be completed on one set of hand-picked modules
  - Need to ensure that all modules that are manufactured within the factory's process window will still pass the test
- **May not be adequate to test for wear out**
  - UV induced discoloration
  - Thermal cycles are not adequate for all locations

If reliability is a "feature" – how much will a customer pay?

…We need to quantify the value of reliability

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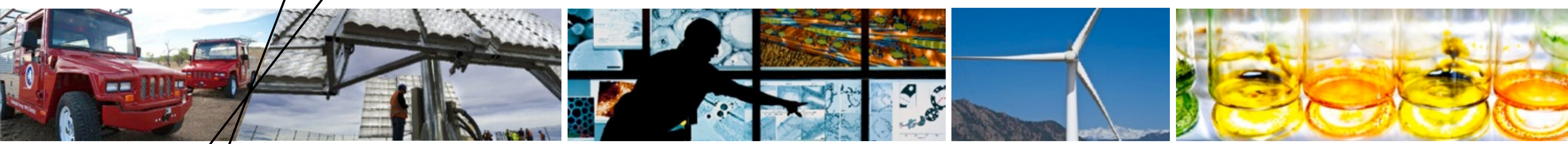


What reliability issues need to be quantified? (ALL of them?)

If a module can pass a “hammer” test..

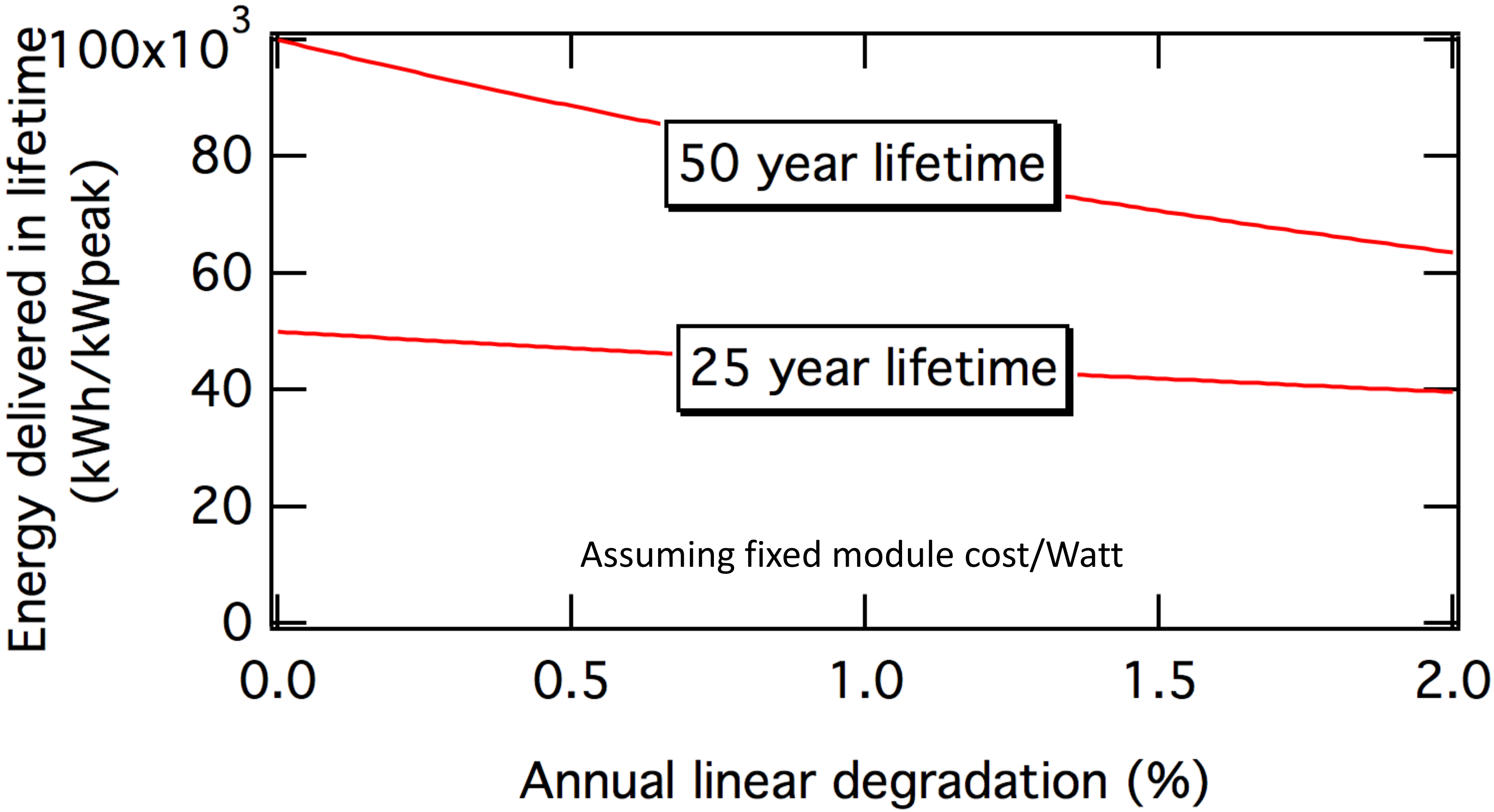
If a module can pass a more difficult test *without adding cost*

