Practical Issues when Selecting PV Technologies

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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.

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

Outline

- Practical considerations: initial cost, efficiency, reliability
- Three primary approaches today
  - Silicon
  - Thin film
  - Concentrator
- Strategies for tomorrow
  - Breakthrough
  - Incremental reductions in cost and improved efficiency
  - Lifetime as a path to low cost

Three key practical issues

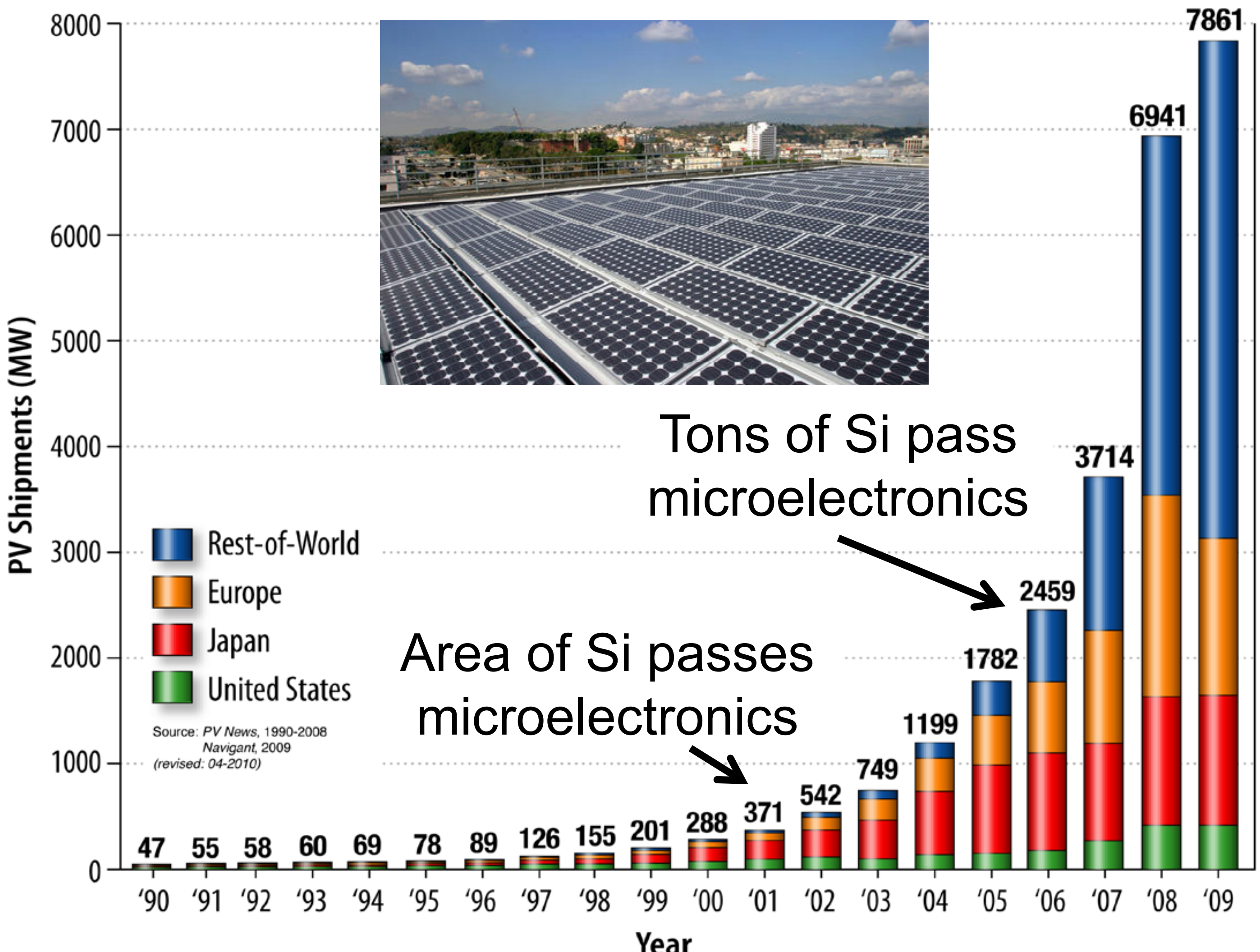
