NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Reliability Challenges for Solar Energy

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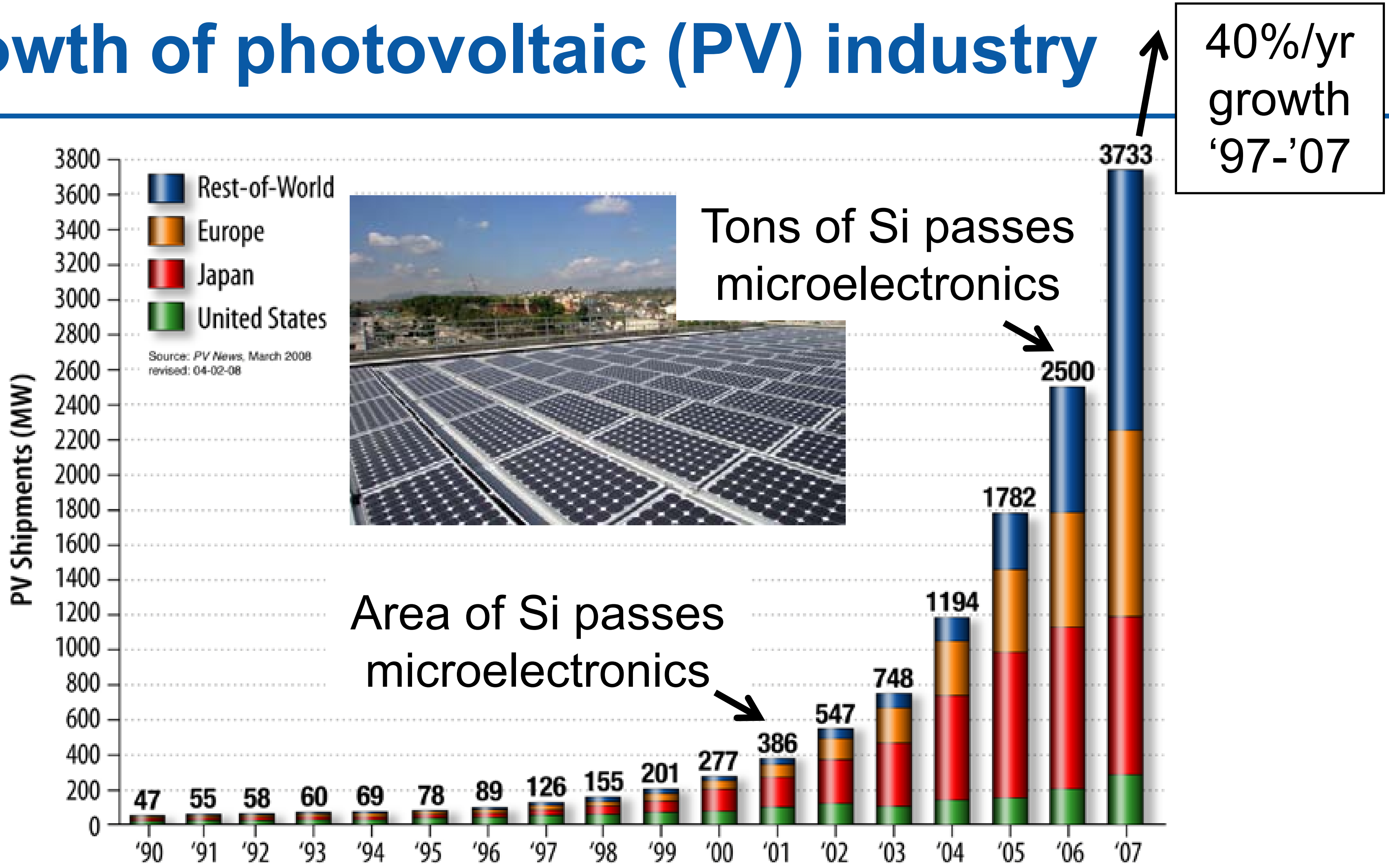
Outline

- Solar – a huge success, but still a long way to go
- Key approaches to solar electricity
  - Solar thermal
  - Crystalline silicon
  - Thin film – amorphous silicon, CdTe, CIGS
  - Concentrator – low- and high-concentration approaches
- Importance of reliability to success of solar
- Reliability issues specific to each approach
  - Silicon – strong performance; continuous improvement; quantitative predictions
  - Thin film – uniform, large-area deposition for product development and sensitivity to moisture; metastabilities
  - Concentrator – product development; simultaneous optimization of multiple components

Growth of photovoltaic (PV) industry



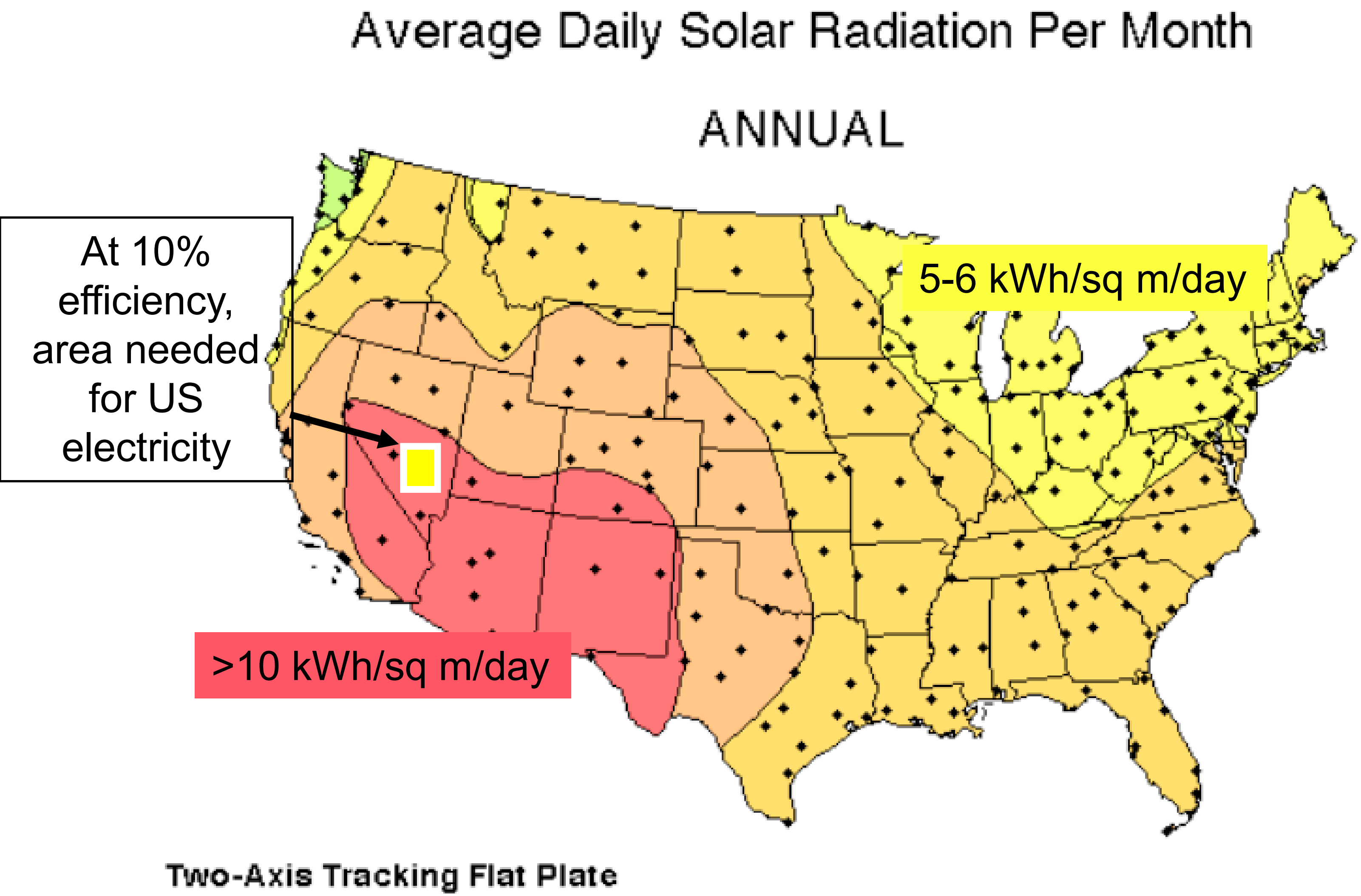
0.01%-0.1% of electricity now comes from PV - extrapolates to > 5% in 2020

competitive with conventional electricity for 0.1% - 1% of market; more in future

Rogol, PHOTON International August 2007, p 112.