Then, there’s no need to *quantify* the module’s properties!!

If it doesn't add cost, then design a module that can pass every "hammer" test and skip trying to quantify the durability/reliability!

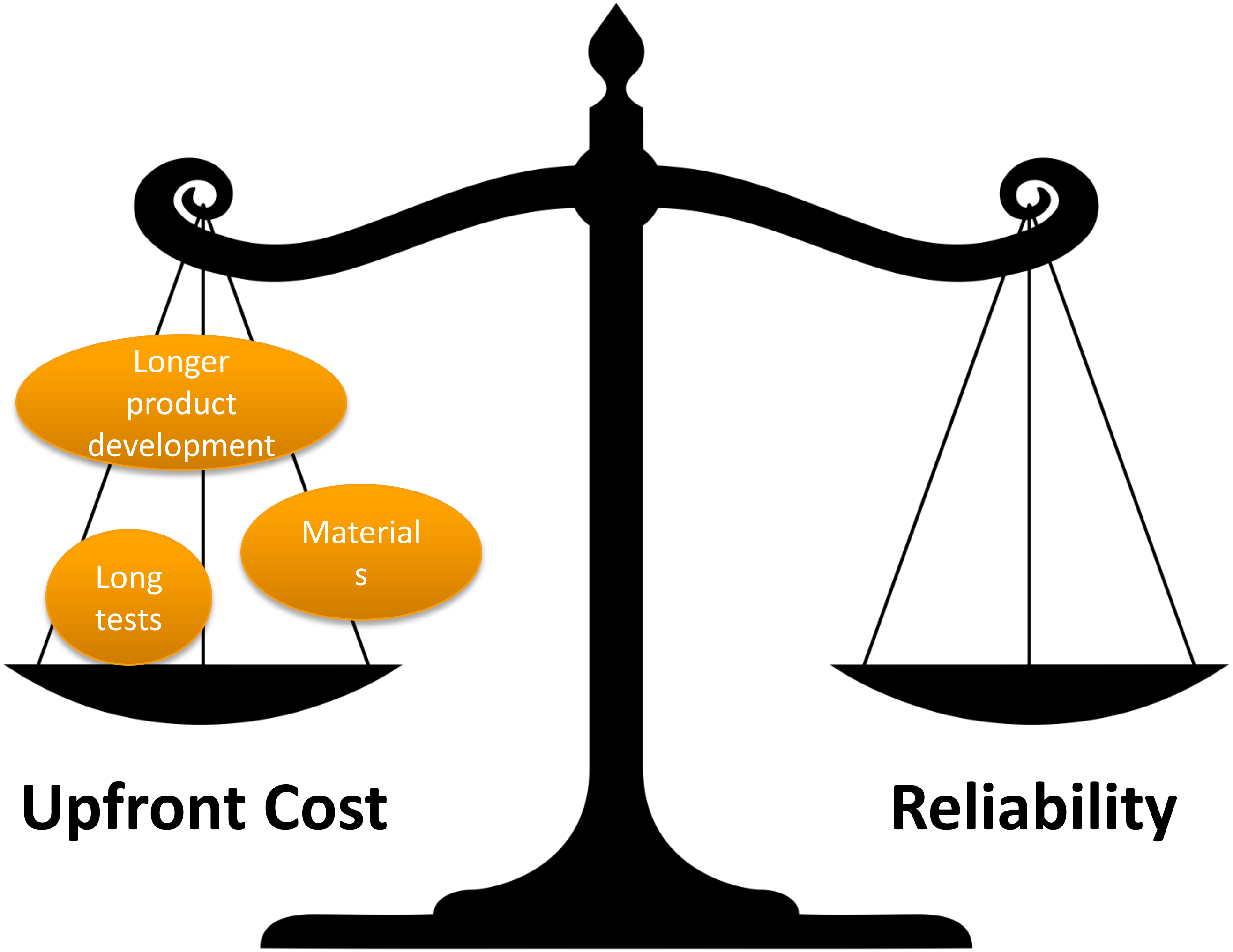
Converse: Need to quantify the durability or reliability when "solving" the problem adds cost

