NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Technology for Today and Tomorrow

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Outline

- Winning technology or many technologies?
- Some history to put today and tomorrow in perspective
- Three primary approaches
  - Silicon
  - Thin film
  - Concentrator
- Comparison of the three and looking at tomorrow

One “winner” or many technologies?

Alkaline

Nickel cadmium

Nickel metal hydride

Lead acid

Lithium ion

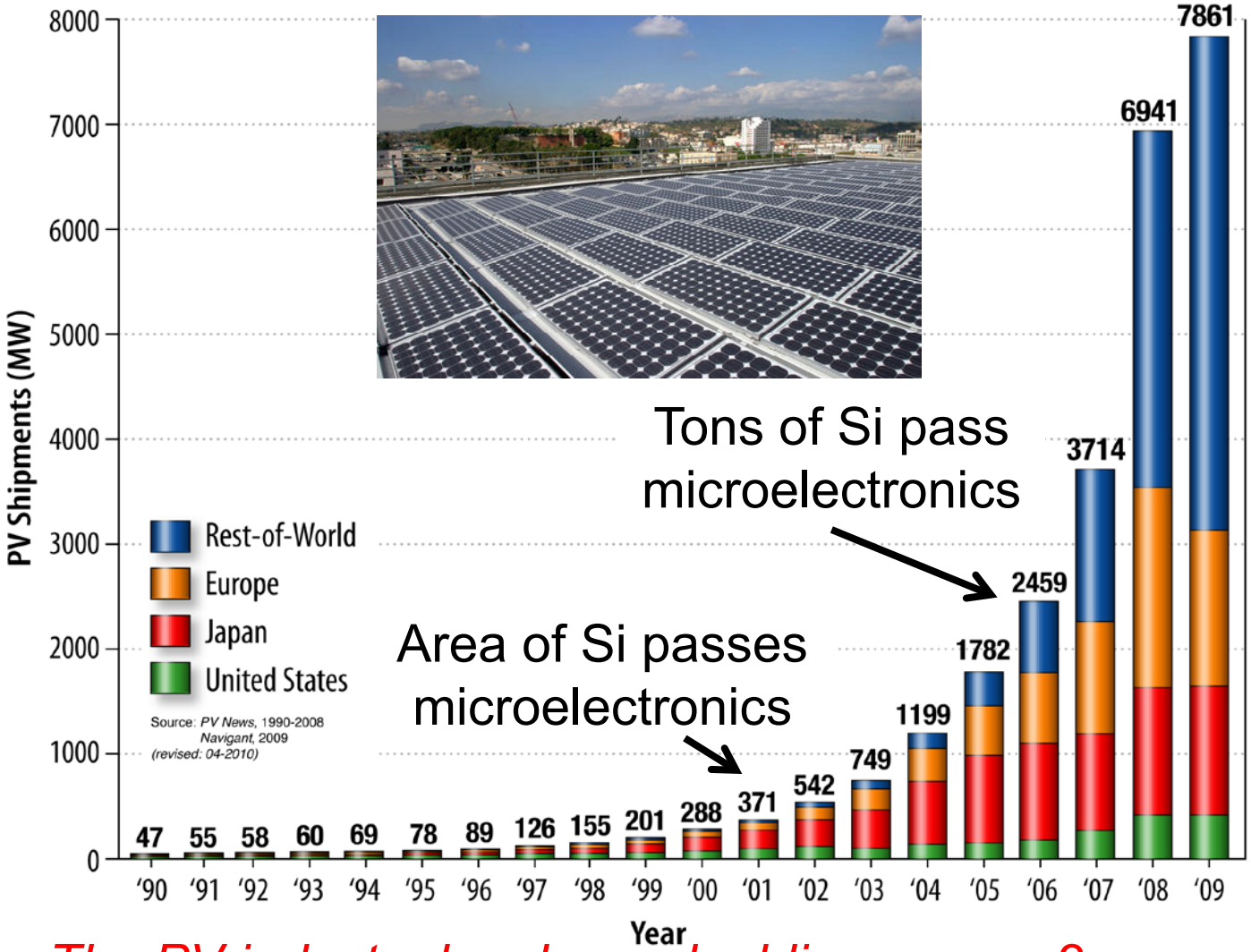
Lithium

Different technologies for different applications

Expect this for both PV and batteries

A little history

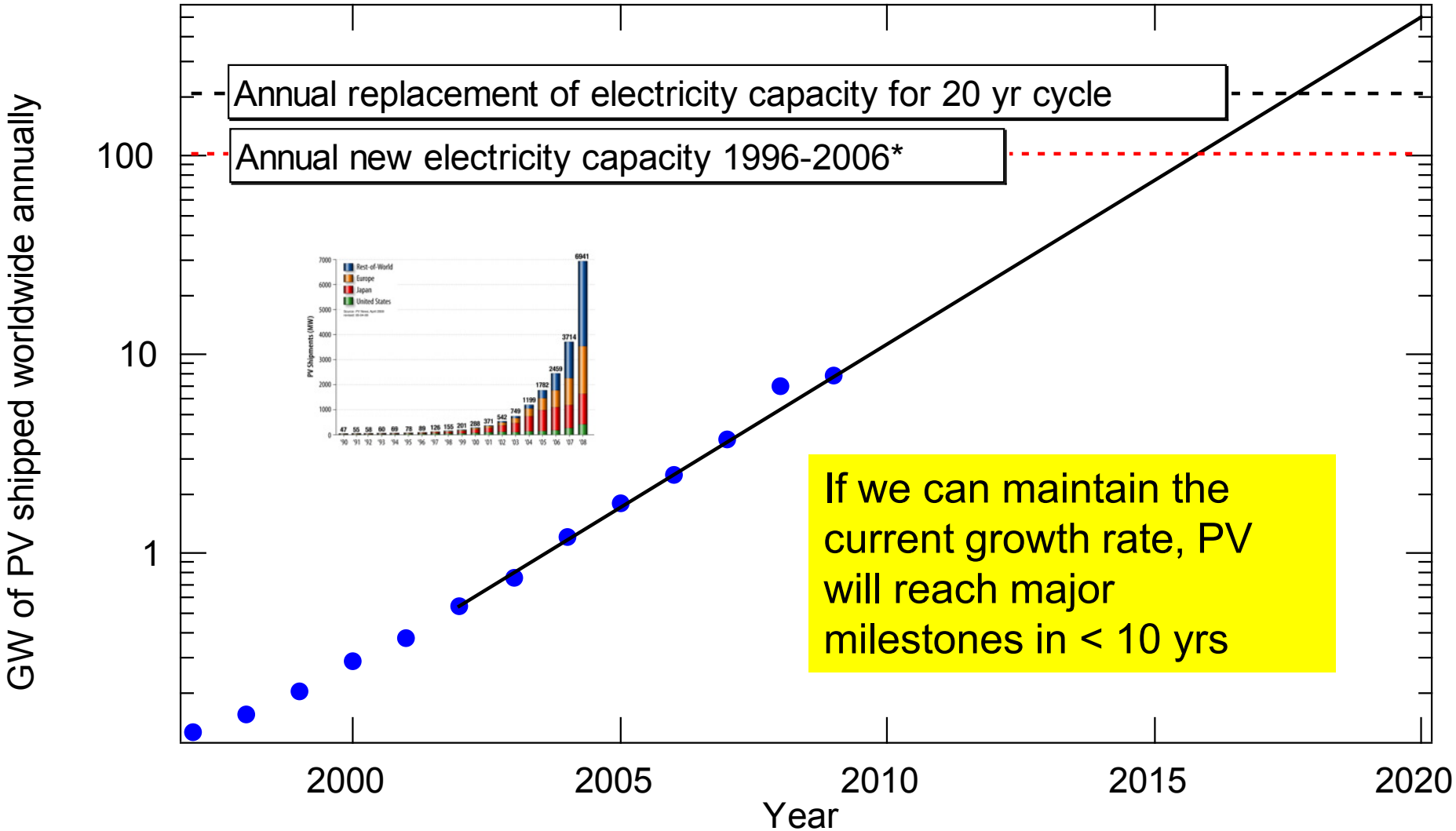
Growth of photovoltaic (PV) industry



The PV industry has been doubling every ~2 years

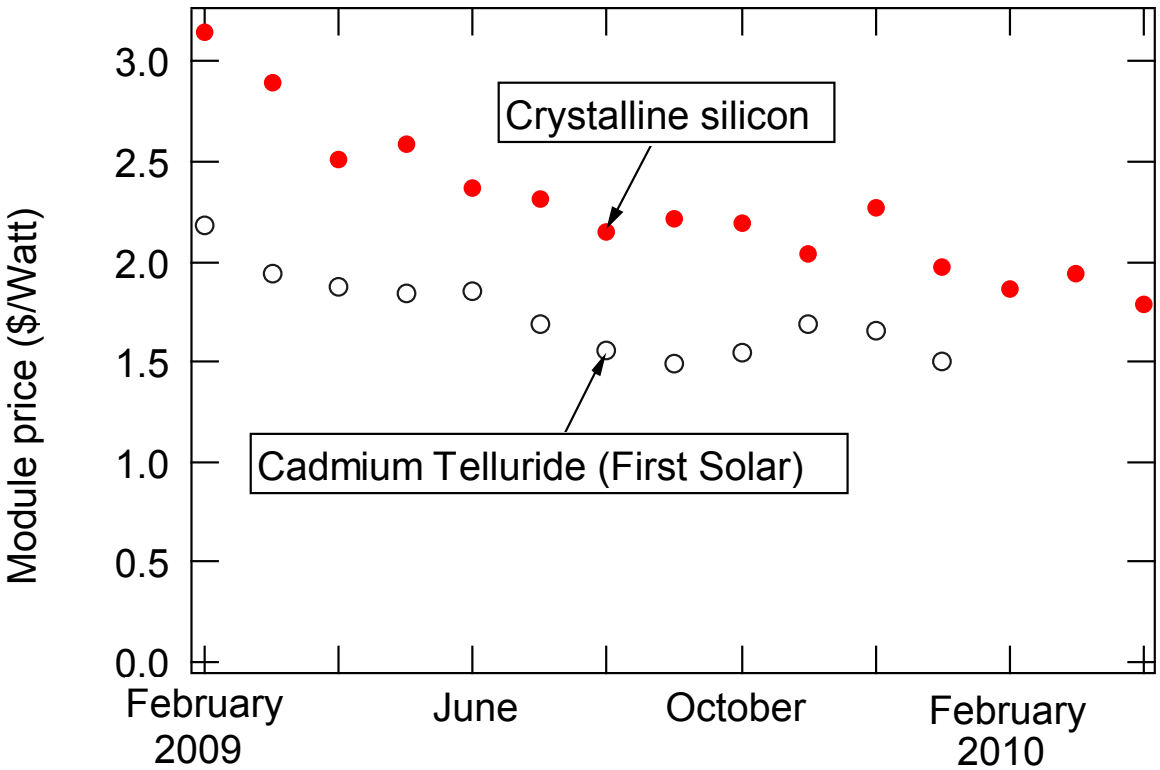
Sources: Prometheus/Navigant

Growth of PV industry



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

PV prices have decreased



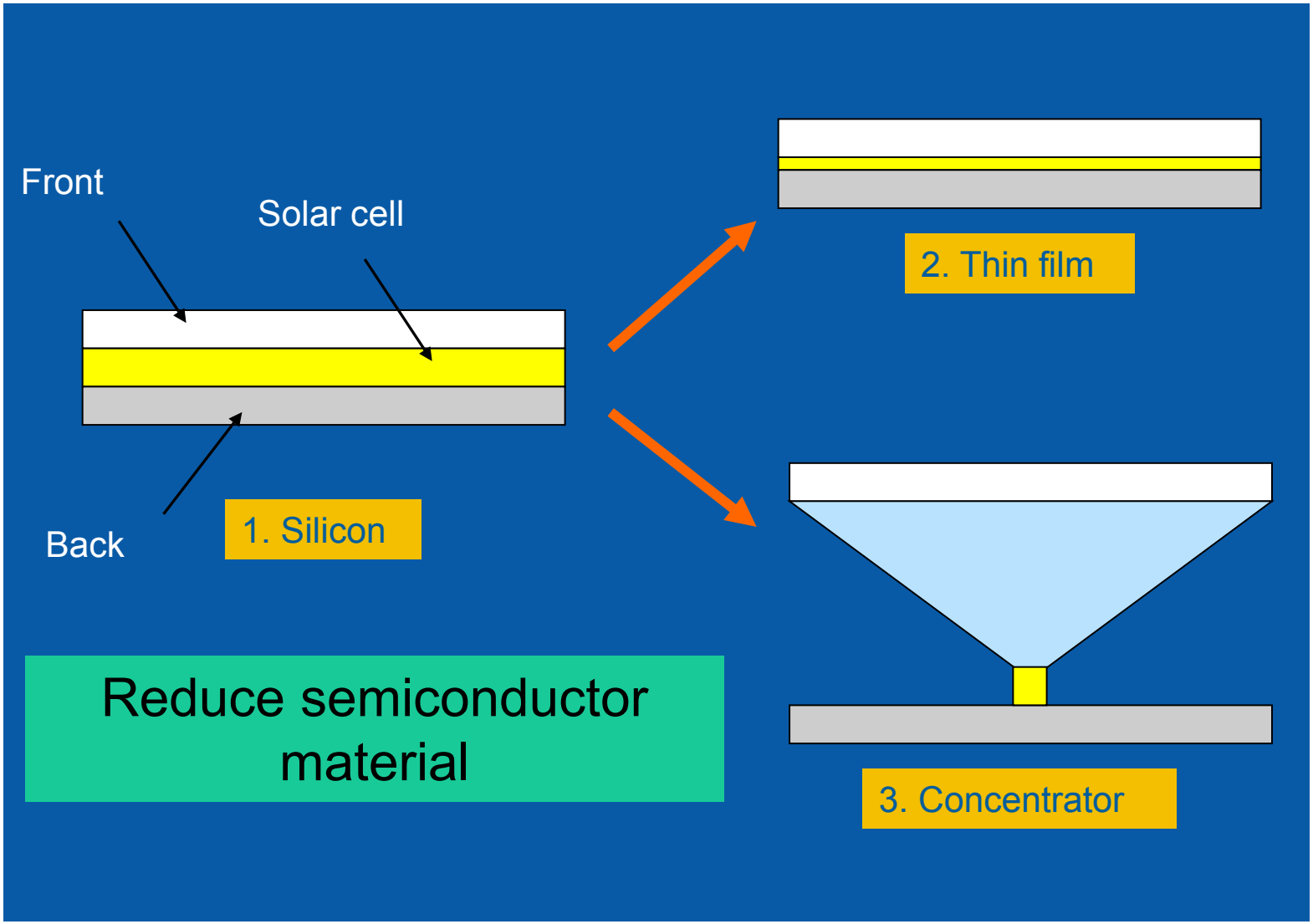
Contributors to lower costs:

- Thinner wafers