Solar energy is abundant

Convenient truth: small area can supply our energy needs



Sunlight reaching earth in 1 hour is enough to power the world for 1 year

Solar thermal electric

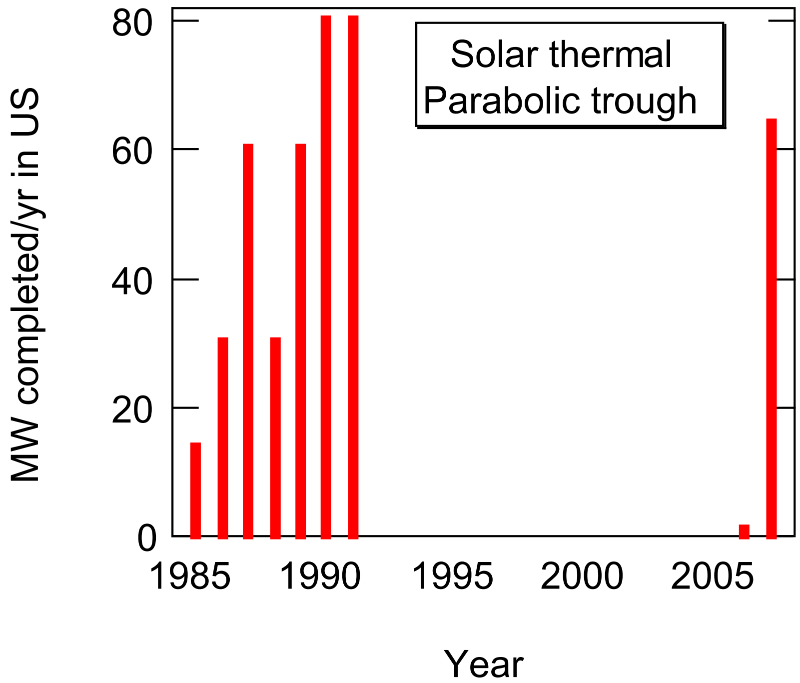
Parabolic trough is the primary technology today

Resurgence of interest

~ 400 MW installed

Currently generates ~ 0.01% of US electricity

Can generate electricity into the evening & use fuel into the night



4 GW planned in US by 2014

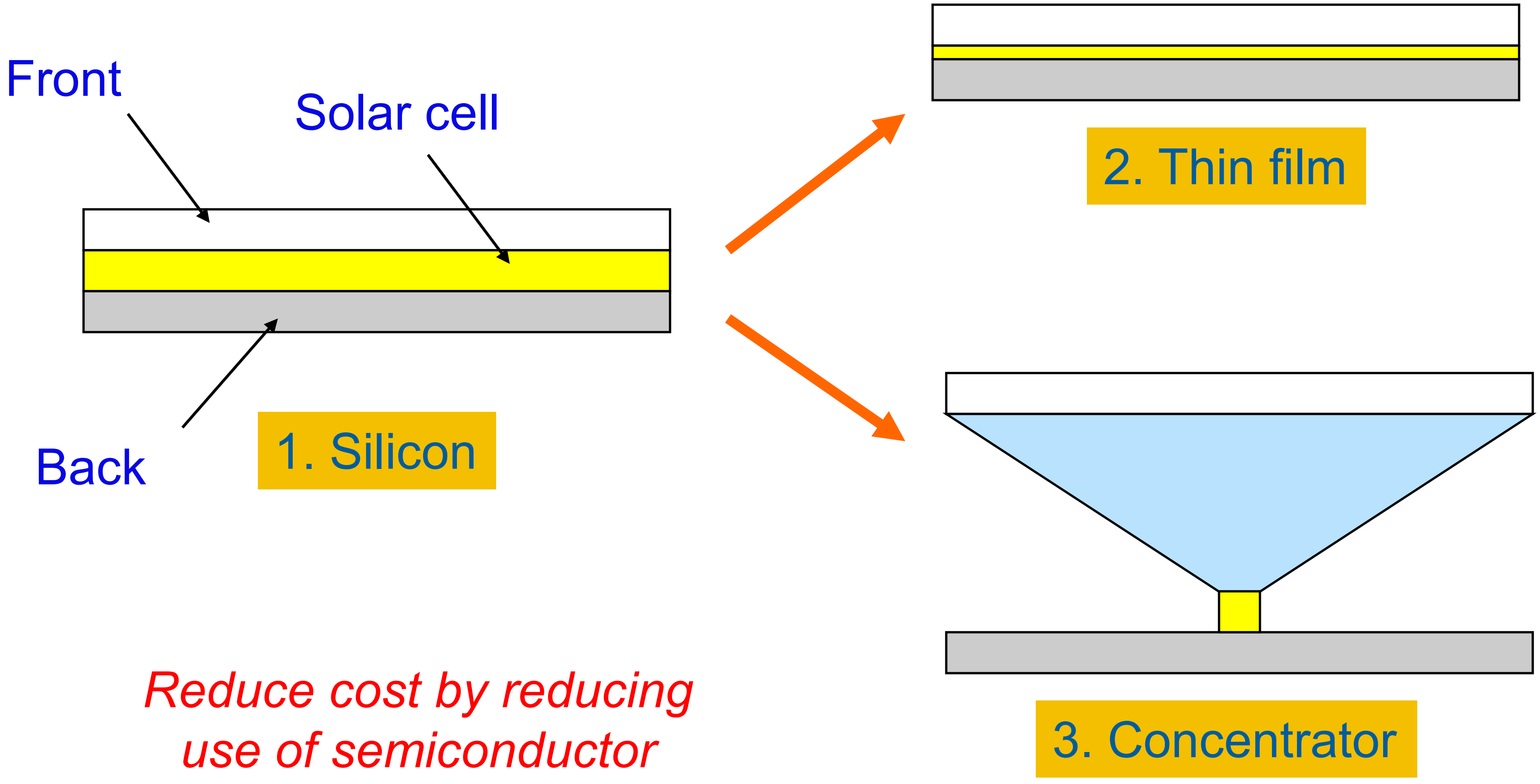
64 MW Solargenix Parabolic Trough Plant in Nevada - 2007