Longer life and less degradation decrease LCOE



LCOE can be decreased by improved module durability, quality, and/or reliability IF the upfront cost does not increase too much!

Optimal balance requires quantification!

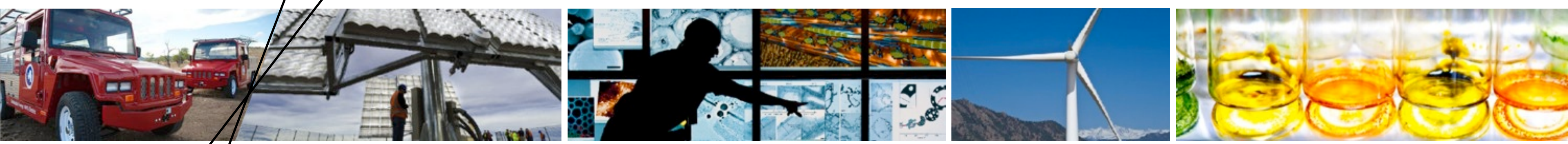


Quantify reliability in order to determine how much more we're willing to pay!

Examples of when added upfront cost is useful

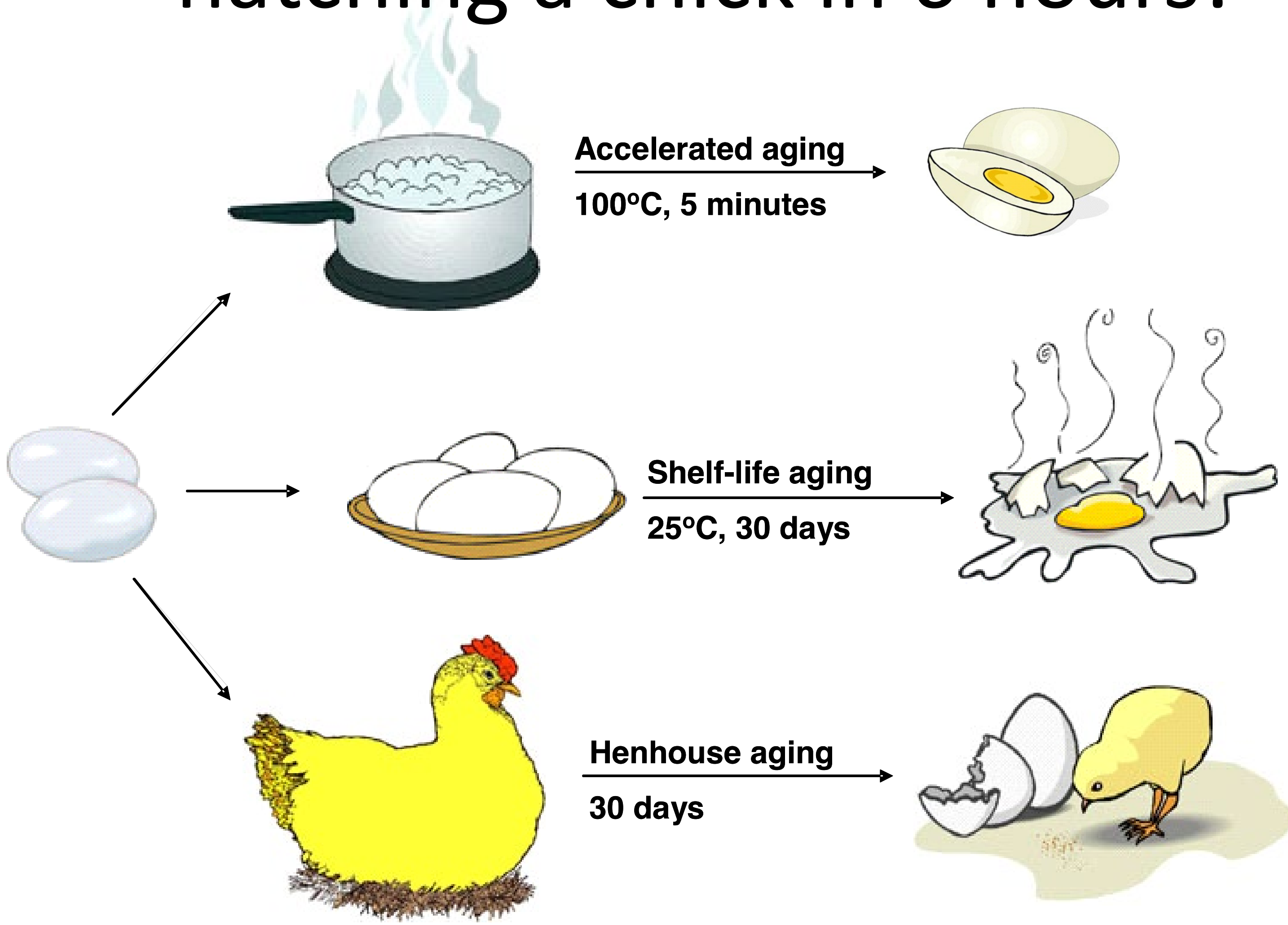
- **Strength to withstand snow & ice justifies added cost of stronger frame or glass**
- **Potential induced degradation (PID) can be avoided, but there is a cost or efficiency penalty**
- **Excellent quality management system reduces number of recalls and returns**