- Automation
- Standard equipment
- Optimized processes

Key to sustaining growth of the industry is price reduction

Source: PHOTON International

Three approaches to PV (and lower cost)

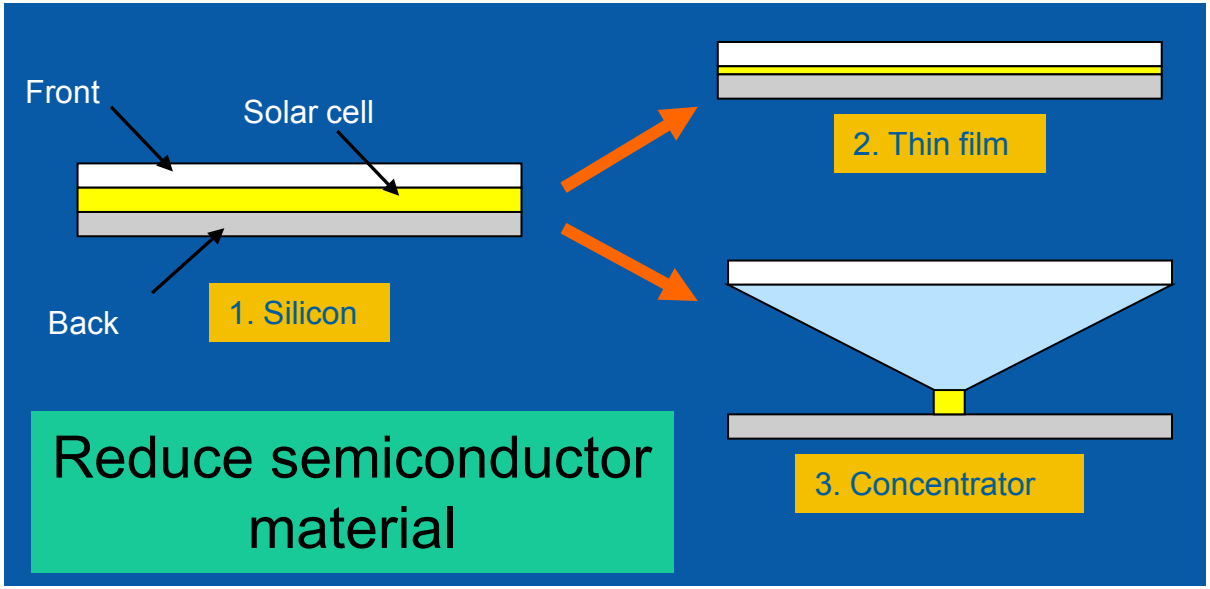


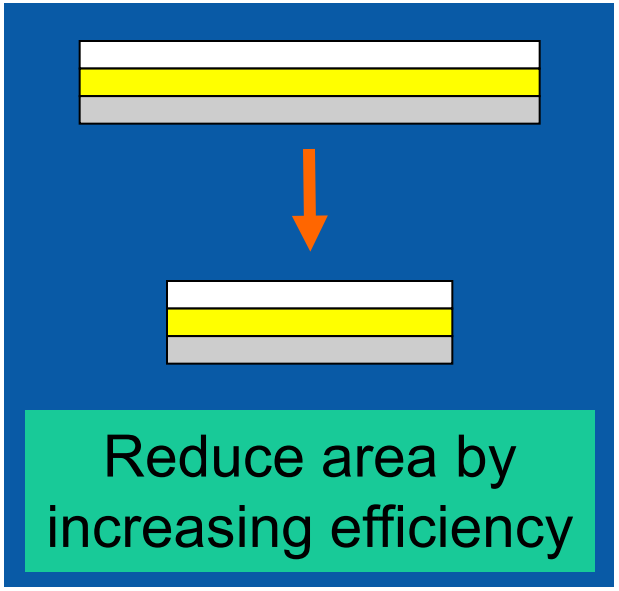
Higher efficiency can reduce cost

Upfront costs:

1. Semiconductor material
2. *Area-related costs (glass, installation, real estate, wiring)*
3. Power-related costs (inverter)

Two strategies for reducing cost:





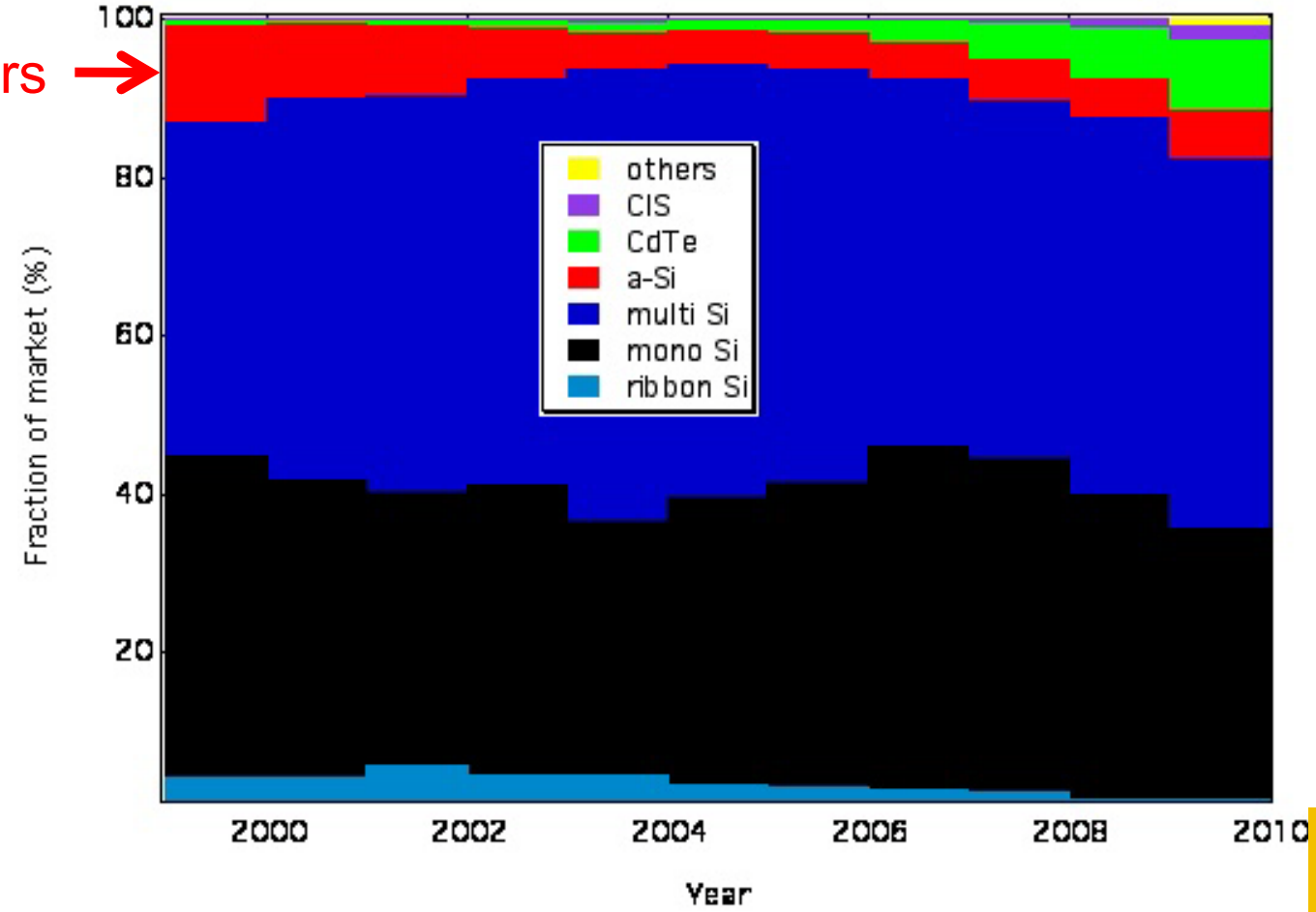
Increasing efficiency may be a key path to reduced cost

Types of PV – currently available

- Crystalline silicon
  - Mono-crystalline
  - Multi-crystalline
  - Ribbon
- Thin film
  - CdTe (Cadmium telluride)
  - CIGS (Copper Indium (Gallium) Selenide)
  - Amorphous silicon – usually combined with microcrystalline silicon layers in a multijunction stack; may contain Ge
  - Organic
- Concentrator (may be classified in many ways)
  - Refractive/reflective
  - Multijunction III-V or silicon