1-MW Arizona Trough Plant – near Tucson, AZ - 2006

Three key approaches to photovoltaic (PV) panels

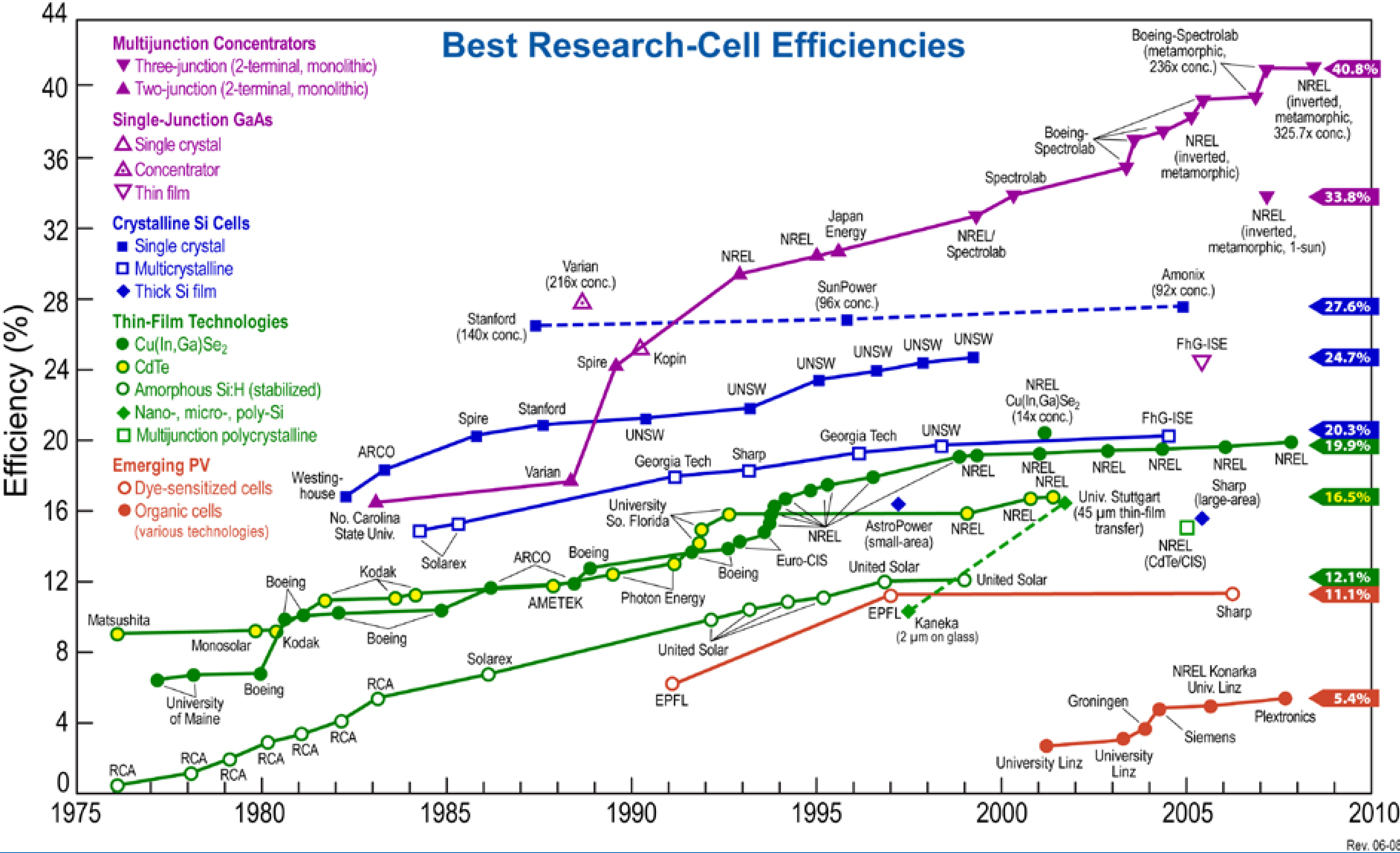
Conventional approach

Two strategies to reduce semiconductor material



Reduce cost by reducing use of semiconductor

Many technology choices



One “winner” or many technologies?

Alkaline

Nickel cadmium

Nickel metal hydride

Lead acid

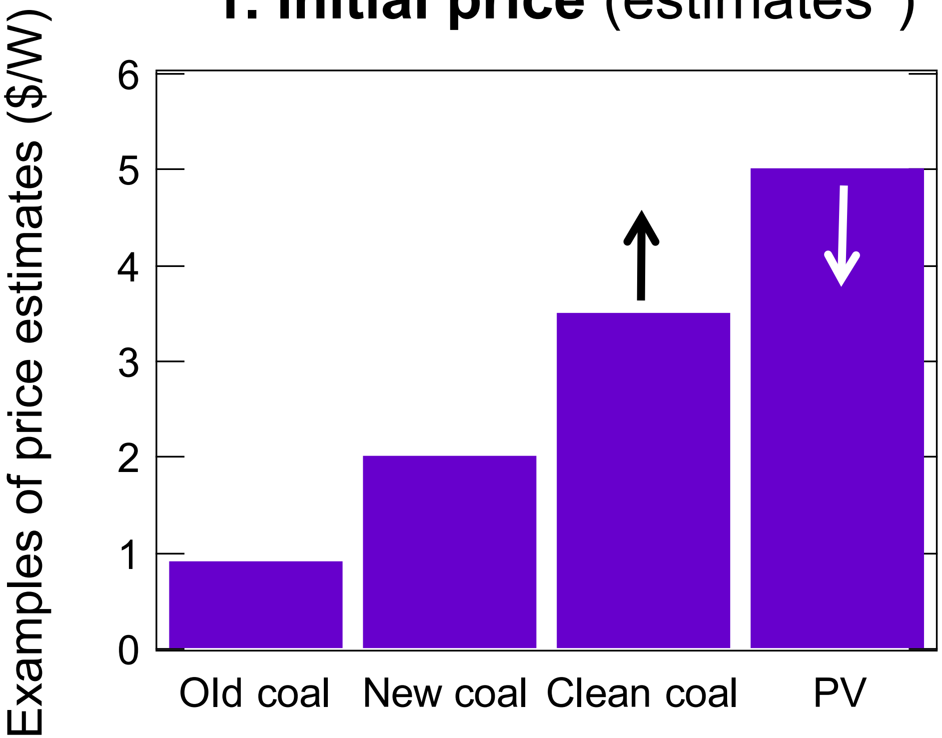
Lithium ion

Lithium

Different technologies for different applications

Cost of electricity: two or three parts

1. Initial price (estimates*)



*Fortnightly's SPARK, p. 10, May 2008

2. Operation and maintenance

- Fuel cost (Coal□ PV□)
- Operation (Coal□ PV□)
- Maintenance (Coal□ PV□)

PV is already competitive for peak power in some locations

3. Total electricity generated

- Capacity factor (Coal□ PV□)
  (Coal ~100%; PV ~ 25%)
- Life of plant (Coal□ PV?)