- **How much more will a customer pay?**



What challenges are there in quantifying reliability?

Accelerating 25 y into 3 months is like hatching a chick in 6 hours!



Some processes cannot be accelerated quantitatively > 10X

Timeline Challenge

3 mo 6 mo 1 y 2 y 3 y

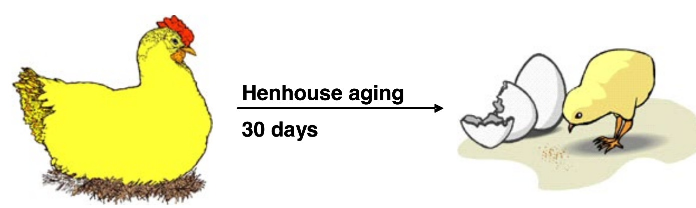
Common product development cycle today

Qualification test can be completed

Preferred quality management testing

X10 acceleration to simulate 25 y

X100 acceleration to simulate 25 y



Some processes can be accelerated;
For others, too much acceleration answers the wrong question!
Different approaches are needed for each type of test

Challenges to quantifying reliability

- Long desired service life (>25 y)
- Rapidly evolving product designs (< 6 months?)
- Complexity of use environments
- High cost of testing for large sample sets

- Many ways a module may fail

What progress is being made toward quantifying reliability?

Requires international solution!

- **Many local organizations are working on aspects of improving reliability and bankability**
- **Two international organizations will be described today**
  - IEC (International Electrotechnical Commission)
  - PVQAT (International PV Quality Assurance Task Force)