Historic PV Technology Mix

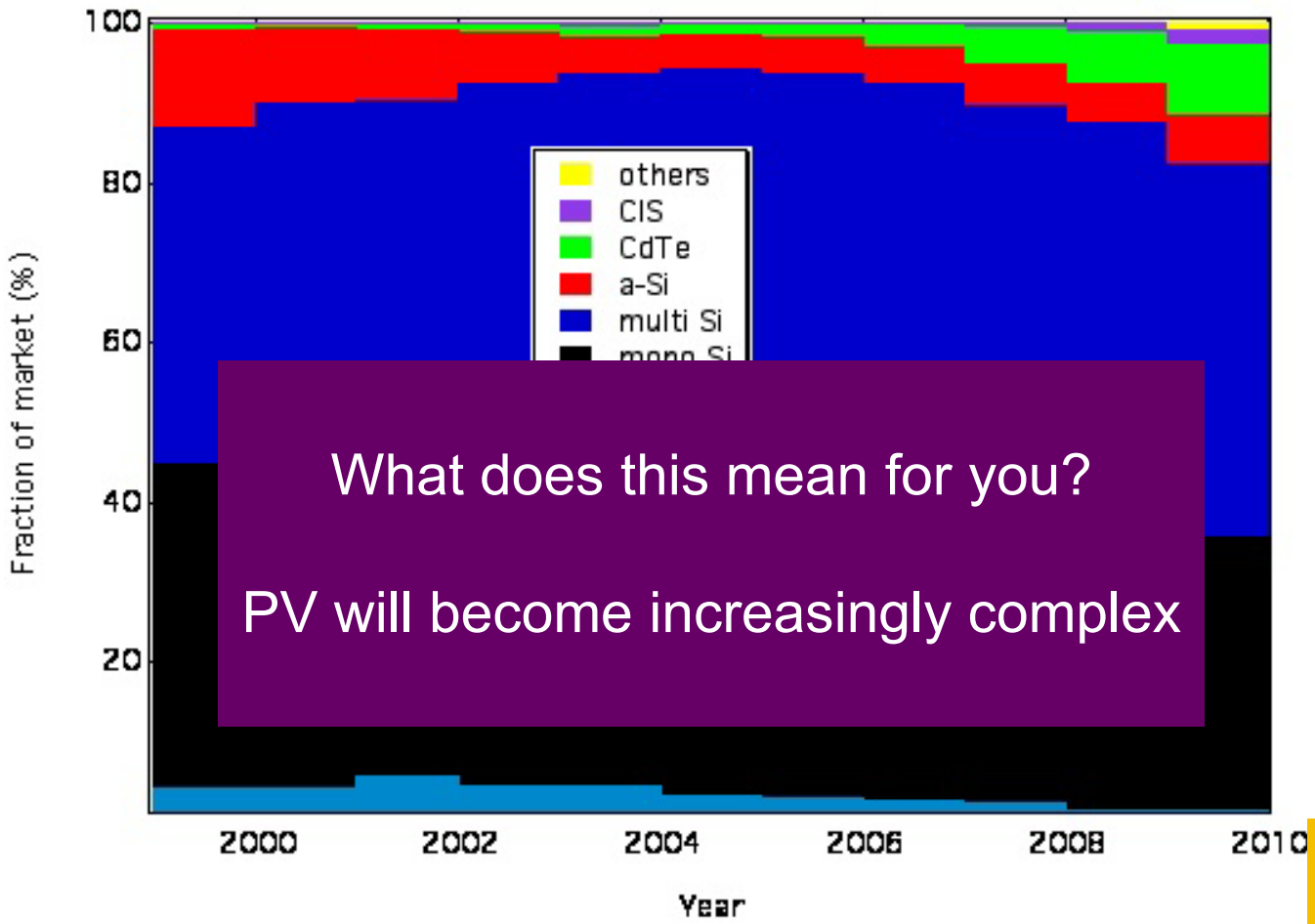
Calculators →



Source: PHOTON International

- Historically, crystalline silicon has dominated the market
- Technology mix is becoming more diverse
- CdTe is primary new entrant; CIS may be 5-7 yr behind; CPV ~ 10 yr
- Long-term trends may take decades to establish

Historic PV Technology Mix



What does this mean for you?

PV will become increasingly complex

Source: PHOTON International

- Historically, crystalline silicon has dominated the market
- Technology mix is becoming more diverse
- CdTe is primary new entrant; CIS may be 5-7 yr behind; CPV ~ 10 yr
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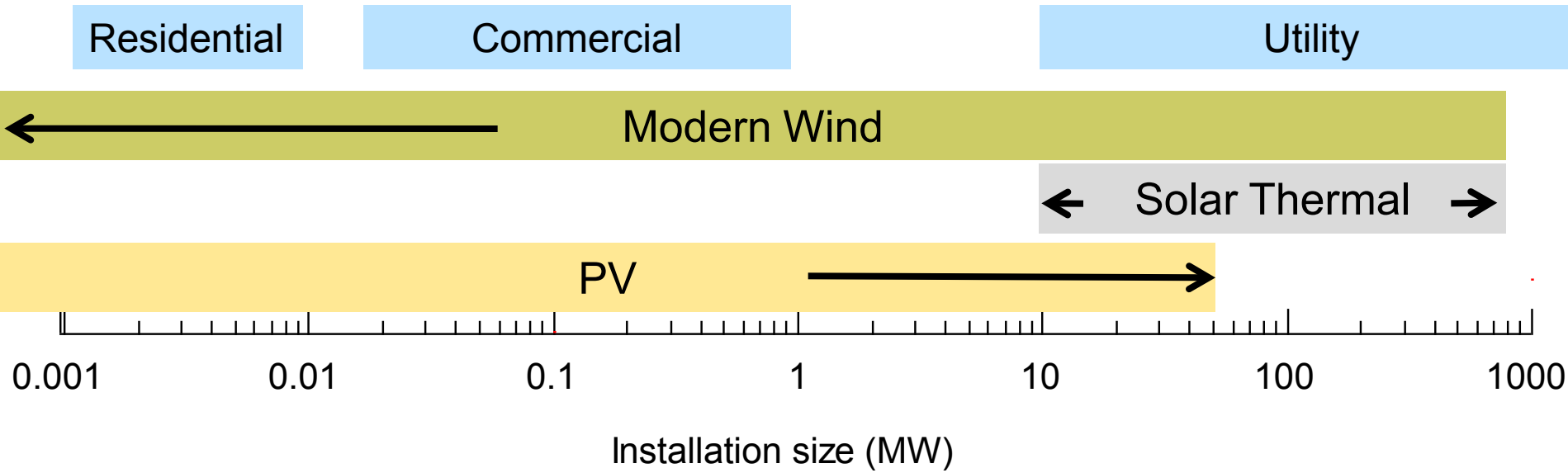
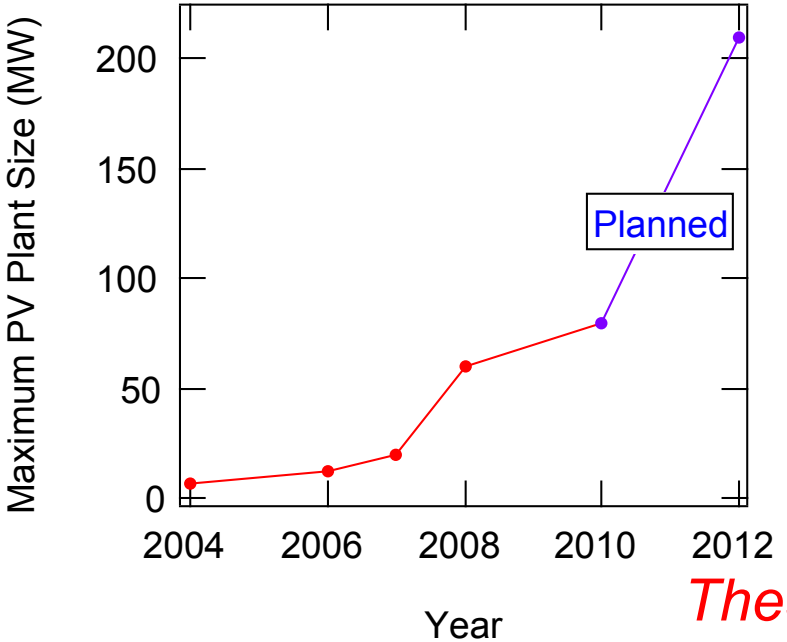
A key factor affecting technology mix: Distributed vs Central



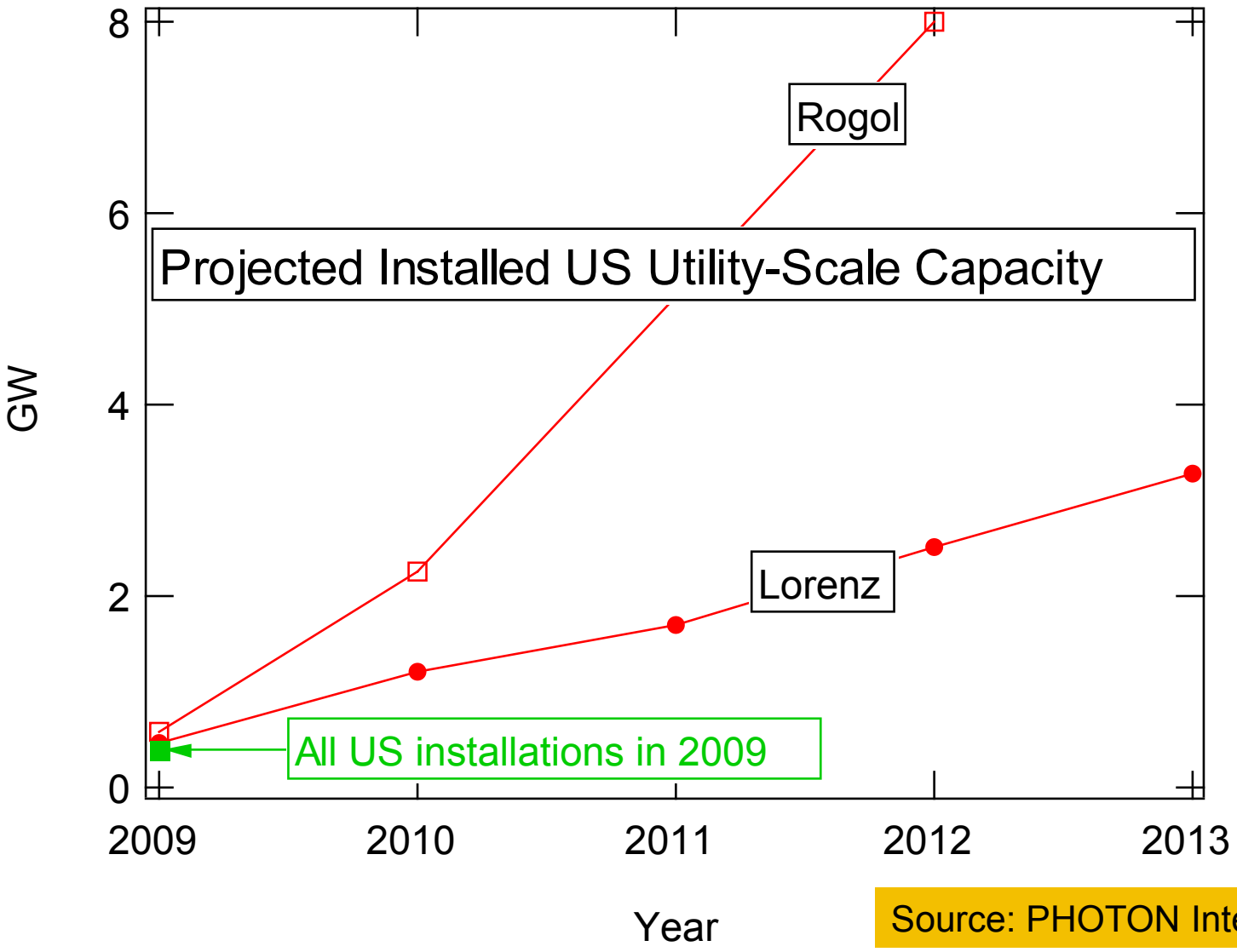


Recently PV has seen increases in:

- Maximum system size
- Average system size
- Ground mount (instead of roof mount)
- Connection at transmission instead of at distribution voltages
- Utility ownership