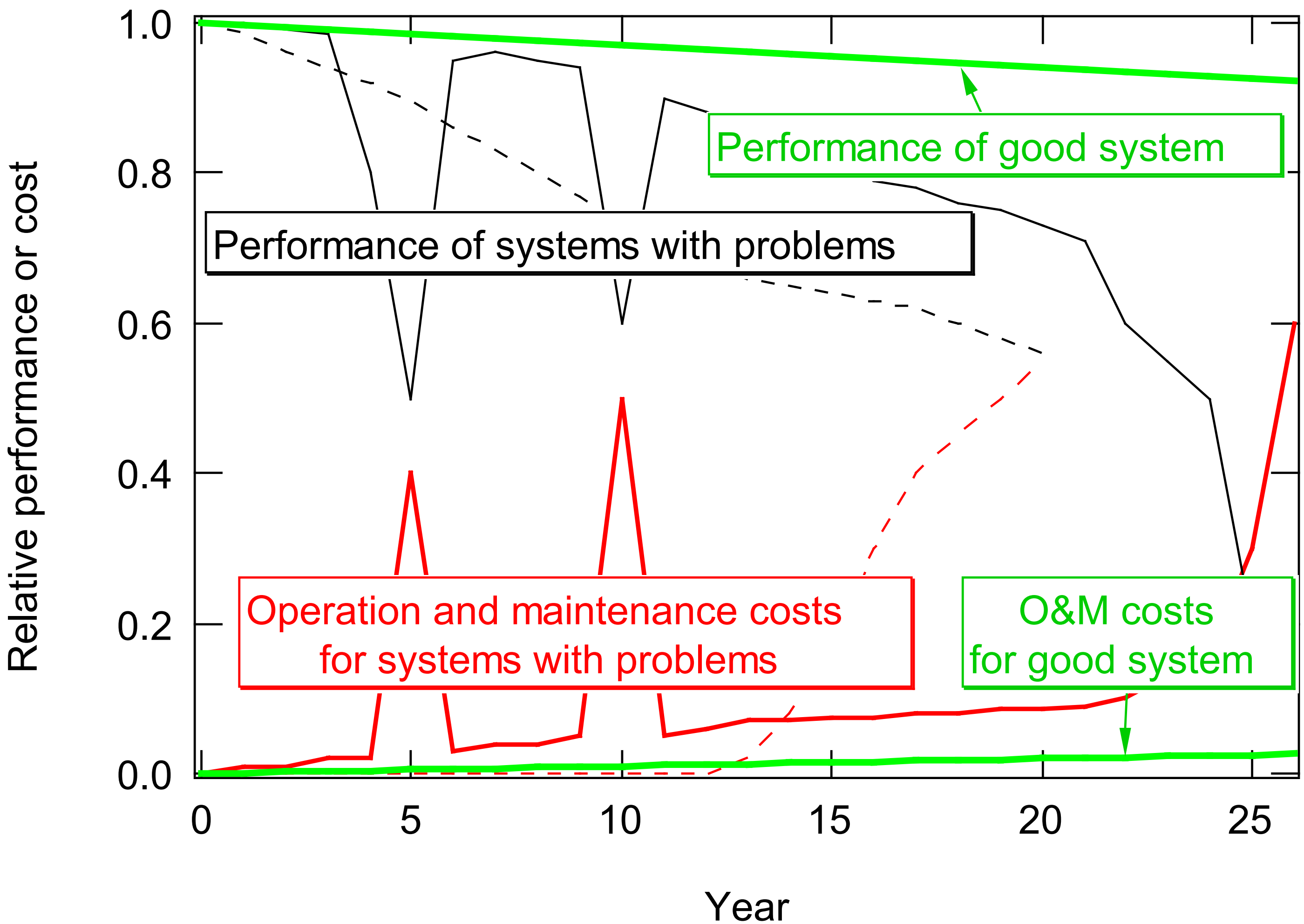
Upfront costs for PV and coal plants are converging

Ongoing costs are less for PV

Operation only during daylight hours increases cost by ~X4

Key remaining question is life of PV plant (30 years?)

Importance of reliability & durability



Cost of solar electricity depends on degradation, lifetime, & ongoing costs

Those paying for upfront investment want guarantee of system life

How to satisfy the investor?

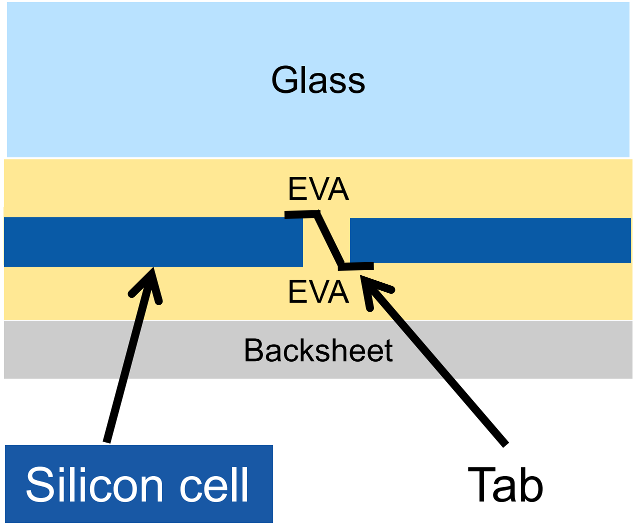
Historically, degradation & failure mechanisms have been found in the field that were not found in accelerated testing

Predictive models need to be validated with field data

Big challenge: How can we give 30-year predictions for degradation & failure rates when the product has only been in the field for 1-2 years?

Silicon modules

Si module cross section



Common encapsulation materials
EVA - Ethylene vinyl acetate
PET - polyethylene terephthalate
PVF - poly vinyl fluoride (Tedlar)

History of Si module qualification 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
- Studies of c-Si modules show that module failures are small (inverters dominate when cost is low)

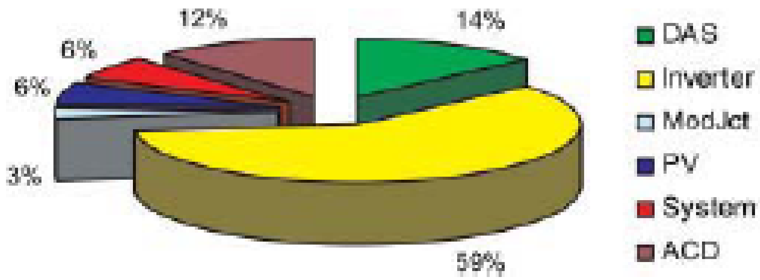


Figure 8. Unscheduled maintenance costs by category

Prog. PV 2008; 16:249

Currently, most reports imply that c-Si module failures are dominated by improper installation, lightning strikes, critters, etc.

Today's qualification standard

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

www.iec.ch

Silicon modules – remaining challenges

New materials (reduce cost, improve performance) – will these have same reliability?