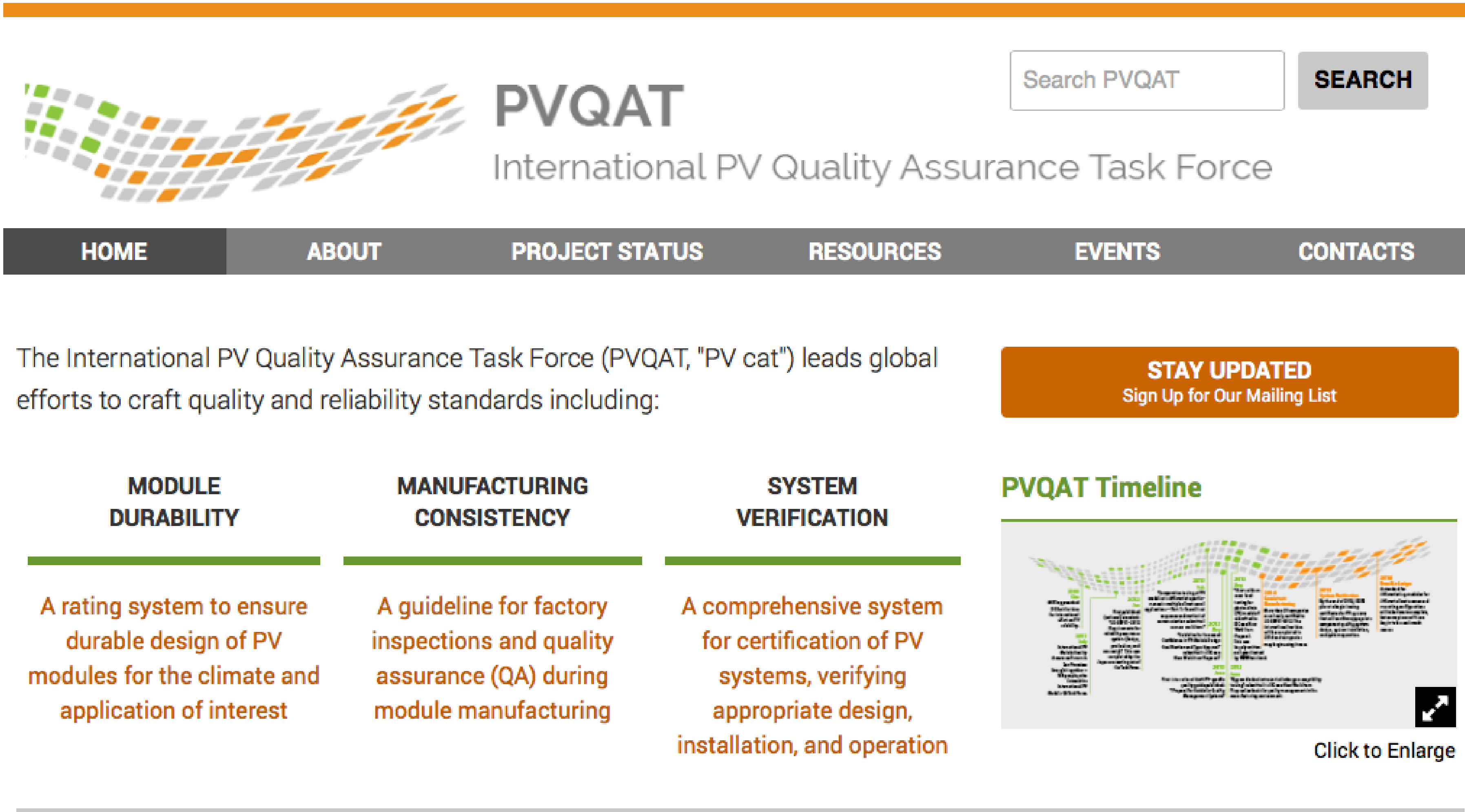
IEC (International Electrotechnical Commission)

- **Technical Committee 82 (Solar PV Energy Systems)**
  - Has written IEC 61215, IEC 61730, etc.
  - More than 80 documents are currently being developed or revised by TC 82.
- **IECRE**
  - Under IEC's Conformity Assessment Board (CAB)
  - System-level certification to consensus standards, including:
    - Component durability and quality
    - System design, installation, operation, maintenance
    - System performance

PVQAT (International PV Quality Assurance Task Force)

- **Formed in 2011, inspired by METI in Japan**
- **Informal organization encourages participation by all**
- **Emphasis on organizing and sharing research results toward how to test for different:**
  - Climates
  - Mounting configurations
- **www.PVQAT.org (English)**
- **www.PVQAT.com (Chinese)**

PVQAT (International PV Quality Assurance Task Force)



Recent progress

- **Consistent Manufacturing – Quality Control**

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Updated Proposal for a Guide for Quality Management Systems for PV Manufacturing: Supplemental Requirements to ISO 9001-2008

Govind Ramu,[1] Masaaki Yamamichi,[2] Wei Zhou,[3] Alex Mikonowicz,[4] Sumanth Lokanath,[5] Yoshihito Eguchi,[6] Paul Norum,[7] and Sarah Kurtz[8]