Initial Cost

Efficiency

Reliability

A little history

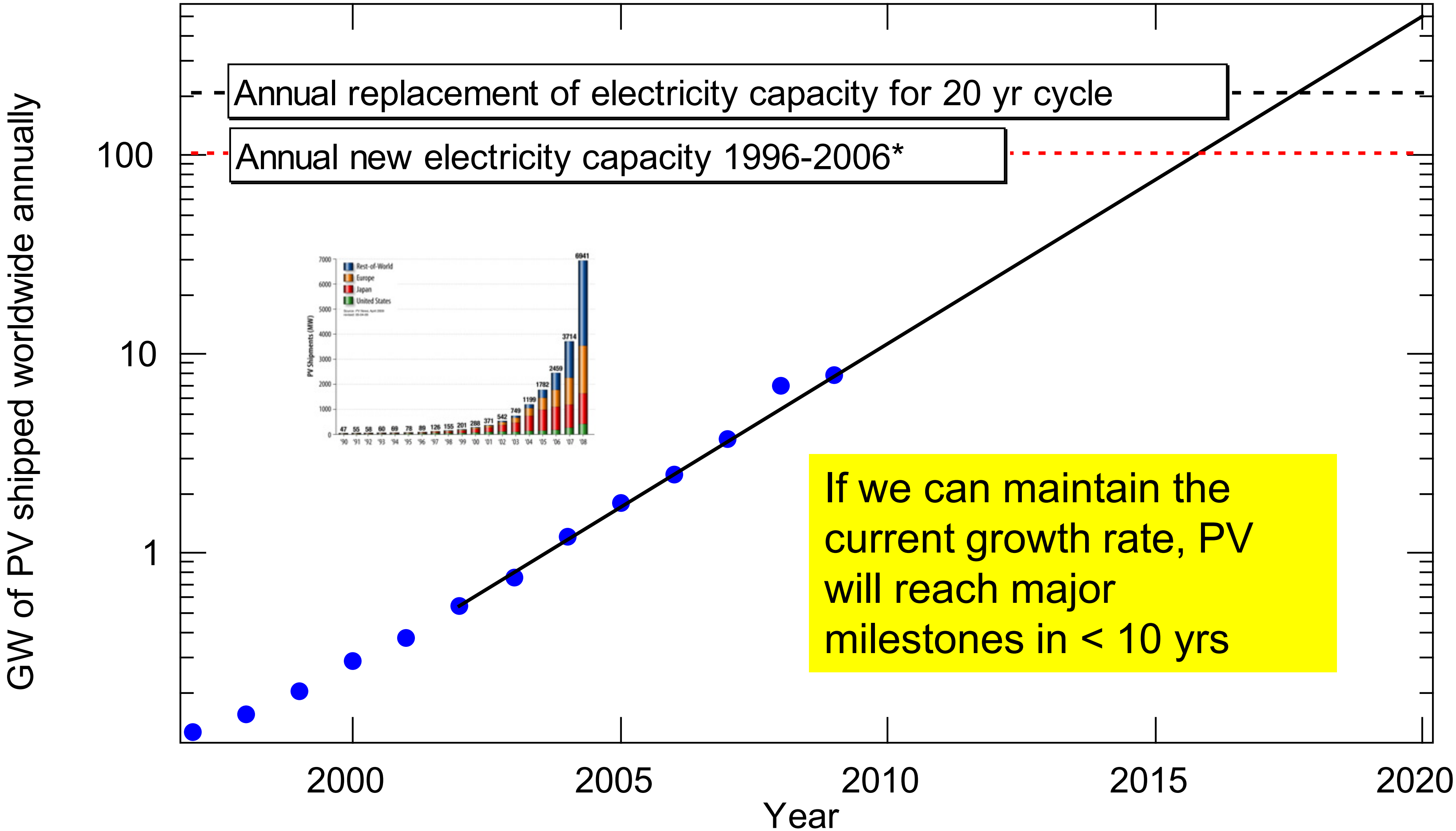
Growth of photovoltaic (PV) industry



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

Ways to look at cost

Market drivers (these motivate people, but depend on cost of money, incentives, etc.):

- Levelized cost of electricity (cents/kWh)
- Avoided cost

Practical ways to look at cost:

- Energy payback
- $ payback

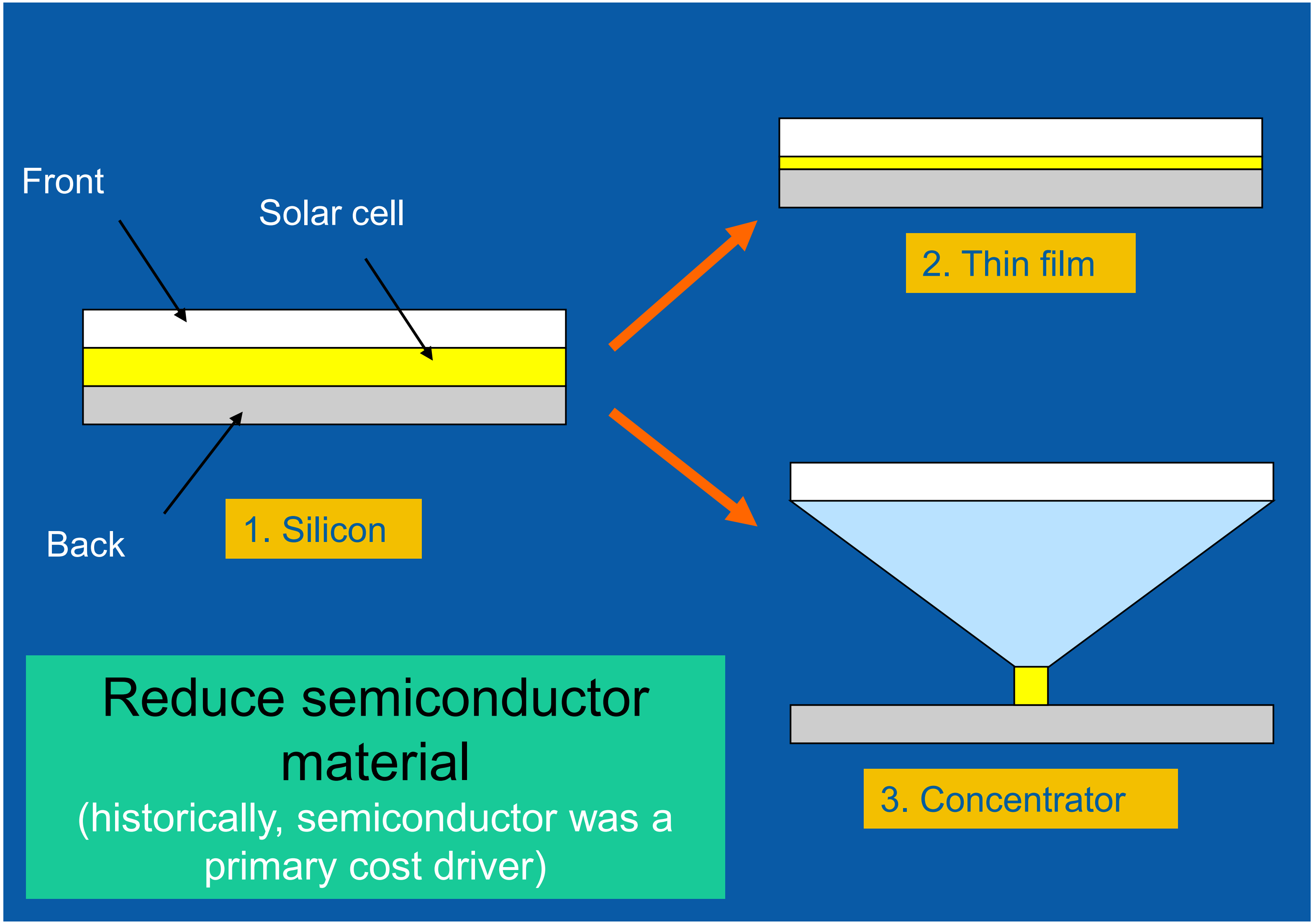
Rule of thumb: 1 kW can generate 1000-2000(+) kWh/y

(At 10 cents/kWh, value after 1 y is $100-200;