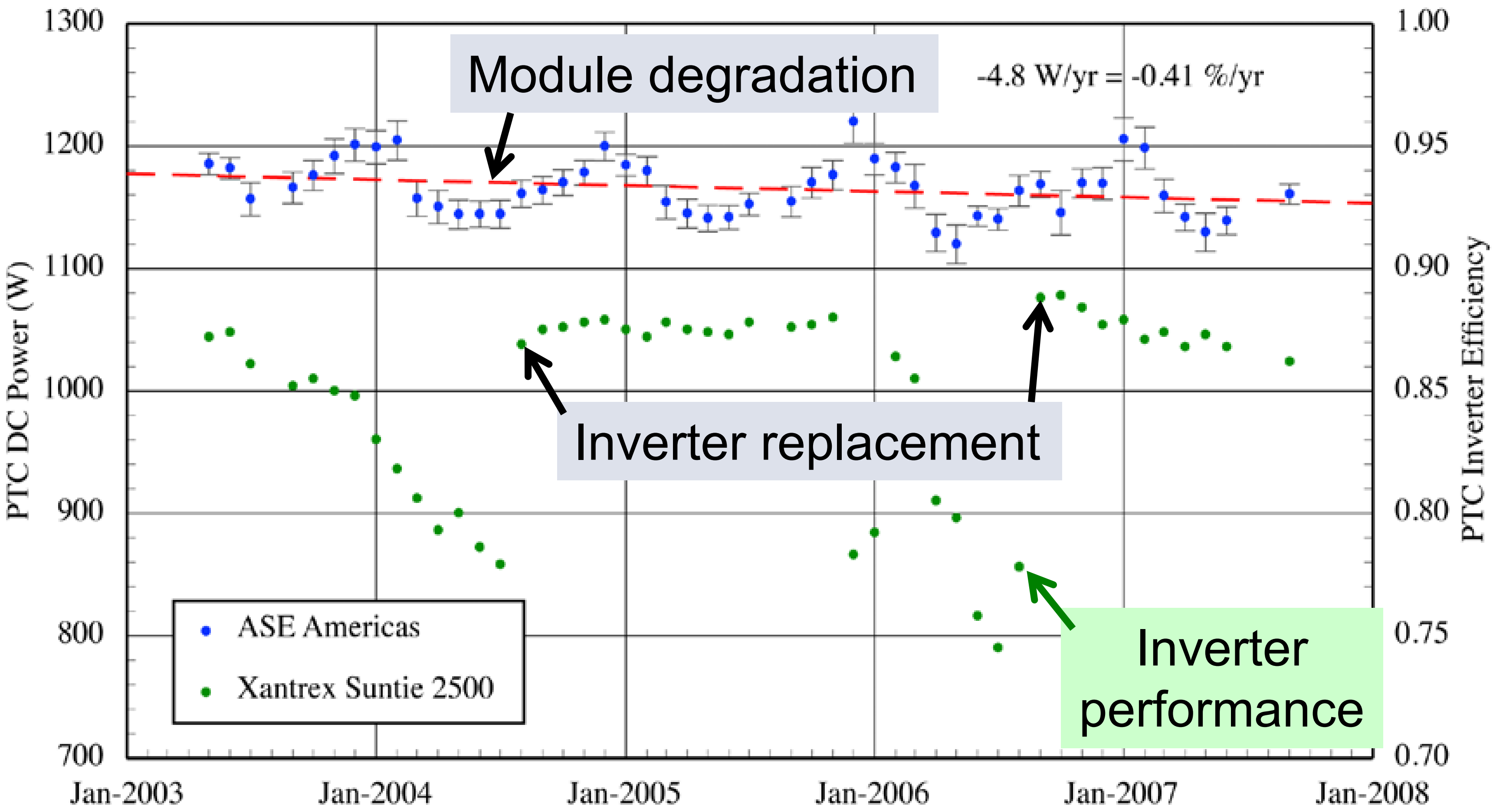
Continued quality assurance (e.g. impurities in Si give light-induced degradation)

Arcing, grounding, power conditioning, other system-related problems

Confident, long-term, quantitative predictions

Typical degradation rates are 0.5%/yr (difficult to measure); field failure rates are often < 0.1%/yr

Measurement of degradation rates takes years



Need precise measurement of irradiance, temperature, etc.

Thin-film approaches on the market

CuIn(Ga)Se

CdTe

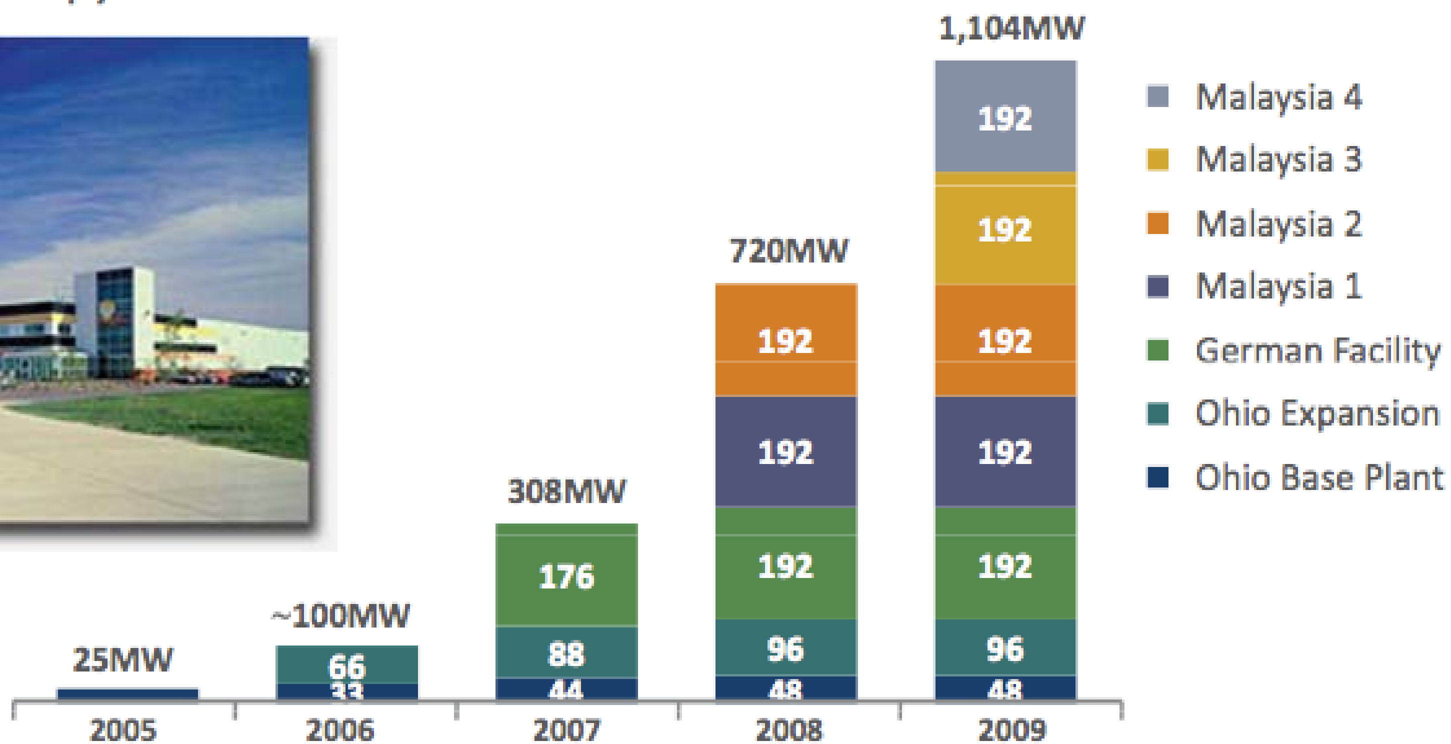
Amorphous silicon

Thin-film approach

- First Solar (Toledo, OH) - 5th biggest PV company in world in 2007

Capacity Expansion Plan
"Copy Smart Process"

First Solar.