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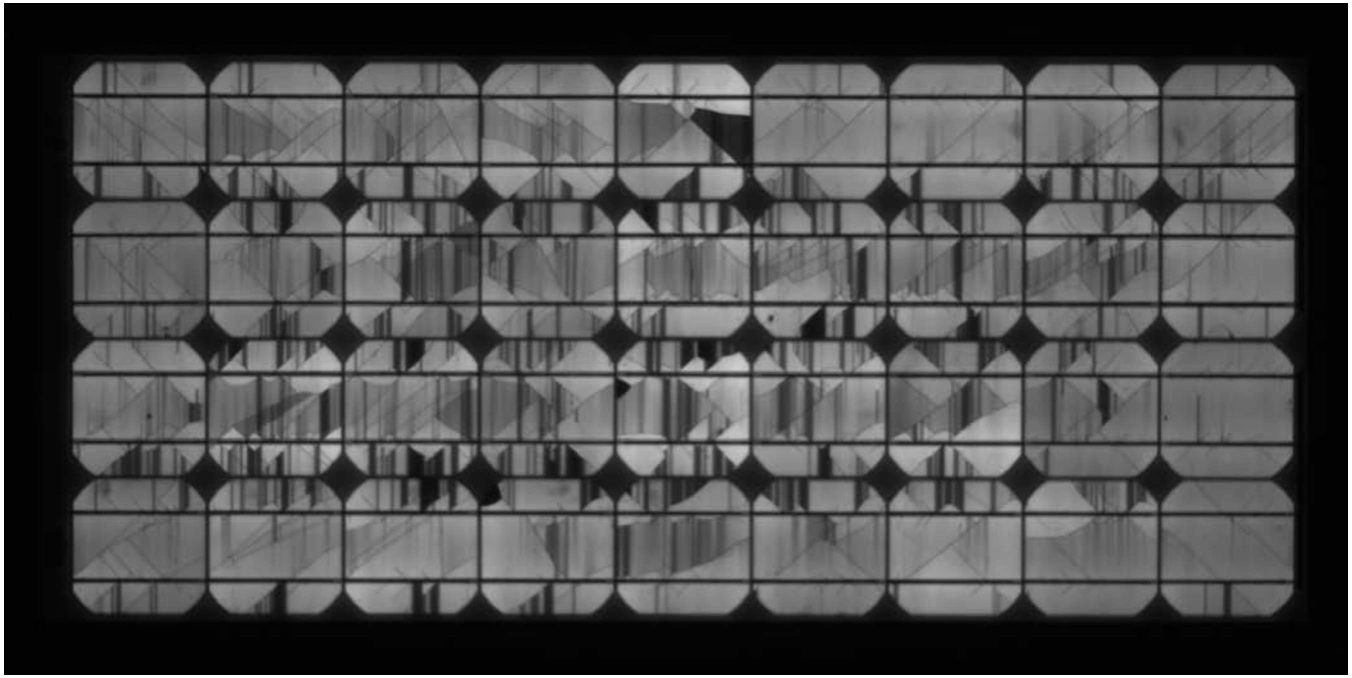
Technical Report
NREL/TP-5J00-63742
March 2015

Contract No. DE-AC36-08GO28308

- PVQAT has written a PV-specific version of ISO 9001
- Focus is on aligning the QMS with the customers' needs such as:
  - Power rating
  - Warranty
- IEC is preparing it for publication (IEC 62941)
- Description is on-line: www.nrel.gov/docs/fy15osti/63742.pdf

Recent progress

- **Qualification test: Edition 3 of IEC 61215**
  - Unifies IEC 61215 (silicon) and IEC 61646 (thin films)
  - Improved hot-spot test
  - Amendments planned to include
    - Test to identify susceptibility to power loss from cracked cells



Recent progress

- **Potential-induced degradation (PID)** test: IEC 62804 (two test methods)
- **Snow and ice**: IEC 62938