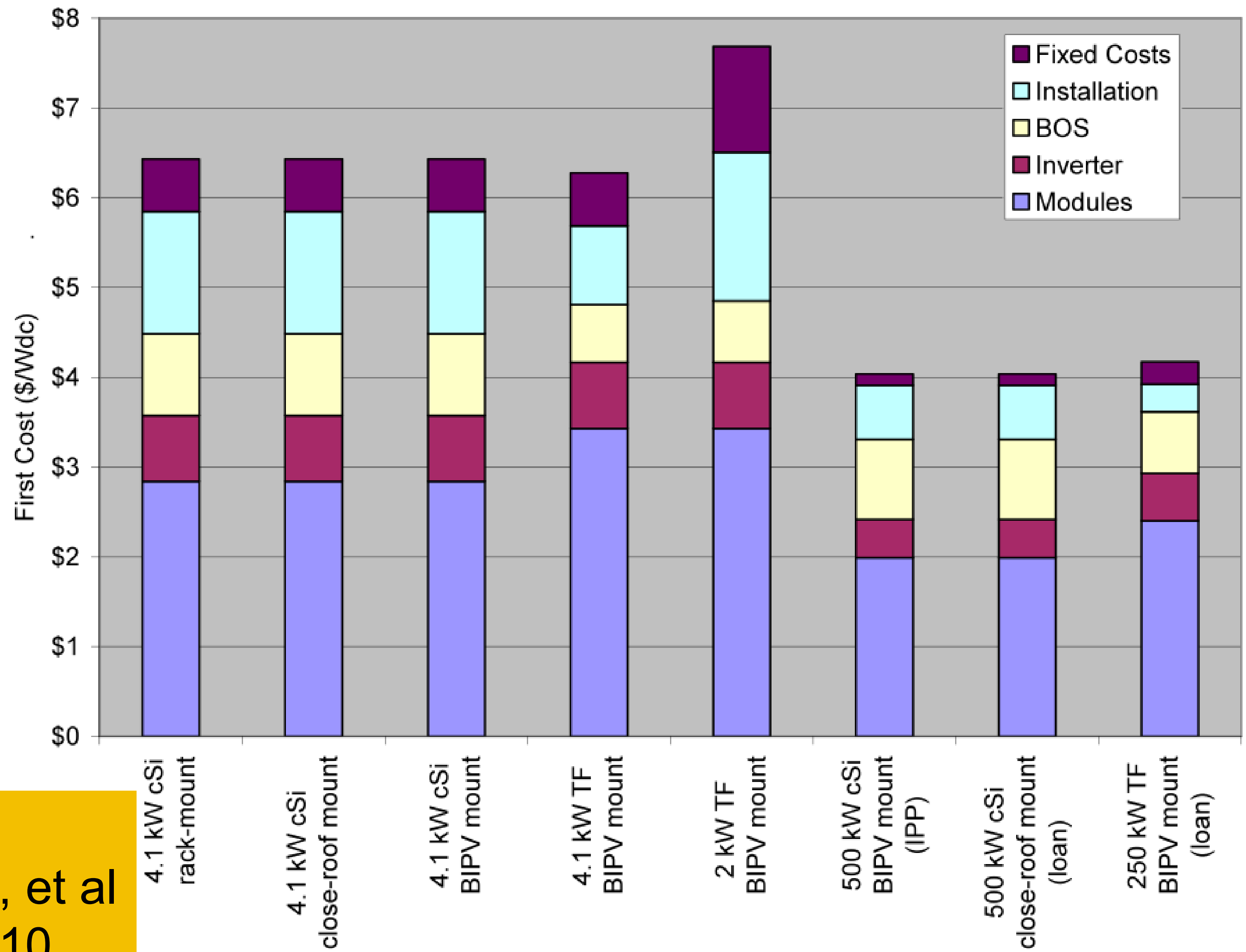
At 10% efficiency, 1 kW covers 10 sq m, so cost target is $10-$20/sq m if want payback in one year)

Note: average electricity price in US in 2009 was 9.7 cents/kWh (EIA)

Three approaches to PV (and lower cost)



Cost breakout – module cost is about half

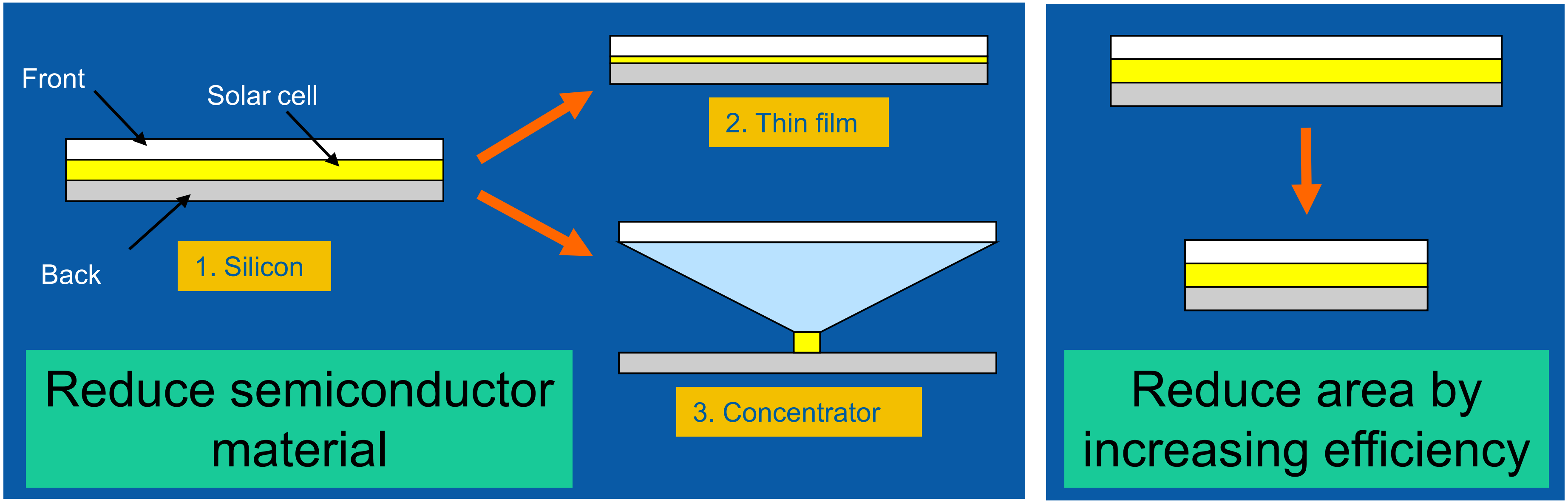


Source: Cameron, et al PVSC 2010

Higher efficiency can reduce cost

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

Two strategies for reducing cost:

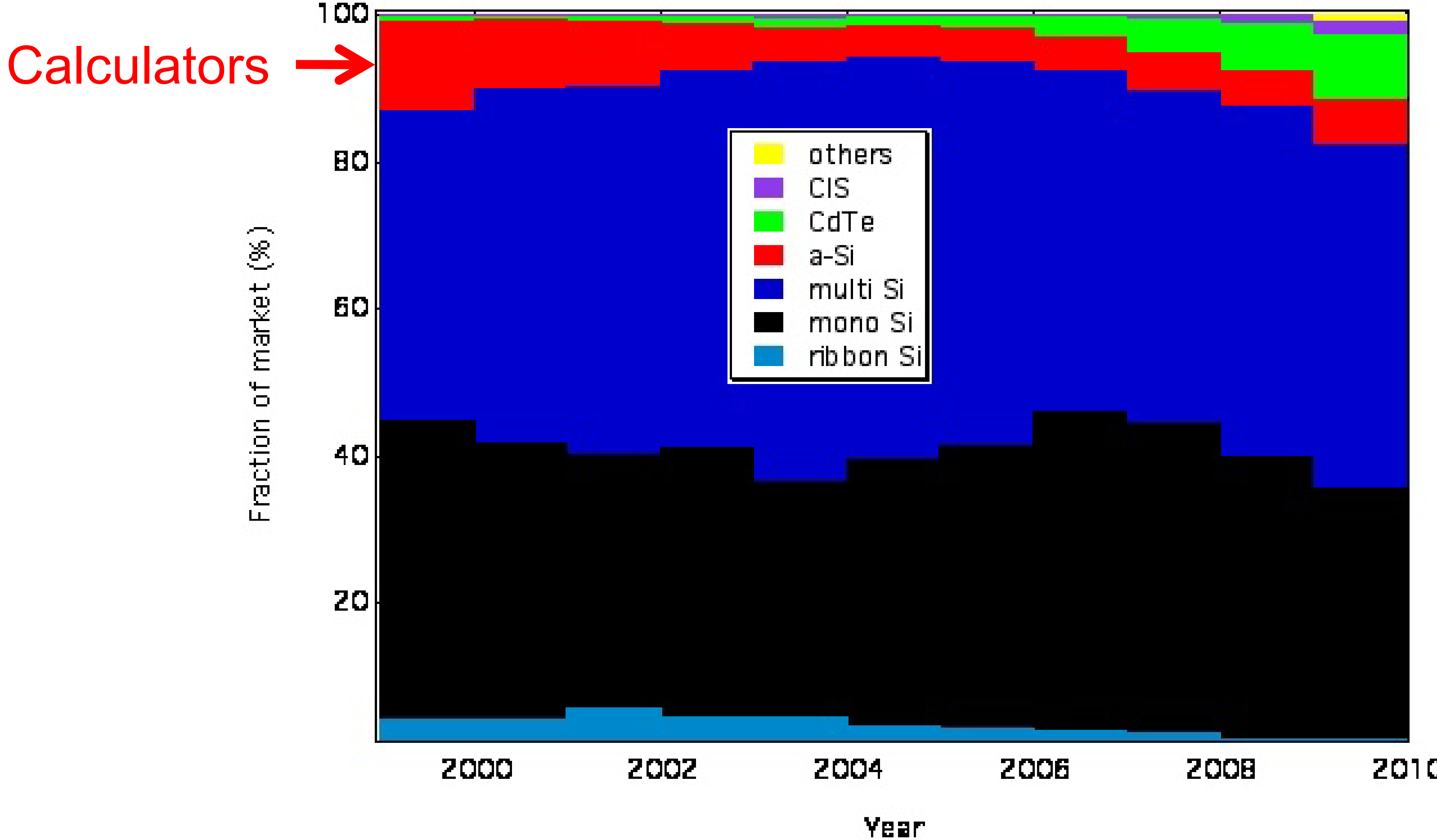


Increasing efficiency may be a key path to reduced cost

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

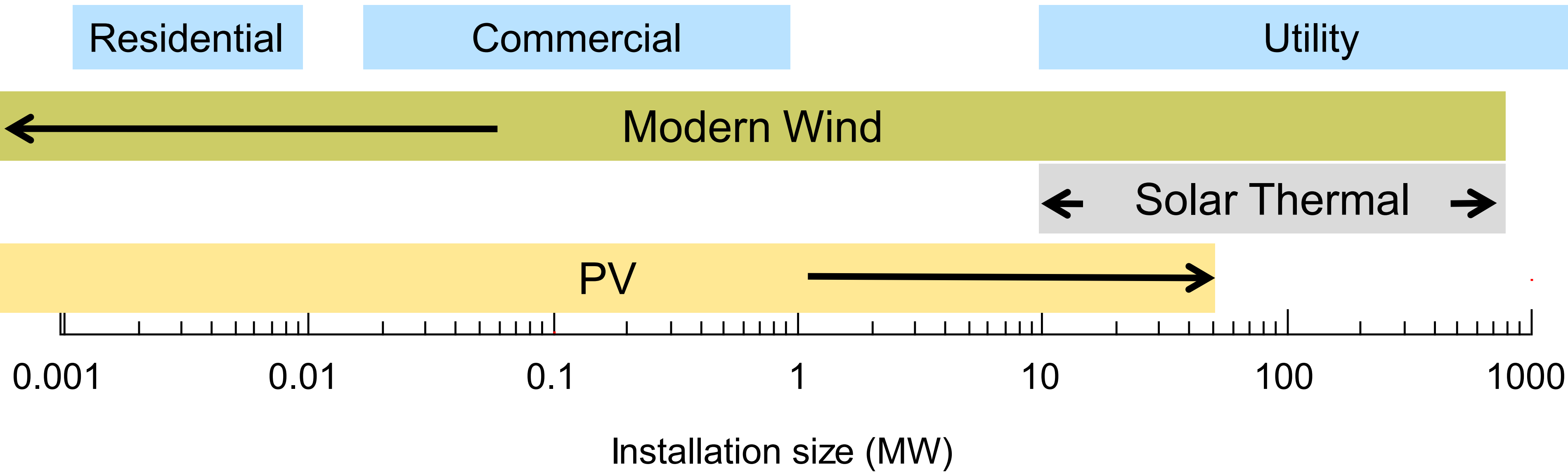
Historic PV Technology Mix

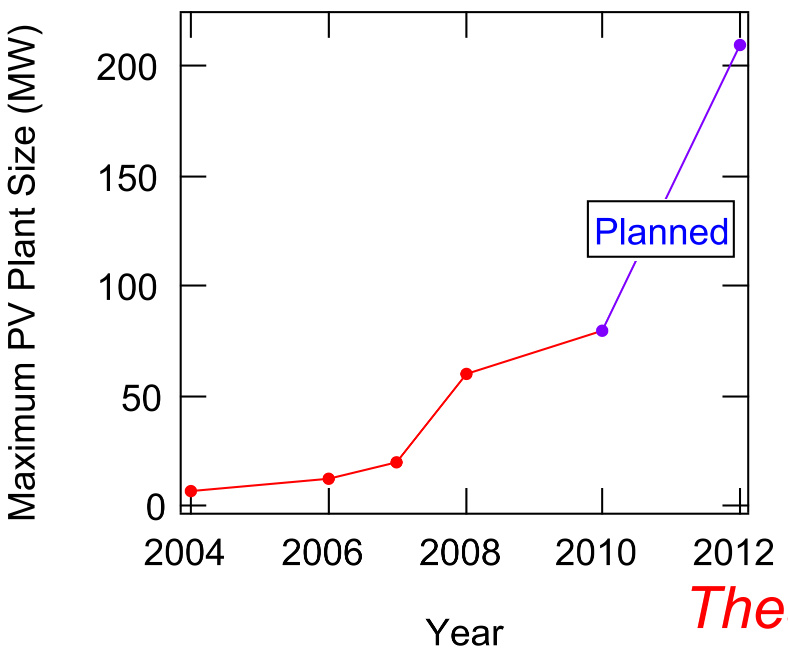


Source: PHOTON International

- Early markets were dominated by consumer electronics
- 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