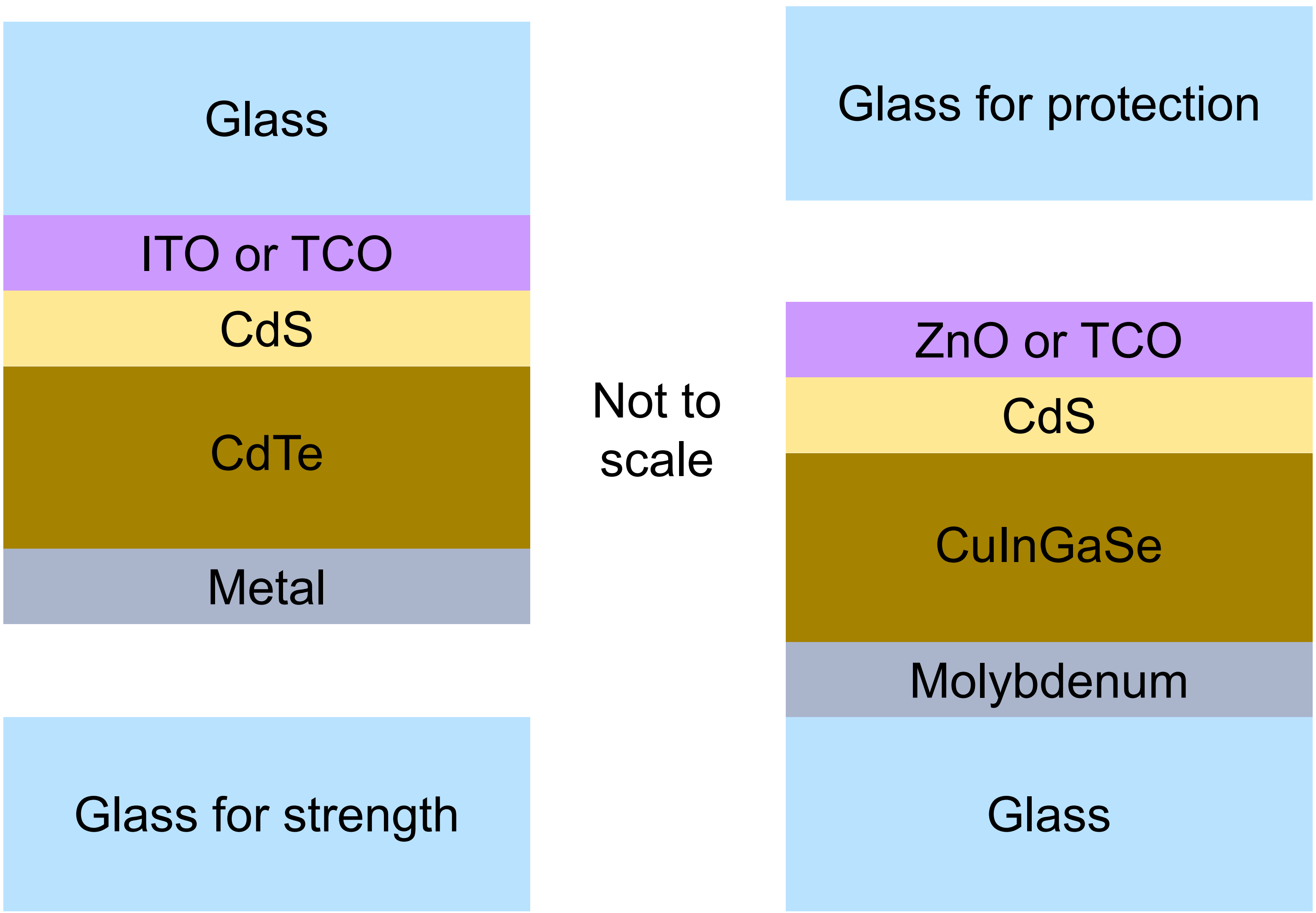


2005 and 2006 based on Q4 06 run rate   2007 based on Q4 07 run rate   2008 – 2009 based on Q2 08 run rate