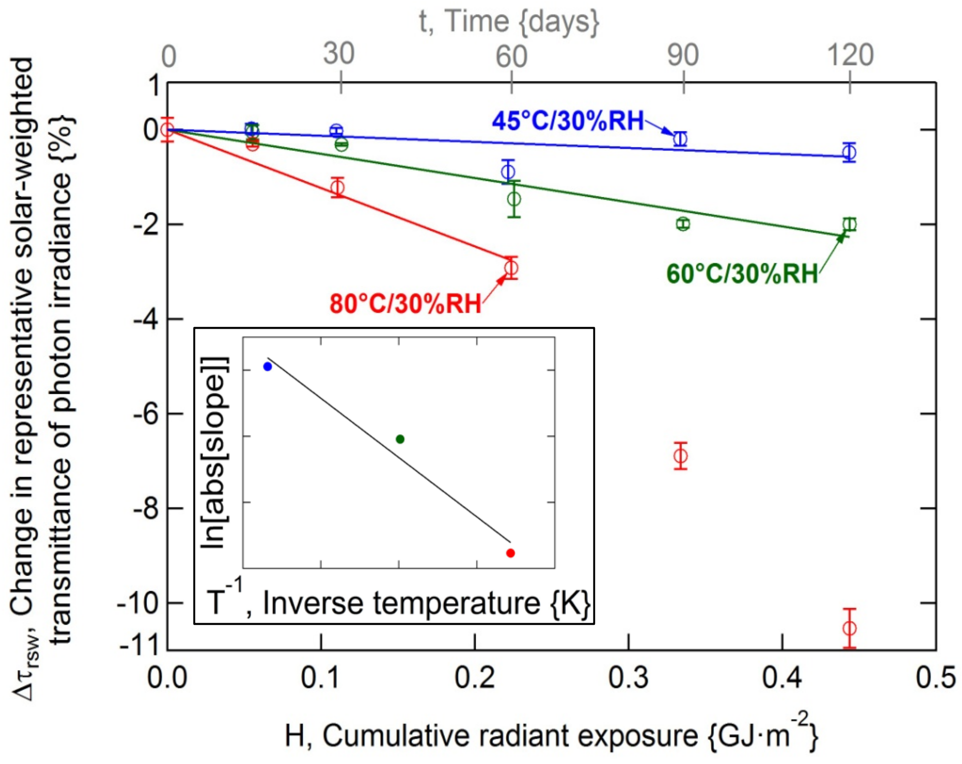
Recent progress

- **Safety for modules Edition 2 of IEC 61730**
  - Will enable harmonization with UL1703
  - Amendment will include:
    - UV weathering test
- **UV durability test IEC 62788-7-2 (and others)**
  - Will include encapsulants, backsheets, etc.
- **System level tests**
  - Performance (IEC 61724-1 measurement, -2 power, -3 energy)
  - Commissioning, design, maintenance, etc.

Kelly, et al, PVSC 2015 (Monday)

Recent progress - studies

- **PVQAT study quantifies temperature dependence of UV-induced discoloration**



Miller, et al, PVSC 2015

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What will it take to reach the end goal of being quantitative?

Service Life Prediction Standard?

- How would you write a standard for making a Service Life Prediction?
- The failure mechanisms that limit the life of a product may vary
- Current research is providing scientific basis, but we don't have a draft standard yet

Steps to a Service Life Prediction:

1. Identify failure/degradation mechanisms that determine end of life
2. Quantify kinetic rates
3. For given use environment, apply kinetic rates within model to estimate expected lifetime
4. Verify model by comparing with field data

This step-by-step procedure is clear, but the actual tests are not

This procedure is similar to quality management

Requirements of quantitative service life prediction

First must understand:

- **Degradation/failure mechanisms**
  - **May differ by location**
  - **May involve a series of stresses**
- **How to test for these in quantitative way**
  - **Need to know kinetics**
  - **May involve a series of stresses**

Requirements of quantitative service life prediction

In addition to understanding:

- **Degradation/failure mechanisms**
- **How to test for these in quantitative way**

We require:

1) **Specific use environment**
2) **Specific bill of materials**
3) **Defined process window**

Why use environment must be defined

- **A test that predicts 25 years in Munich may only predict ~ 2 years in Phoenix!** **(assumes failure is caused by higher temperature with an activation energy of 1.1 eV)**

Kurtz, et al, Progress in PV 2011, p 954

Why bill of materials must be controlled

- **A change in the bill of materials (BOM) may change the chemical composition**
- **An example of possible problem:**
  - Additives in encapsulants affect the discoloration mechanism
  - Some mechanisms are accelerated by temperature more than others
  - If the activation energy changes from 1.1 eV to 0.6 eV, the acceleration factor could change by a factor of ~10
  - A test that predicts 25 years could unknowingly predict only ~ 3 years!