A key factor affecting technology mix: Distributed vs Central



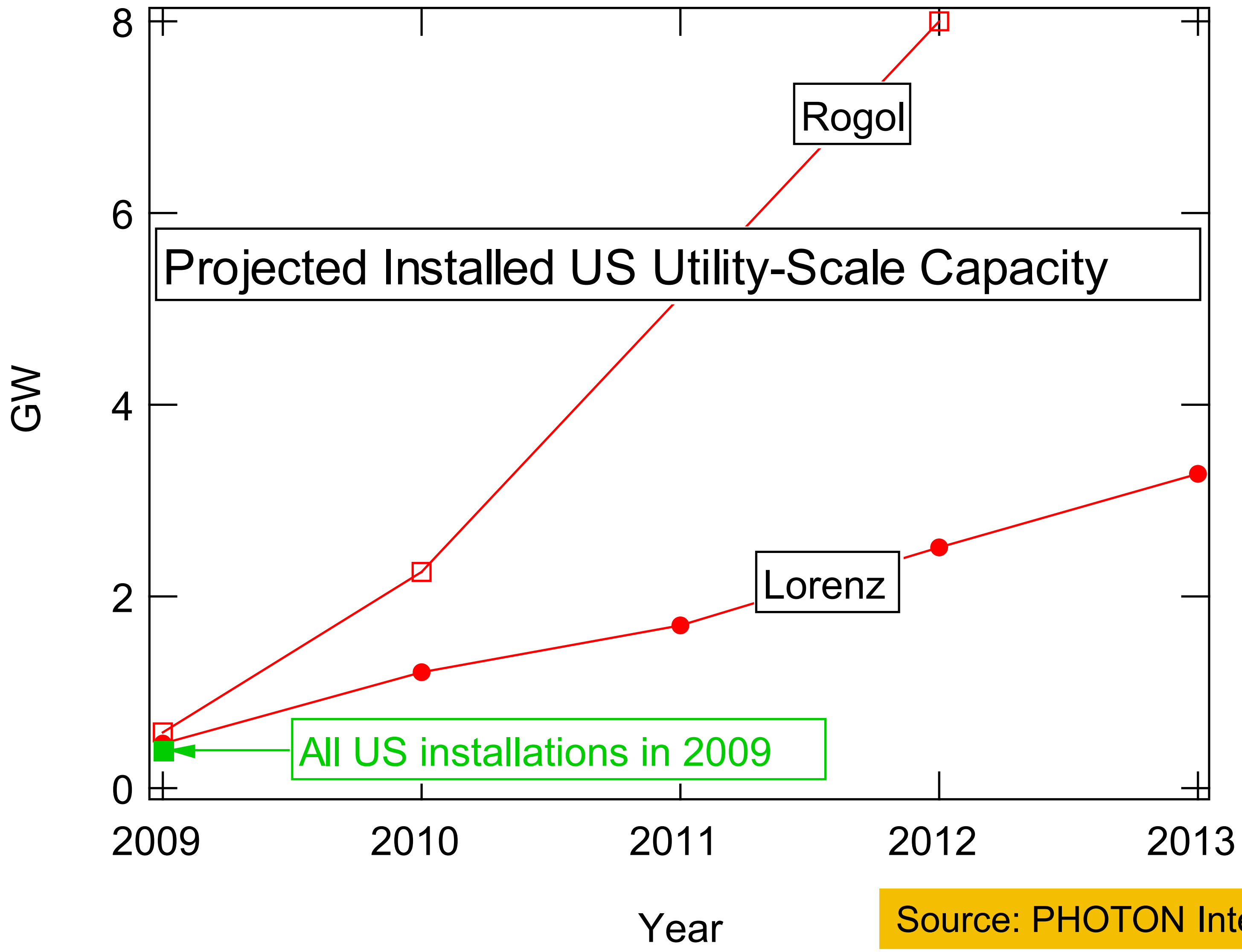


Recently PV has seen increases in:

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

These changes may affect the technology mix

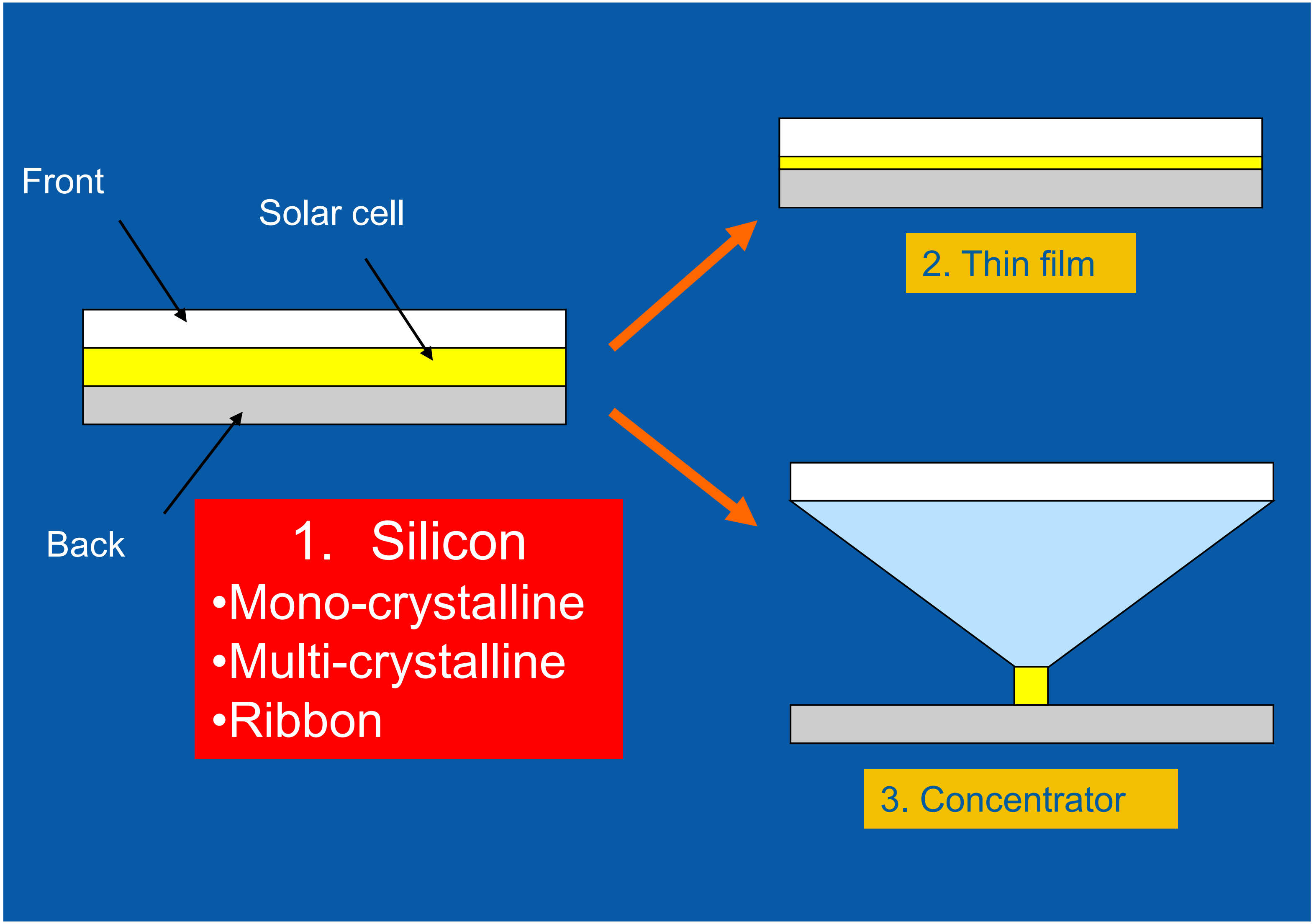
Within US, predictions are for large utility growth