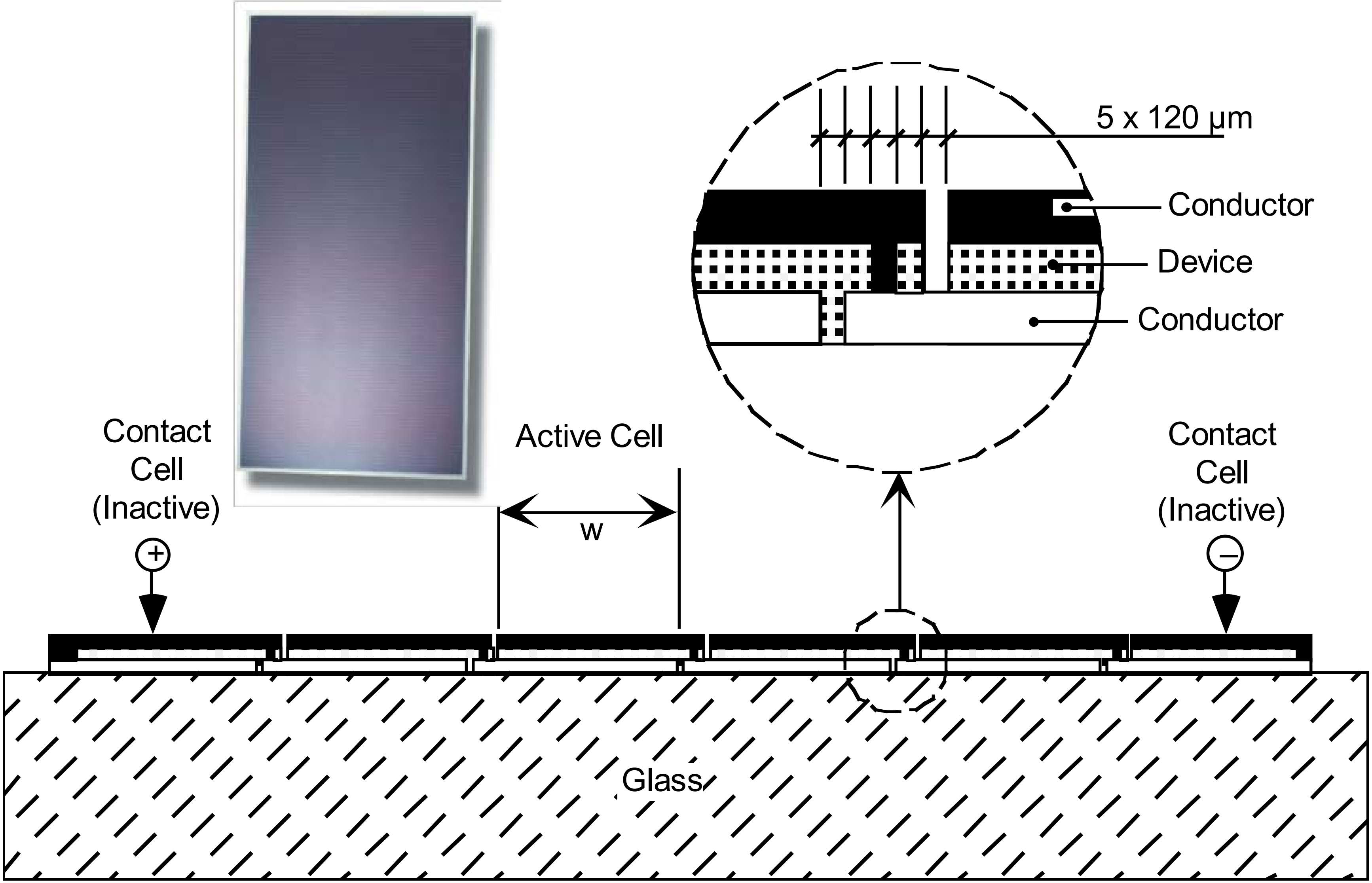
Thin-film structures

CdTe uses superstrate

CuInGaSe uses substrate

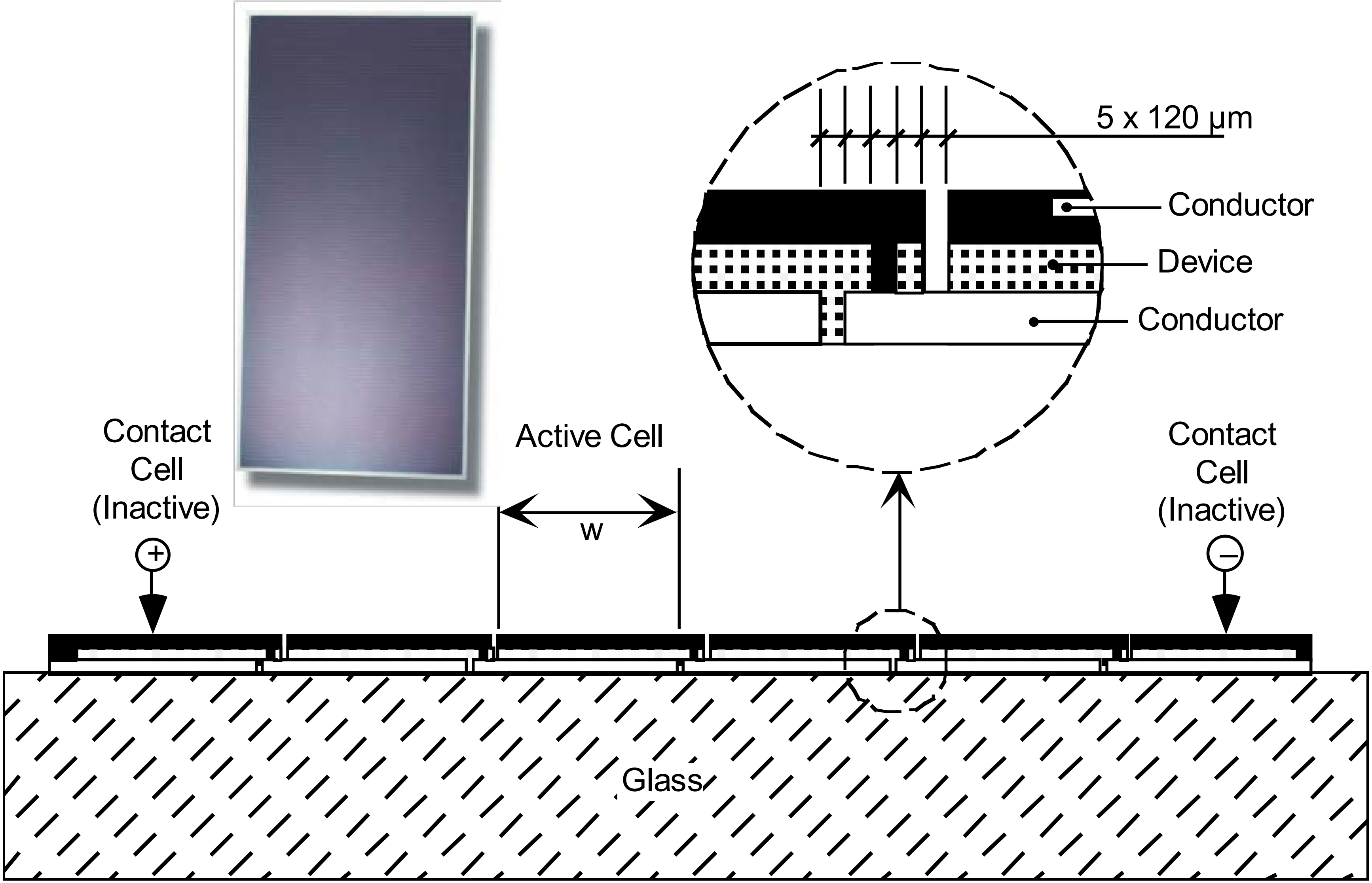


Monolithic module integration



Hurdle for thin films: uniformity of deposition

Hurdle for thin films: uniformity of interconnections



Module metastability

- Reversible vs irreversible changes
- Amorphous silicon degrades in light and recovers when annealed in the dark
- CIGS and CdTe can show transients
- Light soaking – IEC standard calls for 600-1000 W/m^2 @ 50°C (±10°C) for dose of >43 kWh/m^2 under resistive load until power is stable within 2%

Thin-film qualification test

- IEC 61646 – Thin-film design qualification includes 19 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 to produce 90% of rated power
  - Light soaking - 600-1000 W/m^2 @ 50°C (±10°C) for dose of >43 kWh/m^2 under resistive load until P_{max} is stable within 2%

Damp heat can cause degradation

ZnO (and other transparent conductors) react with moisture, causing increase in series resistance

CuInGaSe may react with moisture

Transparent Conductive Oxides

Table I. Typical resistivity and transmission (in the visible) for various TCO materials investigated for TFSC application (data from References 41 and 42)

Material	Resistivity (Ω cm)	Transparency (%)
SnO_2	8×10^{-4}	80
In_2O_3:Sn (ITO)	2×10^{-4}	>80
In_2O_3:Ga (IGO)	2×10^{-4}	85
In_2O_3:F	$2{\cdot}5 \times 10^{-4}$	85
Cd_2SnO_4 (CTO)	2×10^{-4}	85
Zn_2SnO_4 (ZTO)	10^{-2}	90
ZnO:In	8×10^{-4}	85

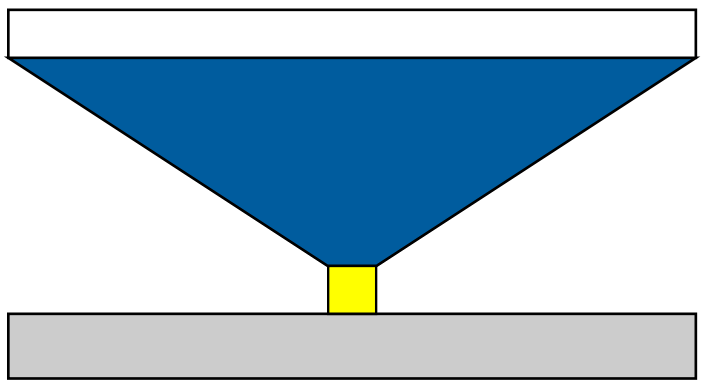
Many possible failure mechanisms

- See tutorial by Dave Albin
- CdTe has shown instability of back contact (diffusion?)
- Edge seal may allow water into glass/glass module
- Partial shunts or conducting diodes may be seen at scribe lines or other defected areas
- Adhesion to glass can be problem
- Role of sodium is important in CuInGaSe modules, but sodium can move
- Currently, the biggest effort with CuInGaSe is to try to put it on a flexible substrate – requires excellent barrier coating unless cell can be hardened to moisture