These changes may affect the technology mix

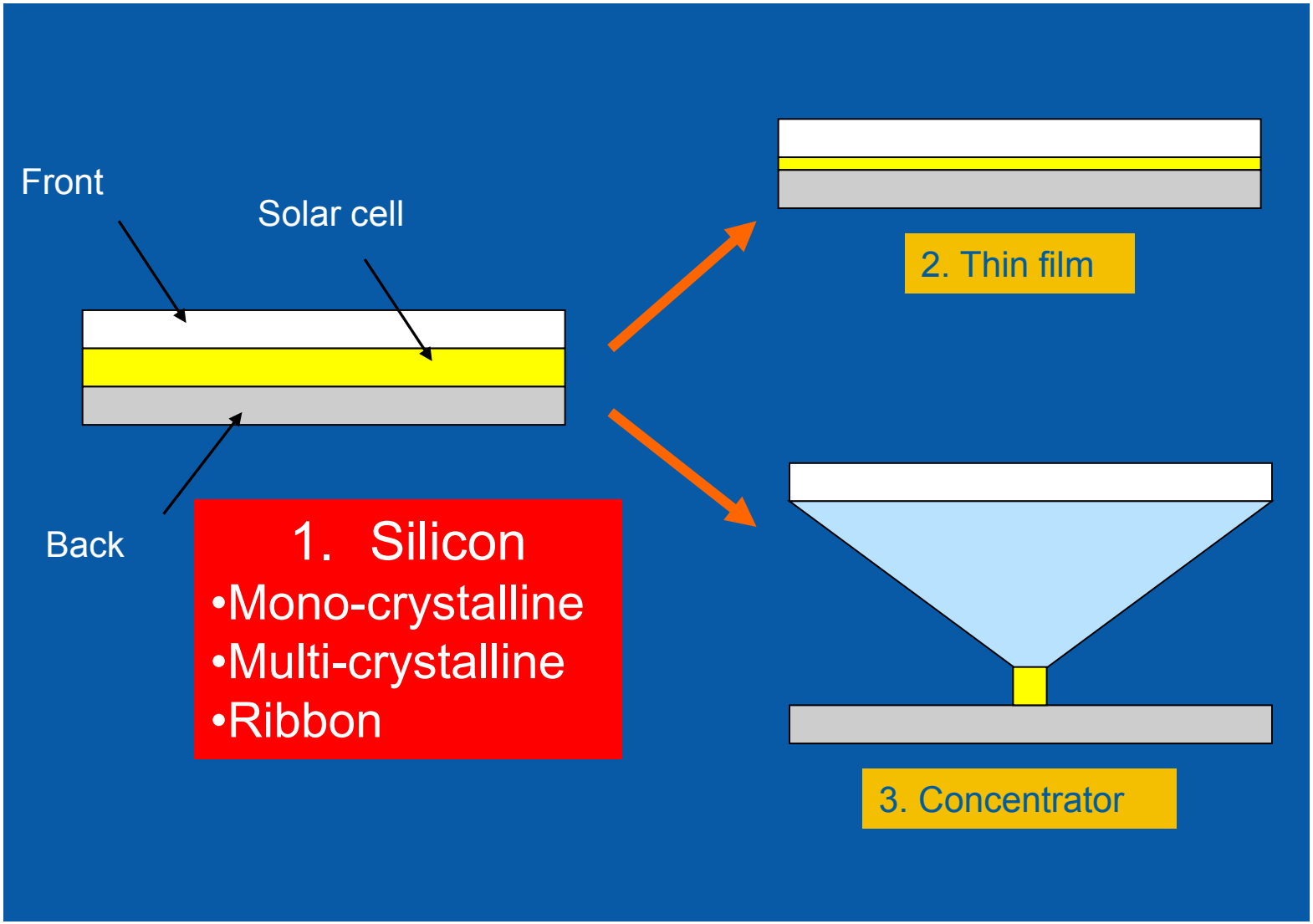
Within US, predictions are for large utility growth



Source: PHOTON International

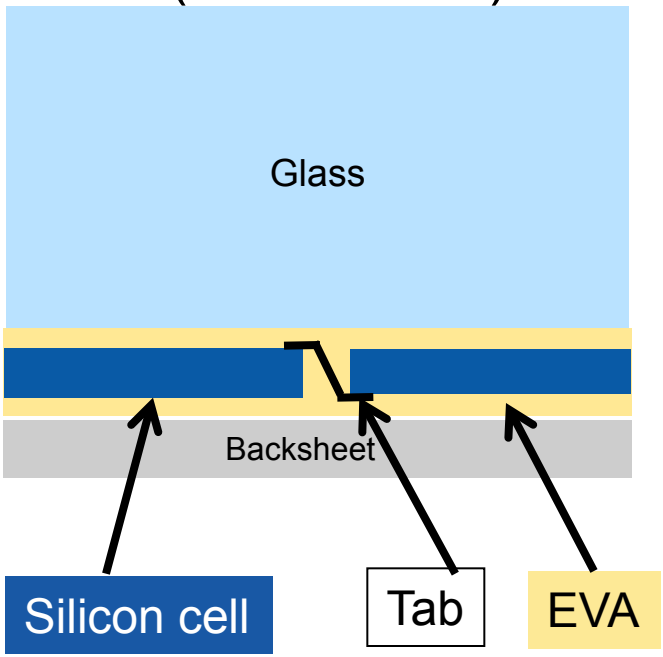
If utility growth is this large, it will change the technology mix

Three approaches to PV – 1. Silicon



Silicon modules

Si module cross section
(not to scale)

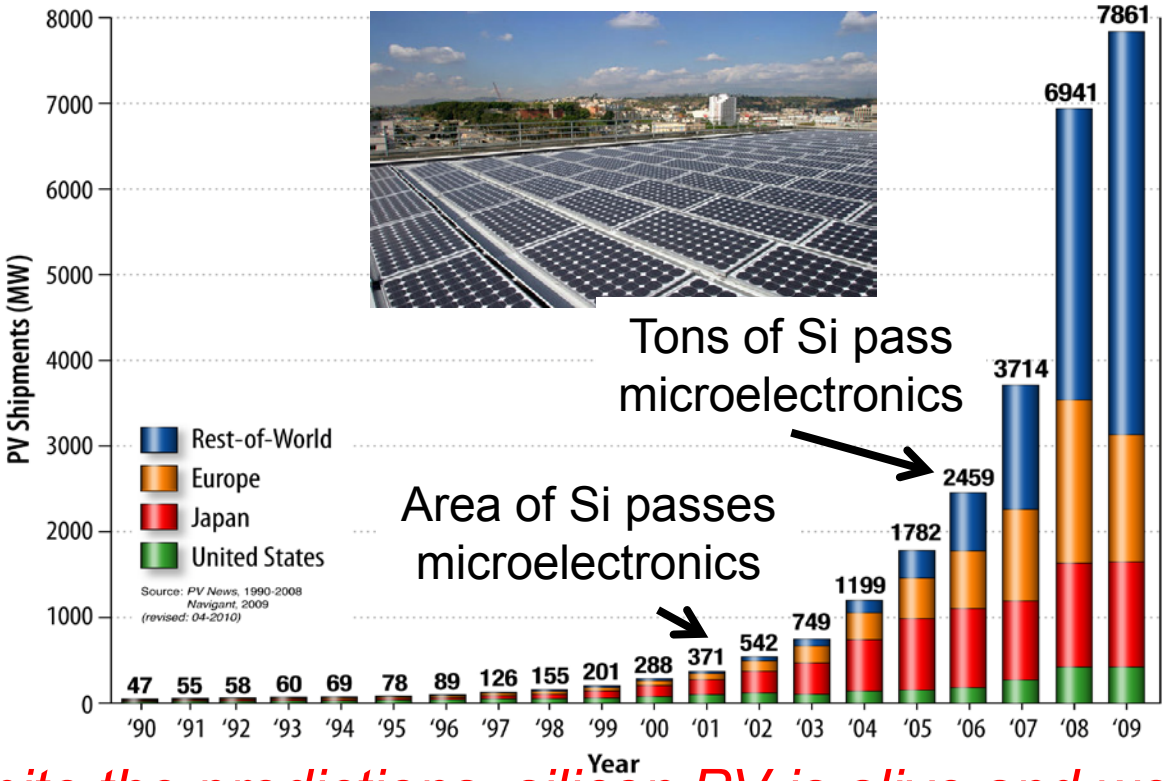


Common packaging materials
EVA - Ethylene vinyl acetate
PET - Polyethylene terephthalate
PVF - Poly vinyl fluoride
ETFE – Ethylene tetrafluoroethylene

Construction of silicon modules is simple in concept

Crystalline Silicon - history

- Predictions of the demise of silicon PV have been voiced for decades:
  - Silicon cells must be fairly thick, increasing material cost
  - Shortage of silicon feedstock – in 2007, 2008 we saw this (fast-growing industries tend to develop shortages)



Despite the predictions, silicon PV is alive and well

Crystalline silicon

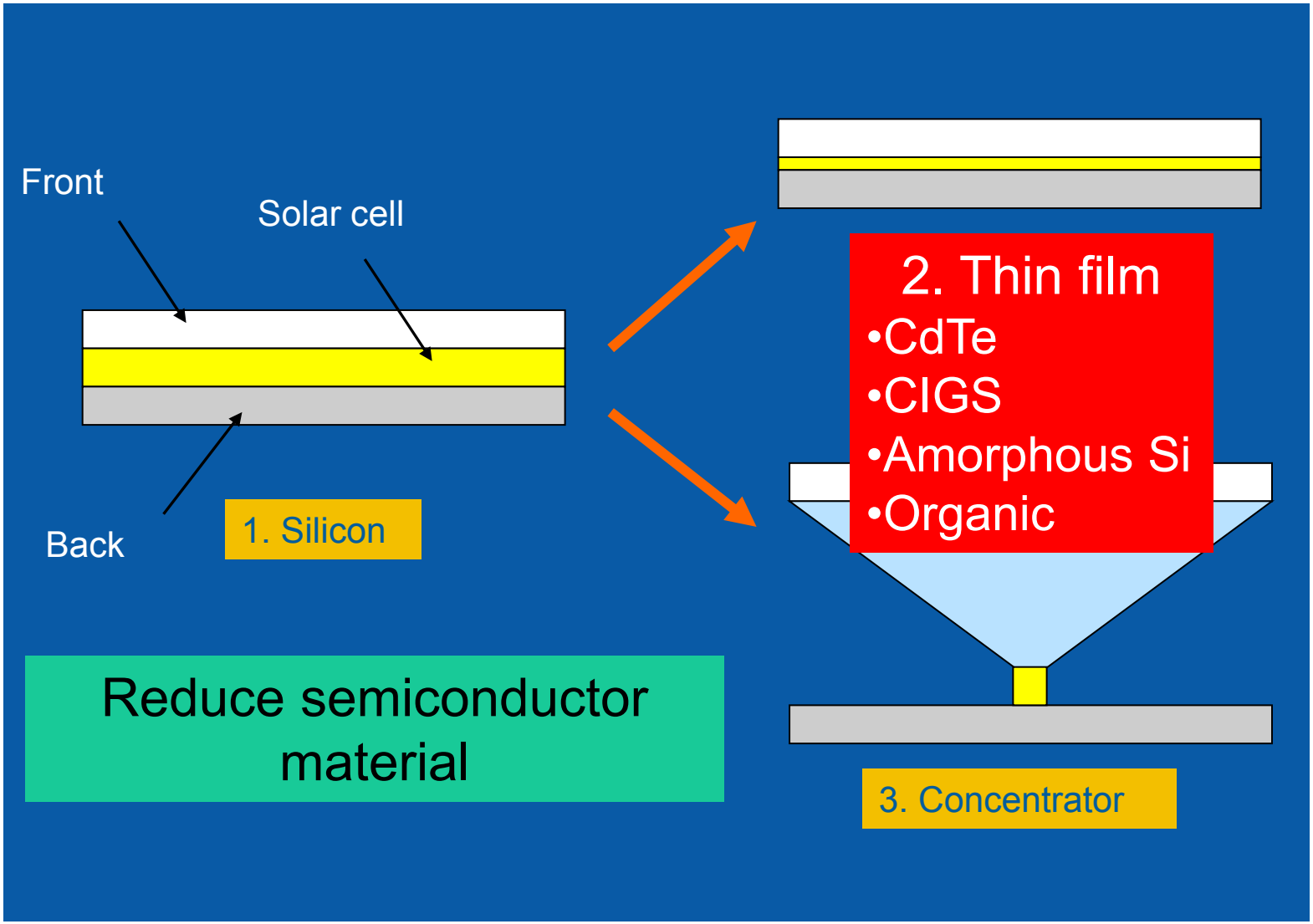
Advantages:

- Builds on strong industry
- Silicon is abundant and non toxic
- Efficiencies of 15%-20% are achievable
- Demonstrated > 20 years performance in field
- Warranties typically < 1% degradation/y
- Potential for further cost reduction

Disadvantages:

- Costs are higher than desired

Three approaches to PV – 2. Thin film



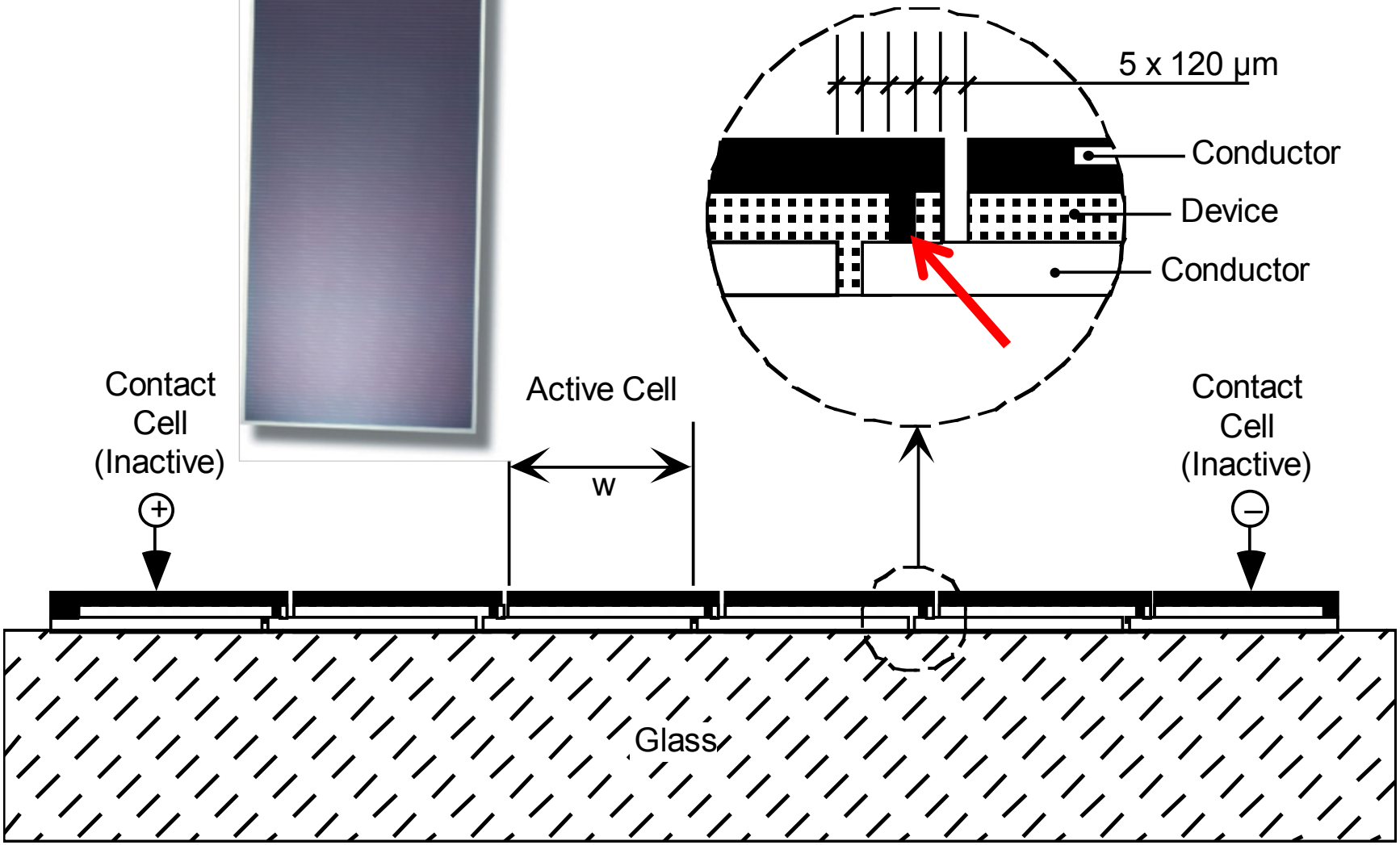
Thin-film approaches on the market

CuIn(Ga)Se

CdTe

Amorphous silicon

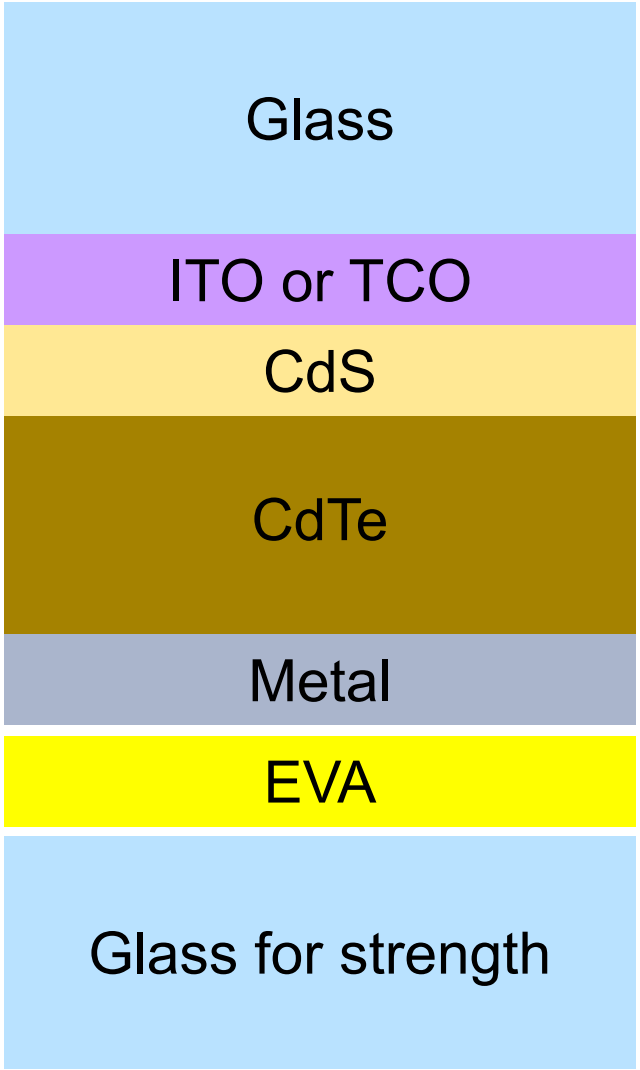
Monolithic module integration



Thin-film modules have a different construction than Si modules

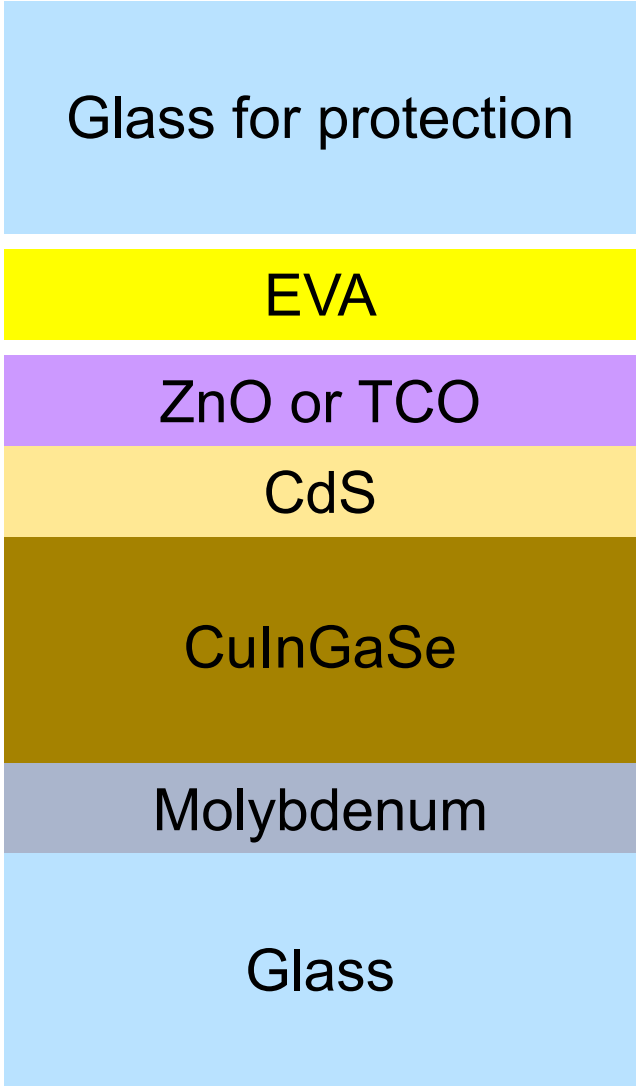
Thin film products vary in their construction

CdTe uses superstrate



Not to scale

CuInGaSe uses substrate



Is glass/glass construction required?

- Moisture sensitive?
  - No: use ETFE or ?
  - Yes: use glass/glass construction with edge seal
- Strategies:
  - Reduce moisture sensitivity (change cell design)
  - Develop flexible moisture barrier

- If successful, opens many markets:
  - Awnings
  - Shingles
  - Car roofs, etc.

If moisture problem is solved, flexible packages can open new markets

Thin film vision – looking to the future

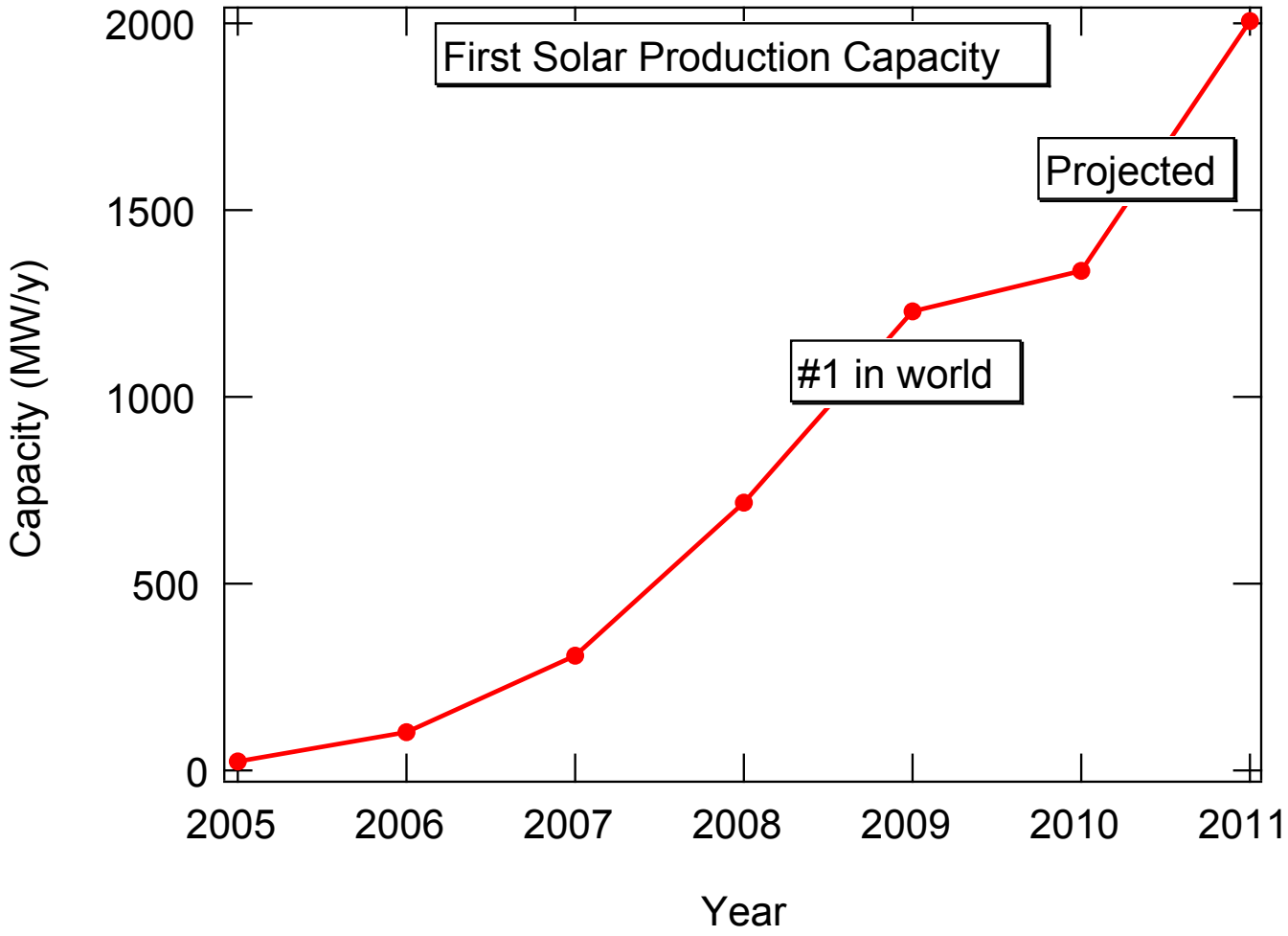
Vision (advantages)