Source: PHOTON International

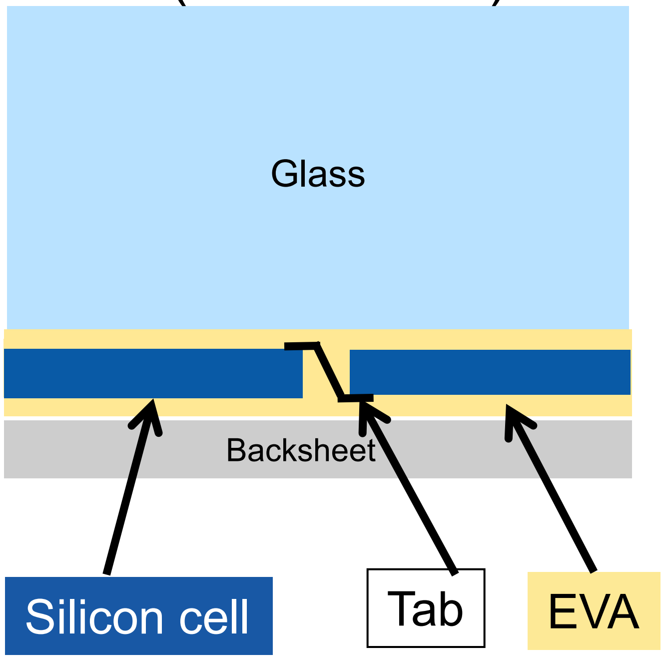
If utility growth is this large, it will change the technology mix

Three approaches to PV – 1. Silicon



Silicon modules

Si module cross section (not to scale)

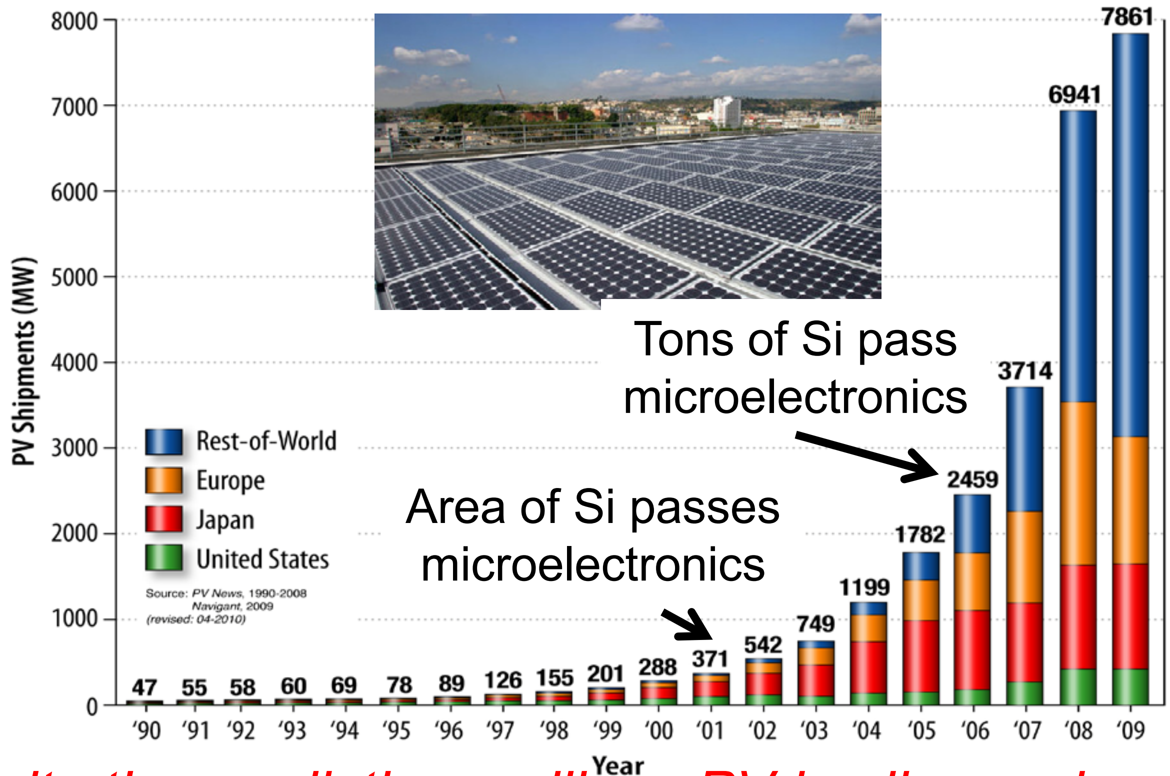


Common packaging materials
EVA - Ethylene vinyl acetate
PET - Polyethylene terephthalate
PVF - Poly vinyl fluoride
ETFE – Ethylene tetrafluoroethylene

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

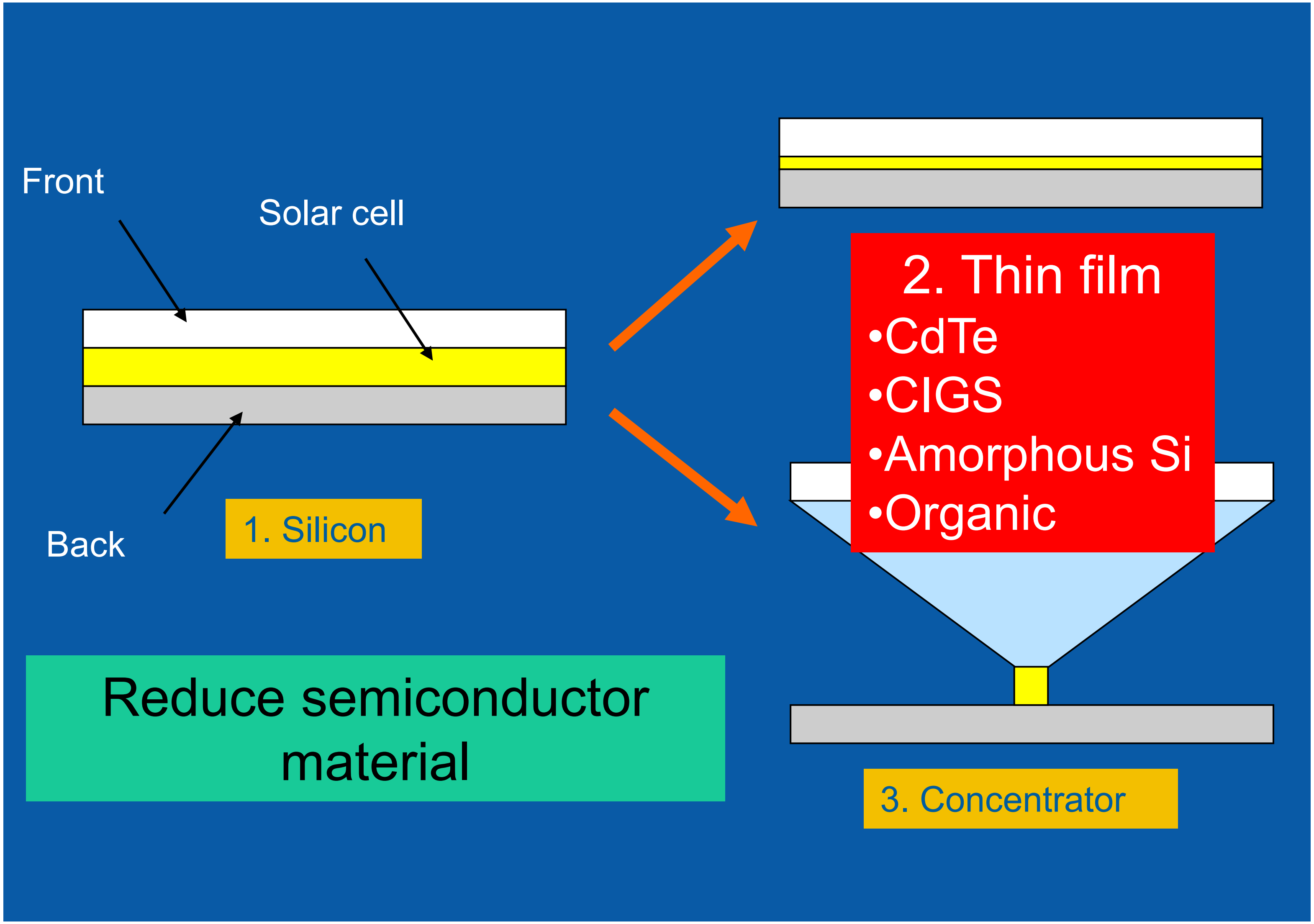
Advantages:

- 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



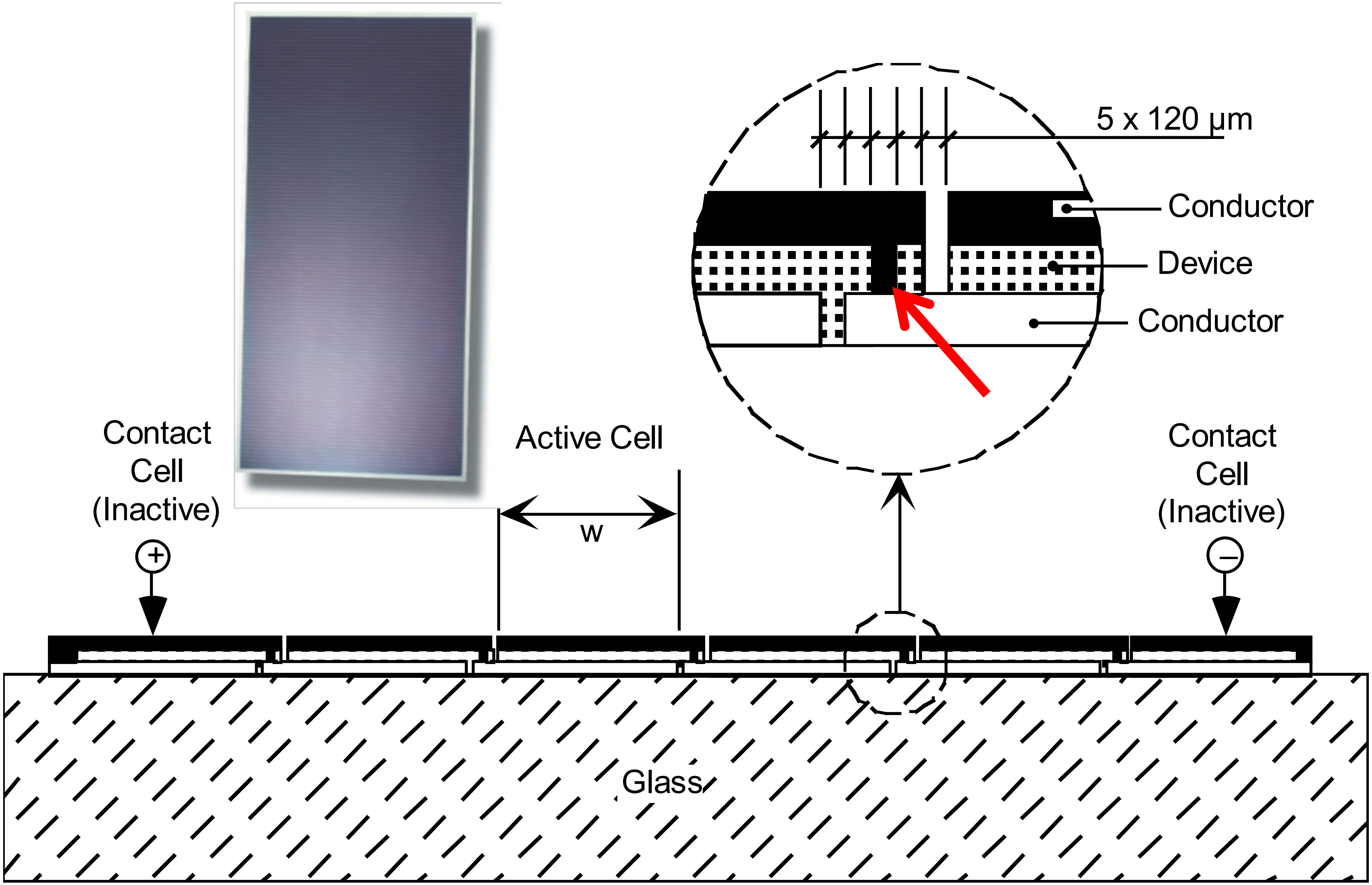
Thin-film approaches on the market

CuIn(Ga)Se

CdTe

Amorphous silicon

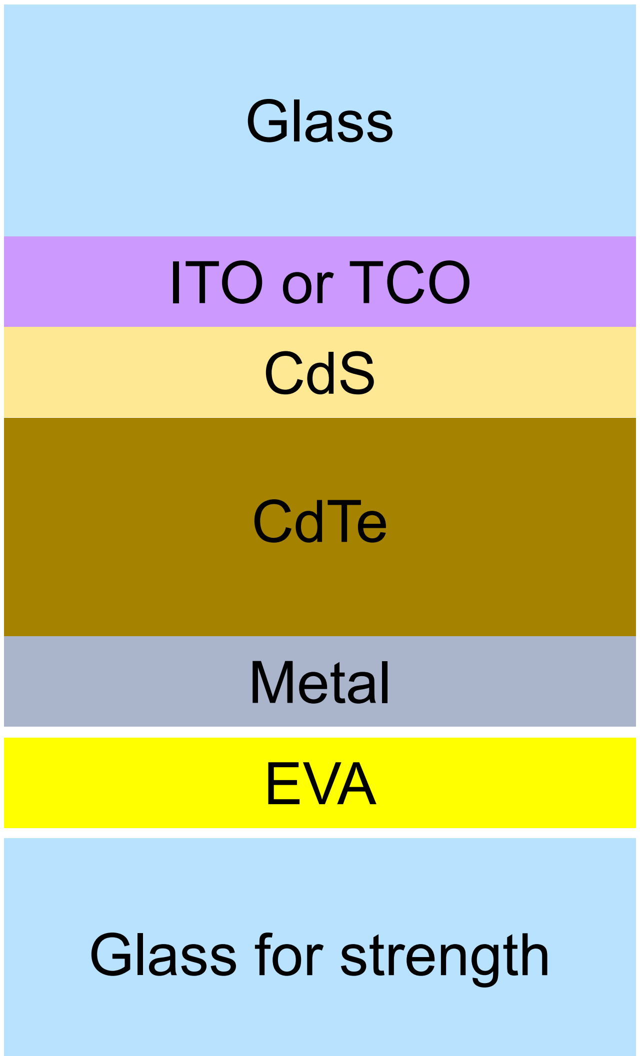
Monolithic module integration



Thin-film modules have a different construction than Si modules

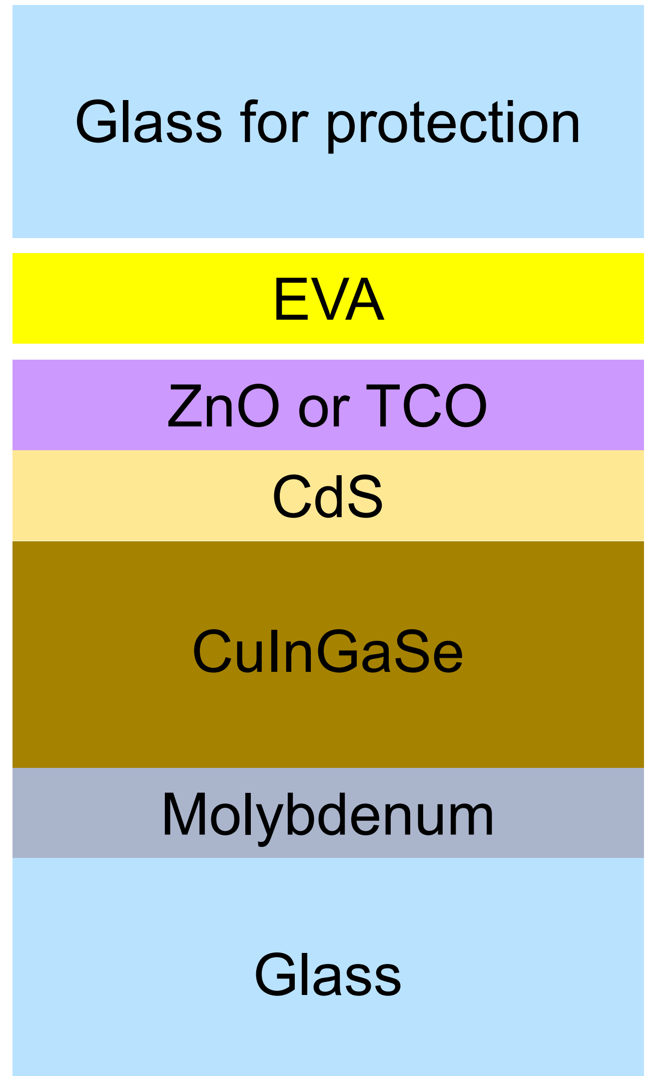