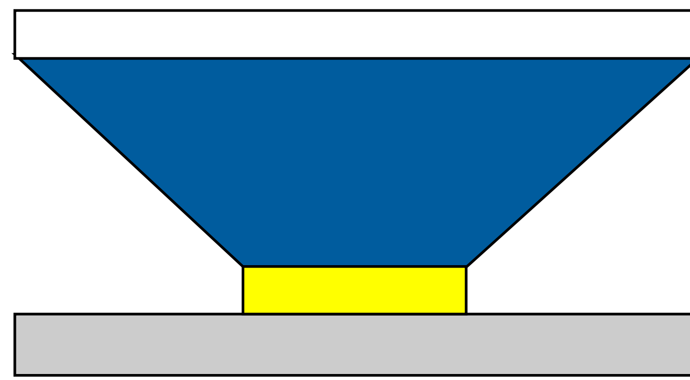
Range of concentrator approaches

Amonix

JX Crystals



High concentration
- 35% - 40% cells
- 400X – 1500 X



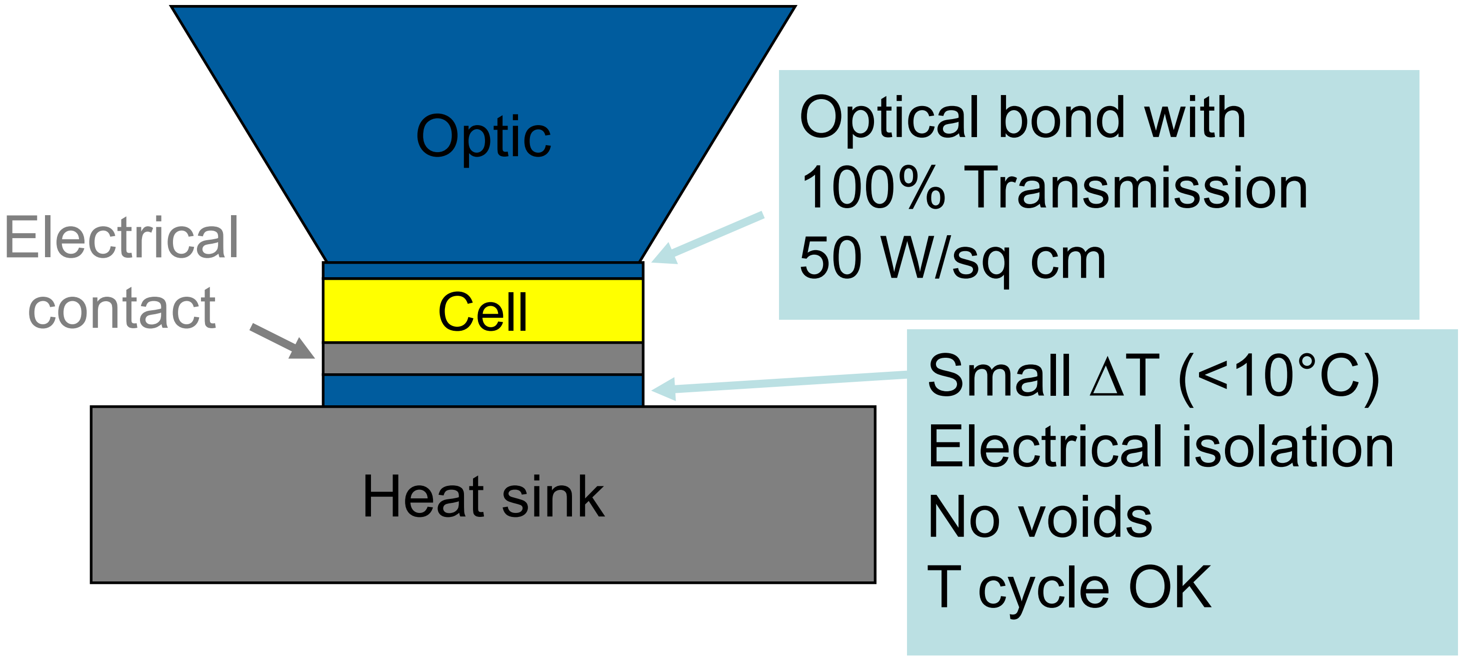
Low concentration
- 15% - 25% cells
- 2X – 100 X

CPV challenges – many interactions

CPV can fail in many ways, but it can be difficult to understand where the problem is and to fix the problem without creating a new problem

- Tracking – optics must be aligned with the sun
- Optics – durability can be problem, soiling; optics affect rest of system
- Cell – must be encapsulated, but not affected by UV; size of cell affects rest of system
- Heat sink – must be electrically isolated, but excellent thermal contact
- Modularity may be benefit!

Bonds to heat sink and optics

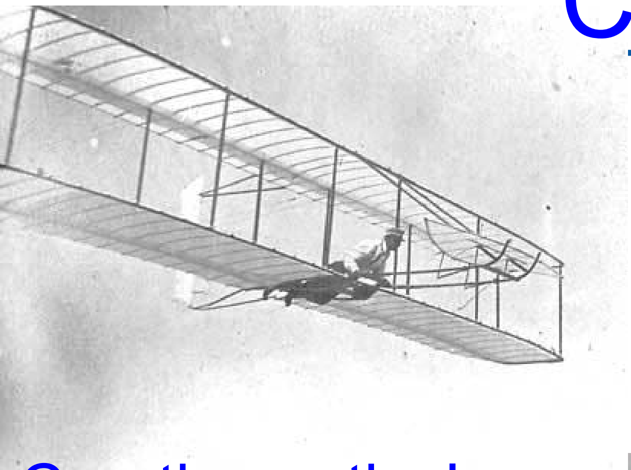


- Borrowing experience from power electronics and DBC (direct bonded copper) makes this a smaller issue
- Intense UV may be a substantial problem, but optics may not transmit UV

Concentrators – reliability challenges

- Wide variety of designs
- Qualification test is not well established
- Companies spend time developing their own accelerated tests to speed product development cycles
- Very few companies have heritage with field testing
- Everyone wants to bring a product to market immediately

Concentrator technology



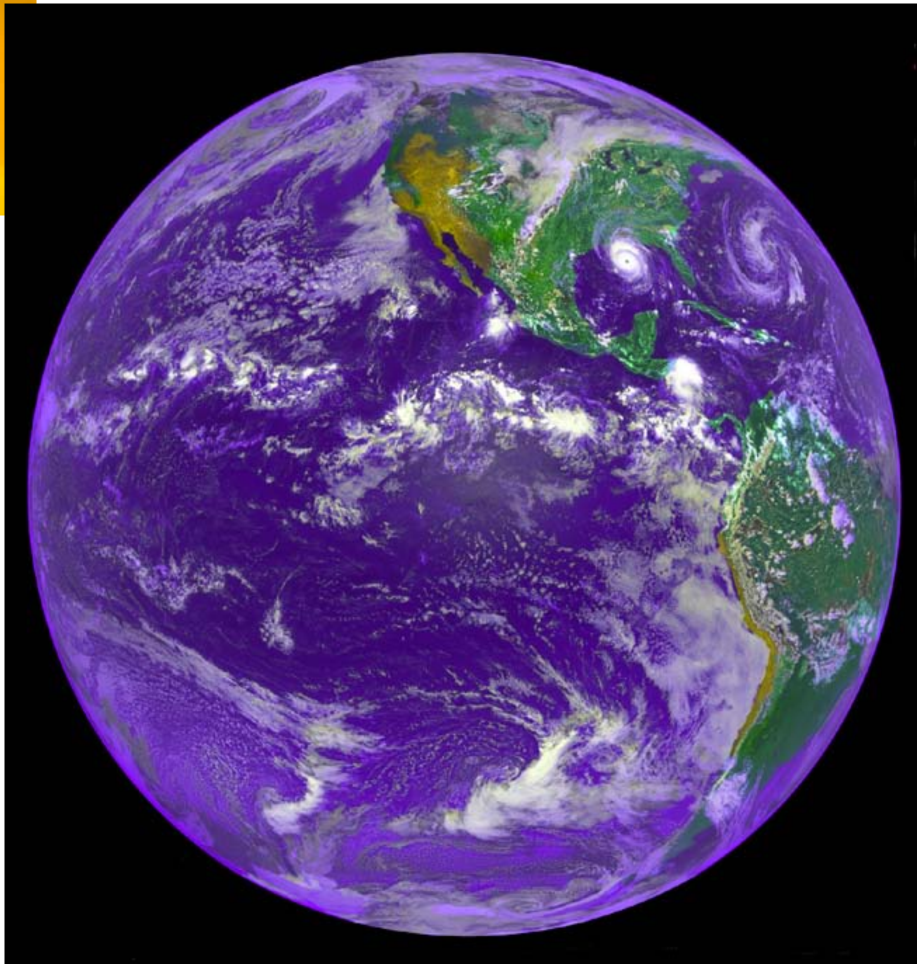
Creative optical designs?

Summary

- Solar is growing rapidly and could become a significant source of electricity within our lifetimes
- Silicon modules are performing well in the field; reliability testing of new designs is still important
- CdTe and CuInGaSe modules are sensitive to moisture, so must be carefully sealed; only amorphous Si modules are available in flexible form
- Concentrator PV is in product development stage, but is benefiting from expertise in other industries
- In general, PV industry can benefit from the reliability testing experience of the microelectronics industry

Let's work together to help PV grow!

Planet powered by renewable energy By year 2100 or before?



Thank you for your attention!

Thank you to :
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