- ~1-µm-thick film on inexpensive substrate
- Materials requirement is small: reduced cost
- Organic PV Vision: a PV plastic wrap
- Dye-sensitized Vision: PV spray-on paint
- Low CapEx enables easy ramp up
- Can be integrated into building façade

Challenges (disadvantages)

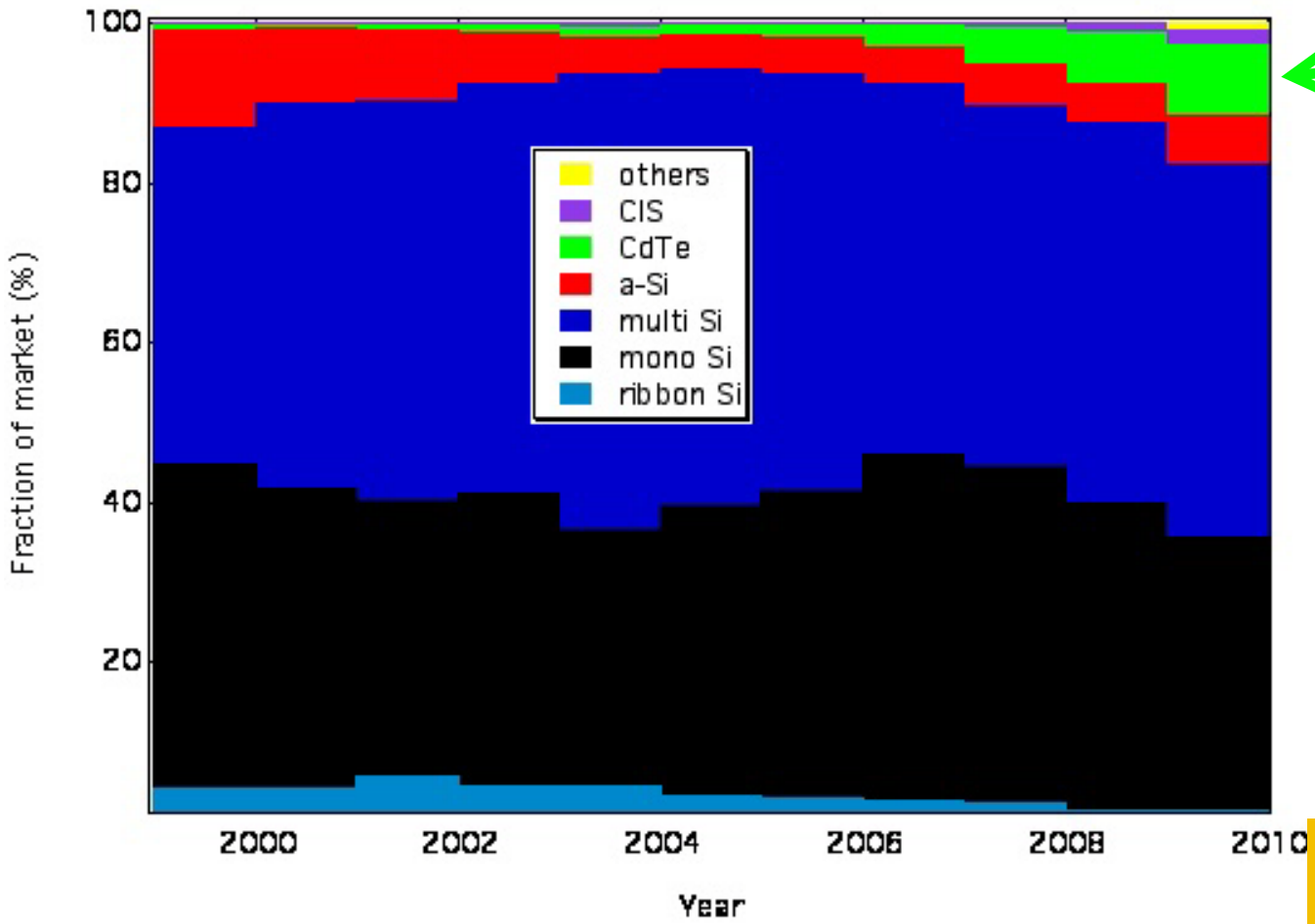
- Growth on inexpensive substrates limits efficiency
- Sensitivity to moisture leads to glass/glass laminate
- Infrastructure is not as well developed as for silicon
- Building integration increases operating temperature

First Solar demonstrated thin-film concept



First Solar grew to be #1 in world in just four years, demonstrating the benefit of using less semiconductor material

Historic PV Technology Mix



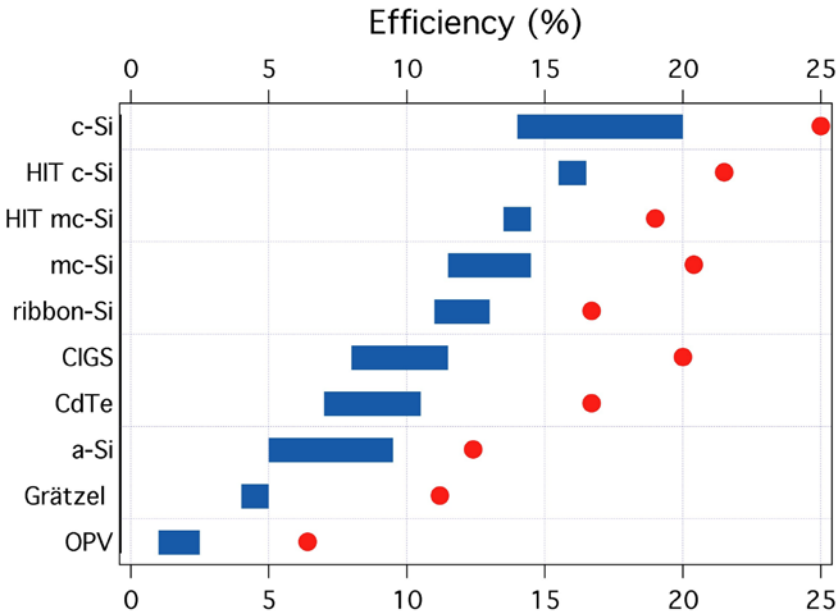
First Solar

Source: PHOTON International

- First Solar has put CdTe on the map
- Dozens of other thin-film companies hope to be the next “First Solar”

Comparison of efficiencies

Flat Panel PV Modules & Cells



From Citigroup Global Markets, equity research, Applied Materials, Inc, (AMT), 19 Feb. 2008

June 7, 2009 *34th IEEE PVSC, Philadelphia* 2

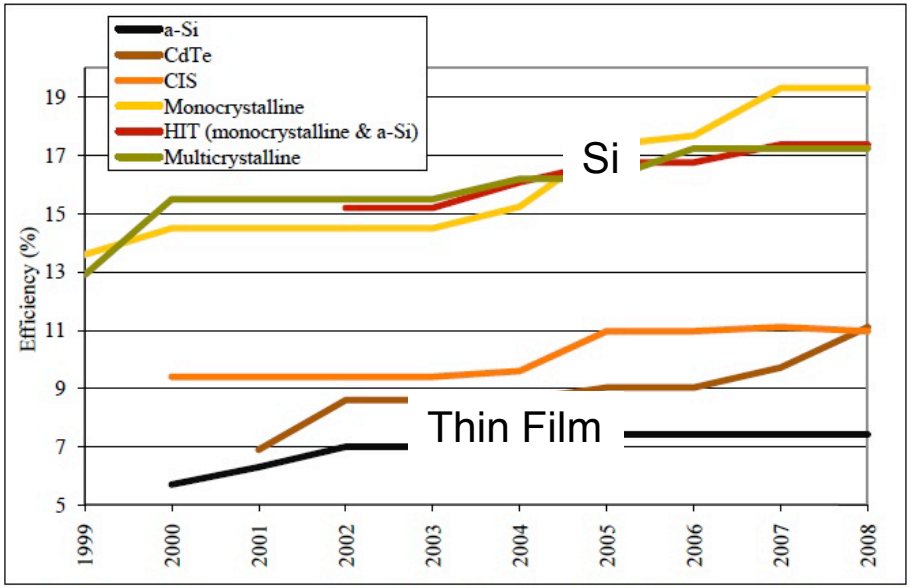
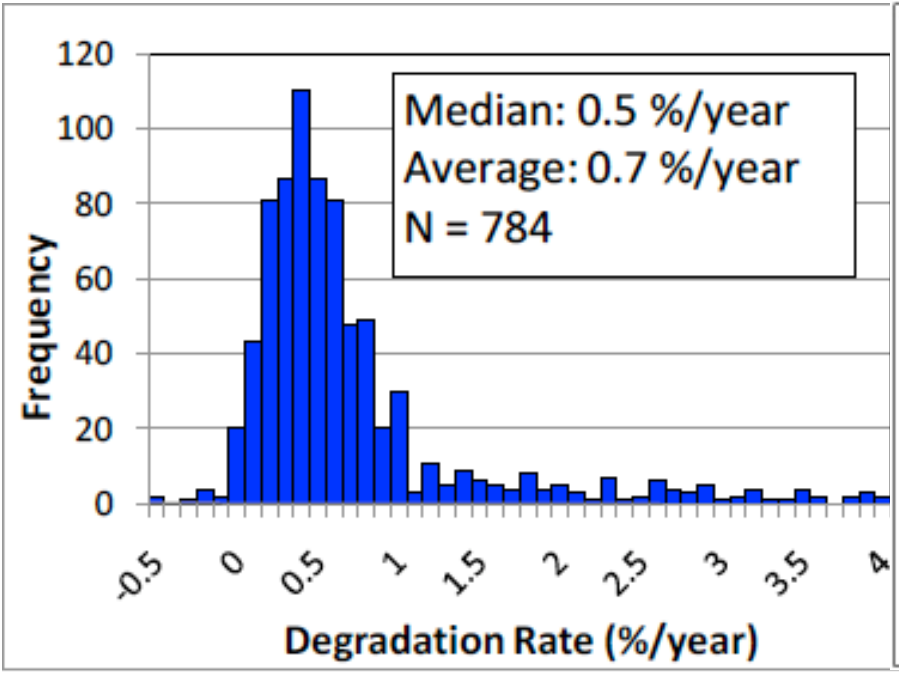