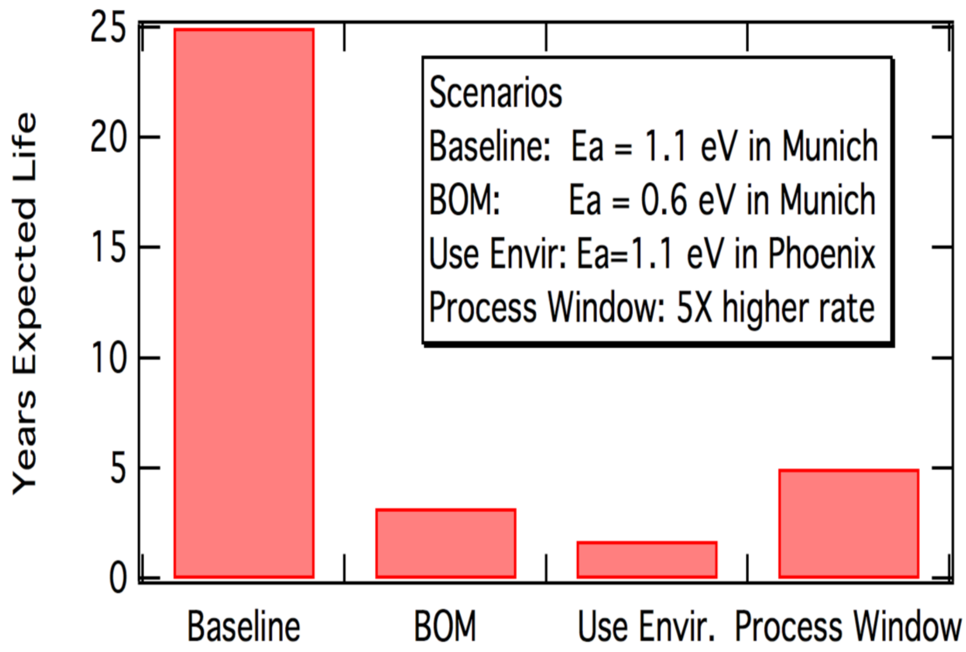
Kurtz, et al, Progress in PV 2011, p 954

Why process window must be defined

- **Variations in the product may cause premature failure**
- **An example of possible problem:**
  - 90% of solder bonds use solder coatings 0.2 mm thick, but sometimes the solder application varies and the thickness drops as low as 0.04 mm.
  - Thermal fatigue occurs faster in the thinner bond (the lifetime is roughly proportional to the thickness)
  - The test may predict 25 years for the product with 0.2 mm solder, but products accidentally made with only 0.04 mm solder might fail after 5 years!
  - The test should be designed so that all products falling within the process window will have the intended lifetime.

A prediction needs to have a low uncertainty

- **A prediction of a lifetime isn't worth much if the uncertainty is a factor of 10!**



The uncertainty may be unknown and large if we haven't controlled the use environment, the BOM, and the process window.

Challenge for the world and role for China

- **Big job!!**
  - Identify all failure modes
  - Quantify rates of degradation/failure
- **All countries need to work together**
- **China has a lot to contribute!**
  - Biggest manufacturer – understand quality control
  - Biggest customer – understand field experience for a range of climates

Conclusions

- **What reliability issues need to be quantified?**
  - *Ones that can't be solved without increasing cost*
- **What are strategies for quantitative testing?**
  - *Test materials: long tests may be used to qualify the material before incorporation into modules*
  - *Detailed understanding of failure mechanisms is needed to design tests:*
    - *Quickly identify lack of susceptibility*
    - *Less quickly quantify rate if there is susceptibility*
    - *Random testing from production line*
    - *Differentiate climate-specific durability*
- **What will it take to reach the end goal of being quantitative?**
  - *Defined use environment, BOM, process window*

PV industry is making great progress toward improved prediction of long-term reliability!

International standards are being developed by IEC with support from PVQAT

Special thanks to the hundreds of individuals who are contributing to this work!

Thank you for your attention!