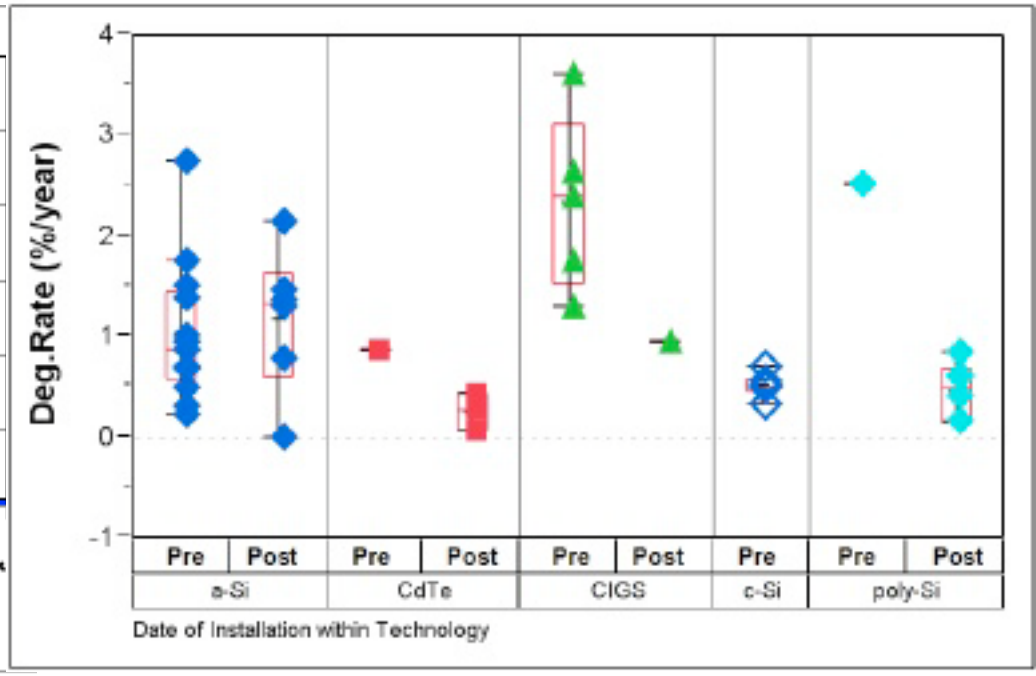
Figure 3.7. Best-in-class commercial module efficiencies, 1999–2008, compiled from modul survey data (Kreutzmann 2008, *Photon International* 1999–2008)

Source: DOE EERE 2008 Solar Technologies Market Report

In general, silicon outperforms thin film in terms of efficiency

Comparison of degradation rates



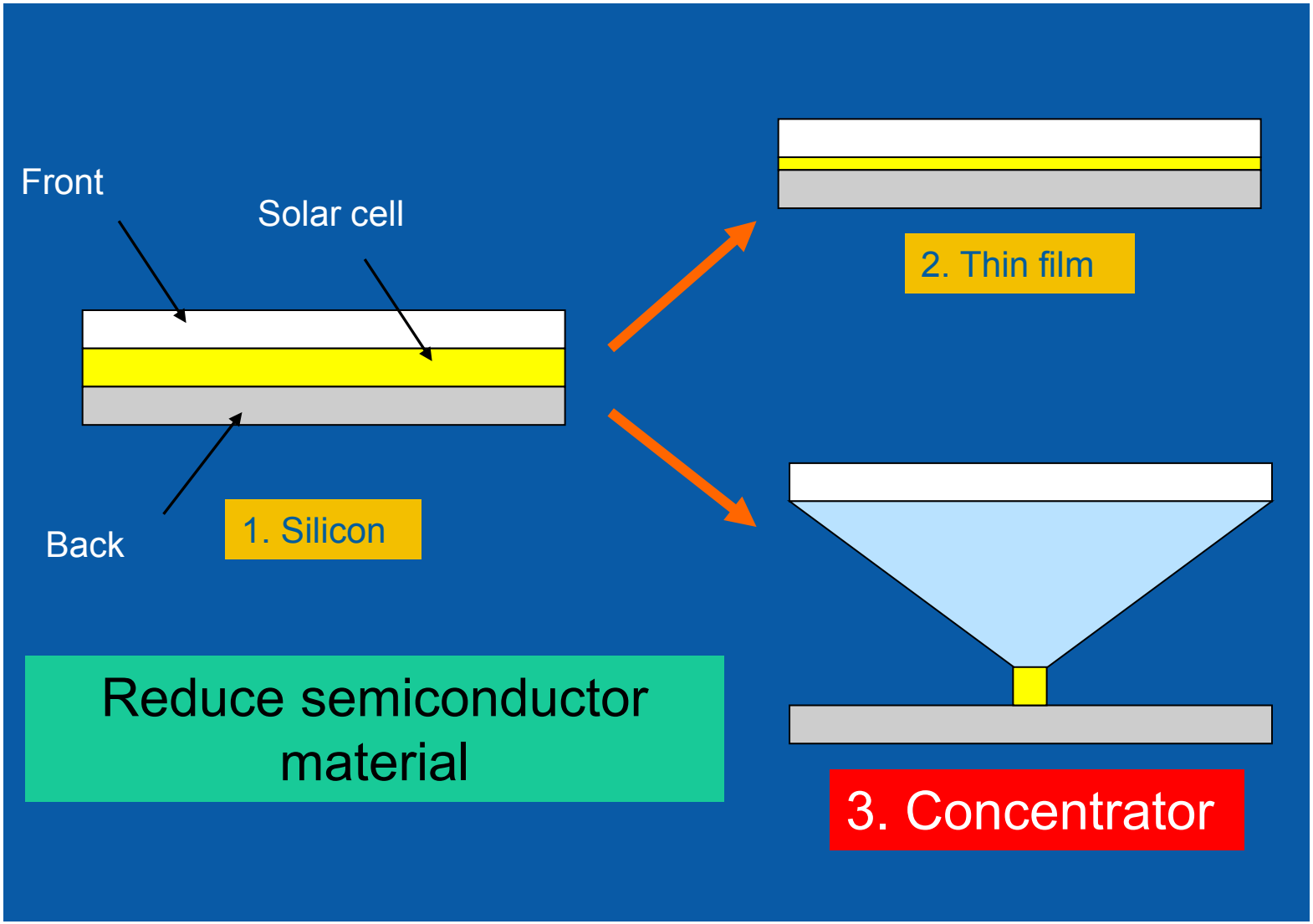


Statistically, observed degradation rates are about 0.5%/y

Degradation rates of recent thin-film products are smaller than for pre-2000 products

Source: Jordan, et al. PVSC 2010

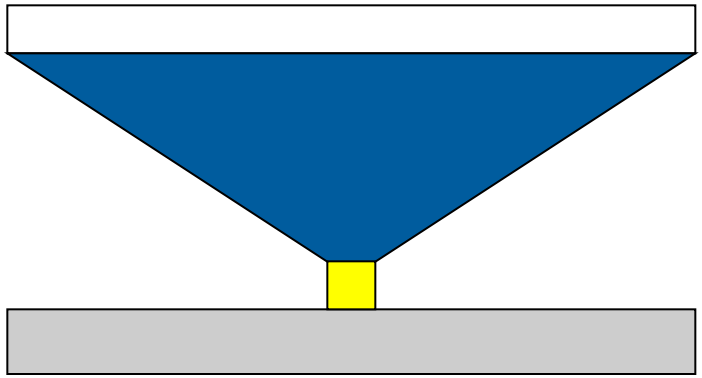
Three approaches to PV

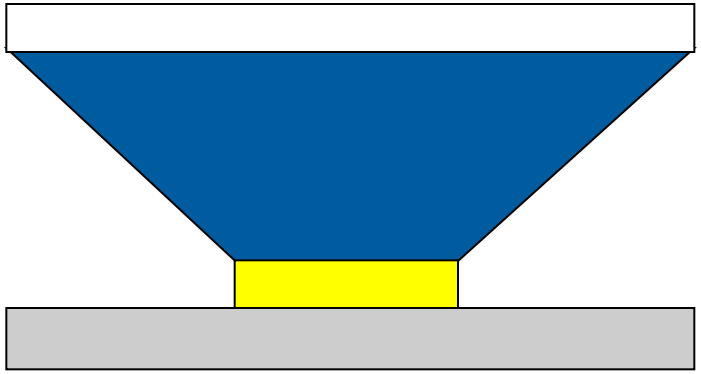


Two primary concentrator approaches

Amonix

JX Crystals





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

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

Concentrator technology

Maturity is similar to that of airplanes 100 years ago

CPV

Advantages:

- CapEx is typically smaller than for silicon
- Reduces use of semiconductor material, potentially enabling low cost
- Allows use of very high efficiency solar cells
- Module efficiency up to ~ **30%** (verified)
- Is mostly an engineering project

Disadvantages:

- Only uses direct beam (no output on cloudy days)
- Not yet well established
- Difficult to integrate into buildings (was rejected in ‘90s)

CPV

Current status

- Dozens of companies exploring CPV
- A handful of companies are setting up automated production
- These companies are likely to each install > 1 MW in 2010
- Amonix just announced 30 MW project in Colorado
- Once bugs are worked out, could ramp quickly
- Not yet clear whether applications will be limited to utility-scale

Future of PV

- Today's technologies have lots of room for improvement – this is the near future of PV
- Other concepts have been studied for decades – need breakthrough:

  - Intermediate band

  - Multiple exciton

  - Hot carrier

Sorting the hype from reality

Questions to ask:

- What efficiency has been achieved? (Most concepts have high theoretical efficiencies but ‘real’ technologies present achieved efficiencies rather than theoretical)
- If high efficiencies are reported, are these for small/large cell/module?
- If high efficiencies have not been achieved, how much will it cost to install, etc?

‘Breakthrough’ or ‘Revolution through Evolution’?

Two camps predicting future of PV:

- Need revolutionary breakthrough
- Achieve revolution through evolution

PV cost is already competitive for peaking power in locations with high electricity prices (Hawaii, California, etc.)

What fraction of penetration is achievable?

Today’s technologies will contribute several % to energy supply
Will we need a breakthrough to achieve tens of %?

Which technology for which application?

Efficiency: important for area-constrained applications

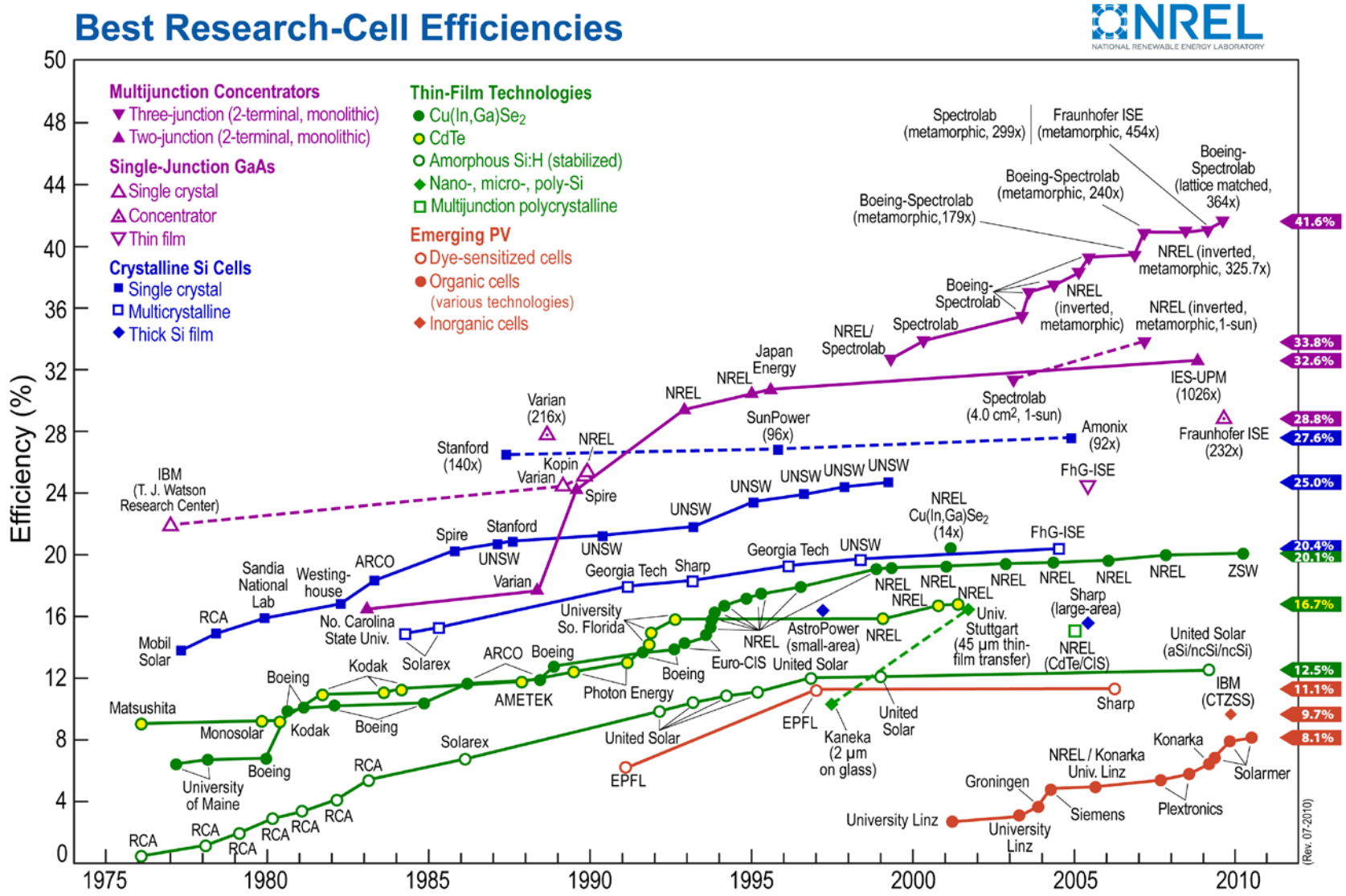
Form factor: e.g. building integrated vs conventional racks

Weather: direct/diffuse; temperature; wind; stresses

Tracking: affects energy yield, packing density, dual use of land

Many factors contribute to deciding which technology is best

Efficiency is key driver



Temperature coefficients affect output

Estimated temperature coefficients

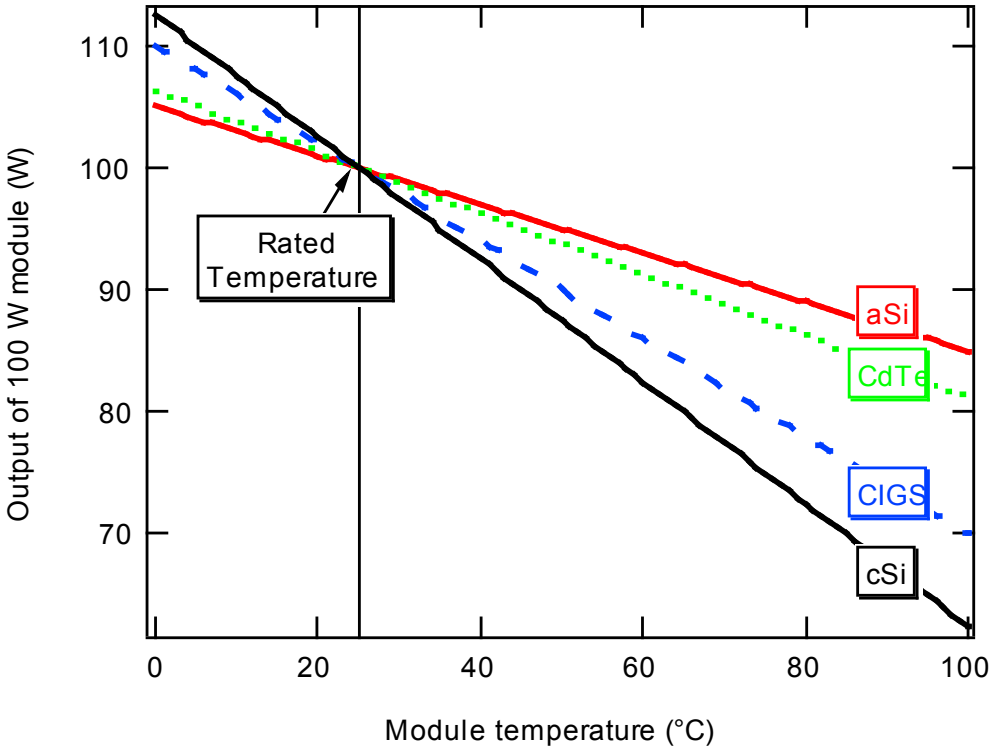
Amorphous silicon: -0.2%/°C (variable)

CdTe: -0.2 to -0.25%/°C

CIGS (CIS): -0.4%/°C

Crystalline silicon: -0.4% to -0.5%/°C

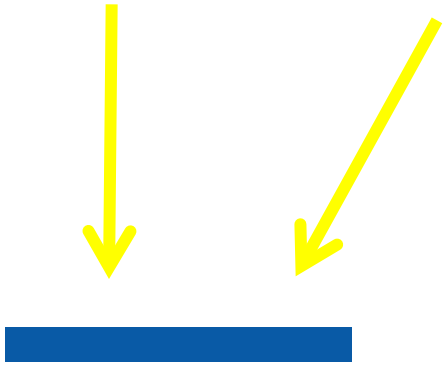
If the temperature varies by 30°C, these translate to relative change in performance of ~6% to 15%



Temperature coefficient can affect the choice of product in a small (~10%) way

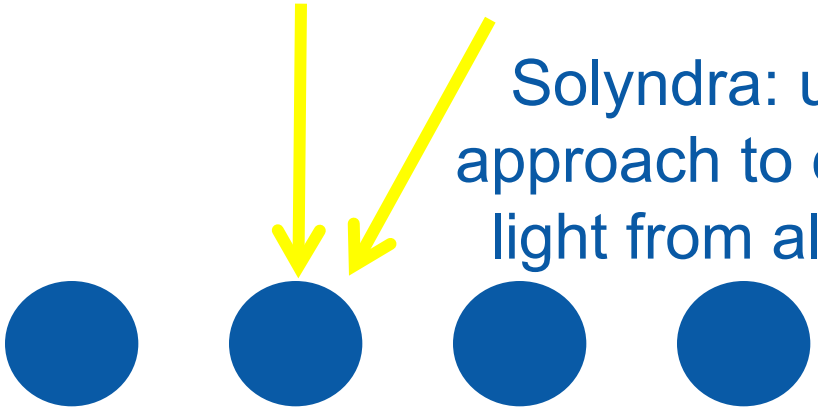
Note: many of the thin-film products show changes in efficiency

Off-axis and diffuse light



Fixed module receives light at variable angle

Tracked module follows angle of sun; especially useful late in the day



Solyndra: unusual approach to collecting light from all angles

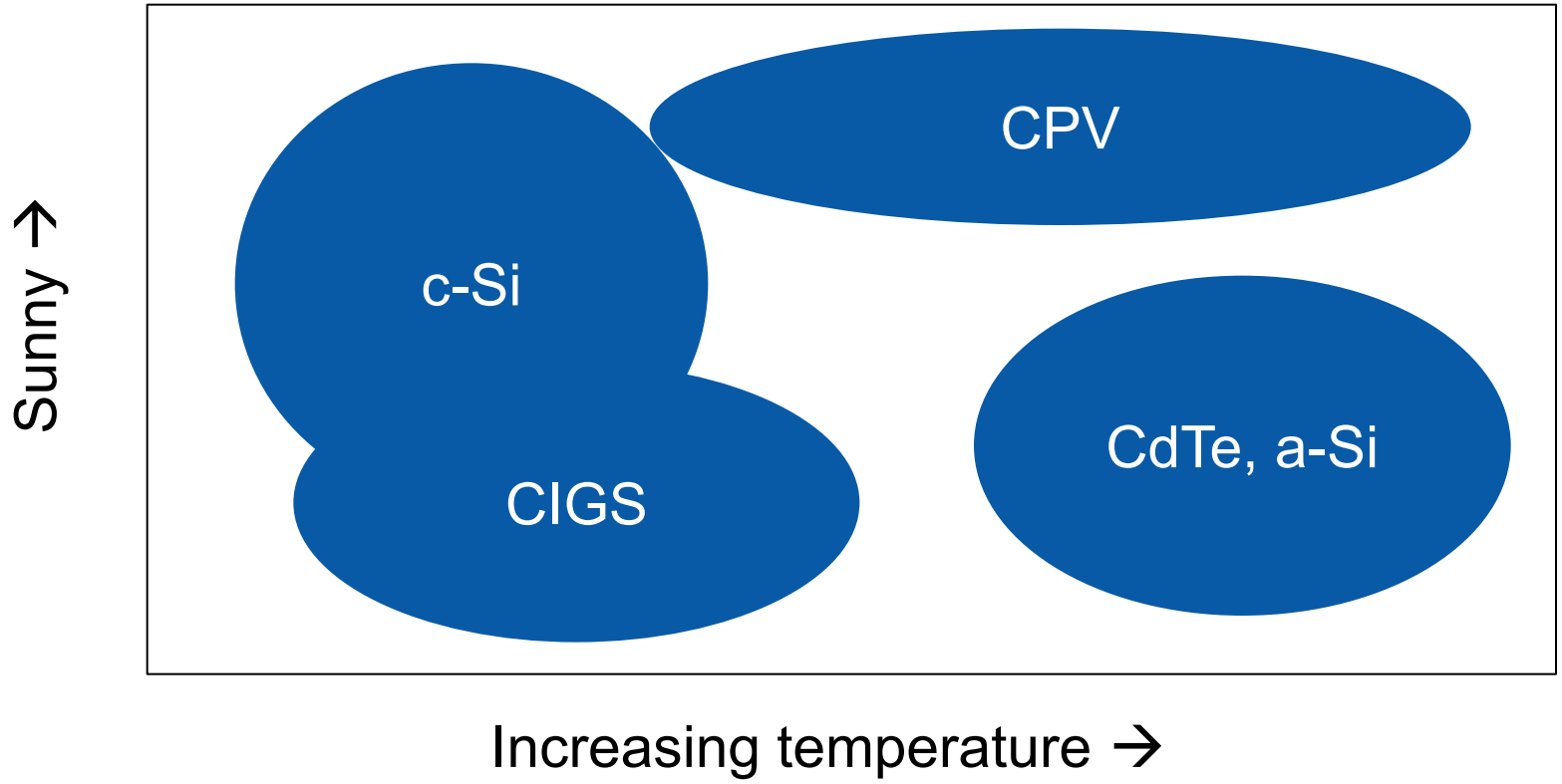
Tracking has > 20% effect; off-axis collection effect is smaller

To frame or not to frame

- Frames are useful to prevent damage to edges of modules
- Frames can provide mechanism for easy attachment
- Frames can collect dirt
- Frames may be damaged by snow and ice
- Framed modules may require ground wires

Differentiation of technologies

- Area constrained = higher efficiency
- Peak shaving = use tracking
- BIPV = consider aesthetics



Technologies may show up to 10% advantage under these conditions

Summary

- As the PV industry grows, the technology mix will be increasingly diverse
- Silicon, thin-film, and concentrator approaches are all making progress
- When choosing between these:
  - Cost is #1 driver
  - Higher efficiency technologies have edge in area-constrained applications
  - Form factor can drive building integration
  - Efficient conversion of diffuse light gives edge in cloudy/hazy regions
  - Tracking can help meet peak loads late in the day

Questions

1) With the recent flooding of the market with Chinese modules, what are the trends in materials or processes that we can look for in a module manufacturer that gives us a better idea of the durability and life of the product they are producing.

See Solar ABCs Recommendation to require qualification testing:

www.solarabcs.com/recommended_standards/Policy_recommondations_ABCS-12B_1page-1.pdf

Ask company about their quality assurance program (if modules are manually assembled, how do you know they're all the same?)

How have they assessed robustness to UV?