Thin film products vary in their construction, but many use glass-glass construction

CdTe uses superstrate



Not to scale

CuInGaSe uses substrate



Is glass/glass construction required?

- Strategies to avoid glass/glass construction:
  - 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

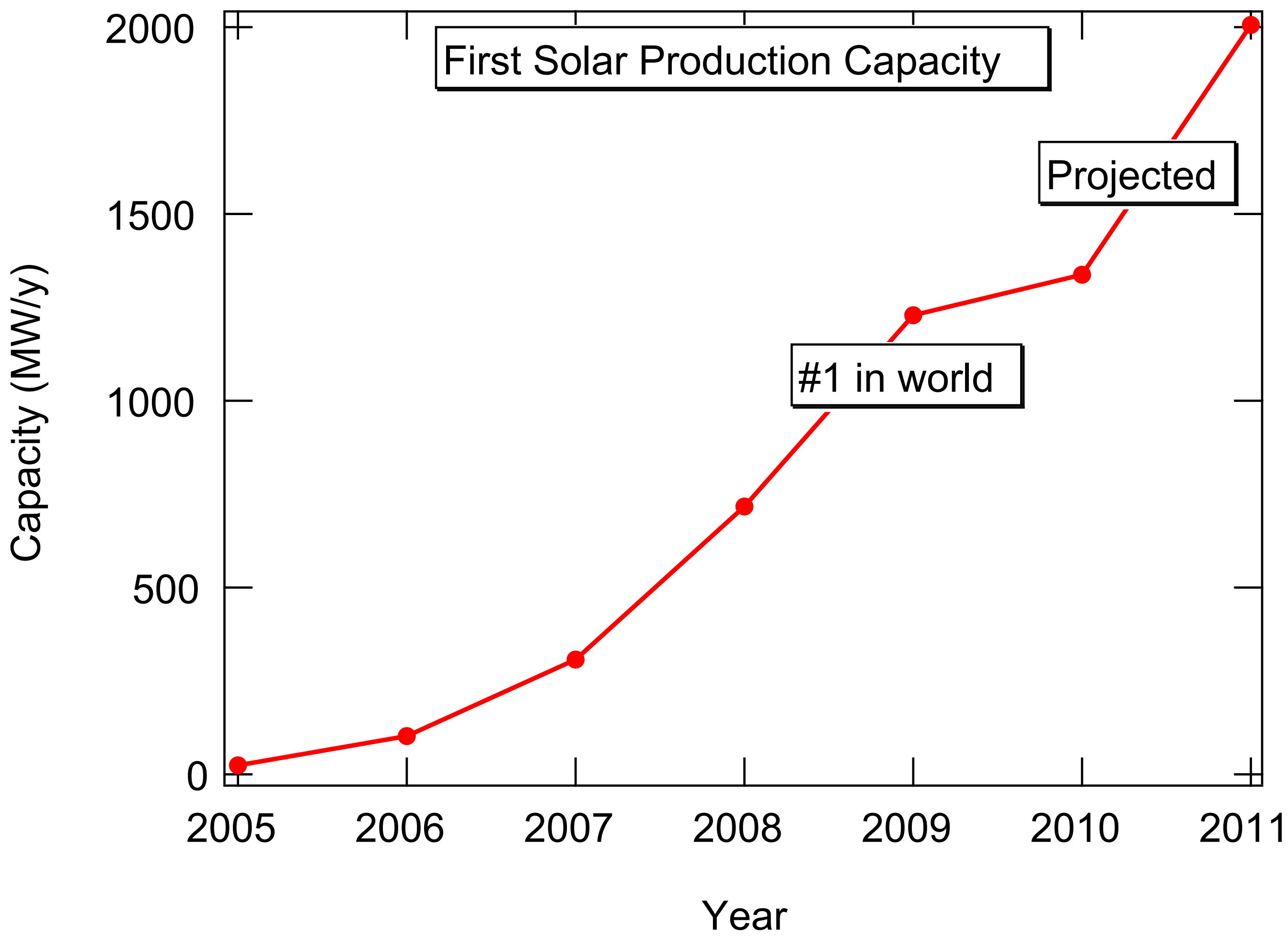
Vision (advantages)

- ~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)

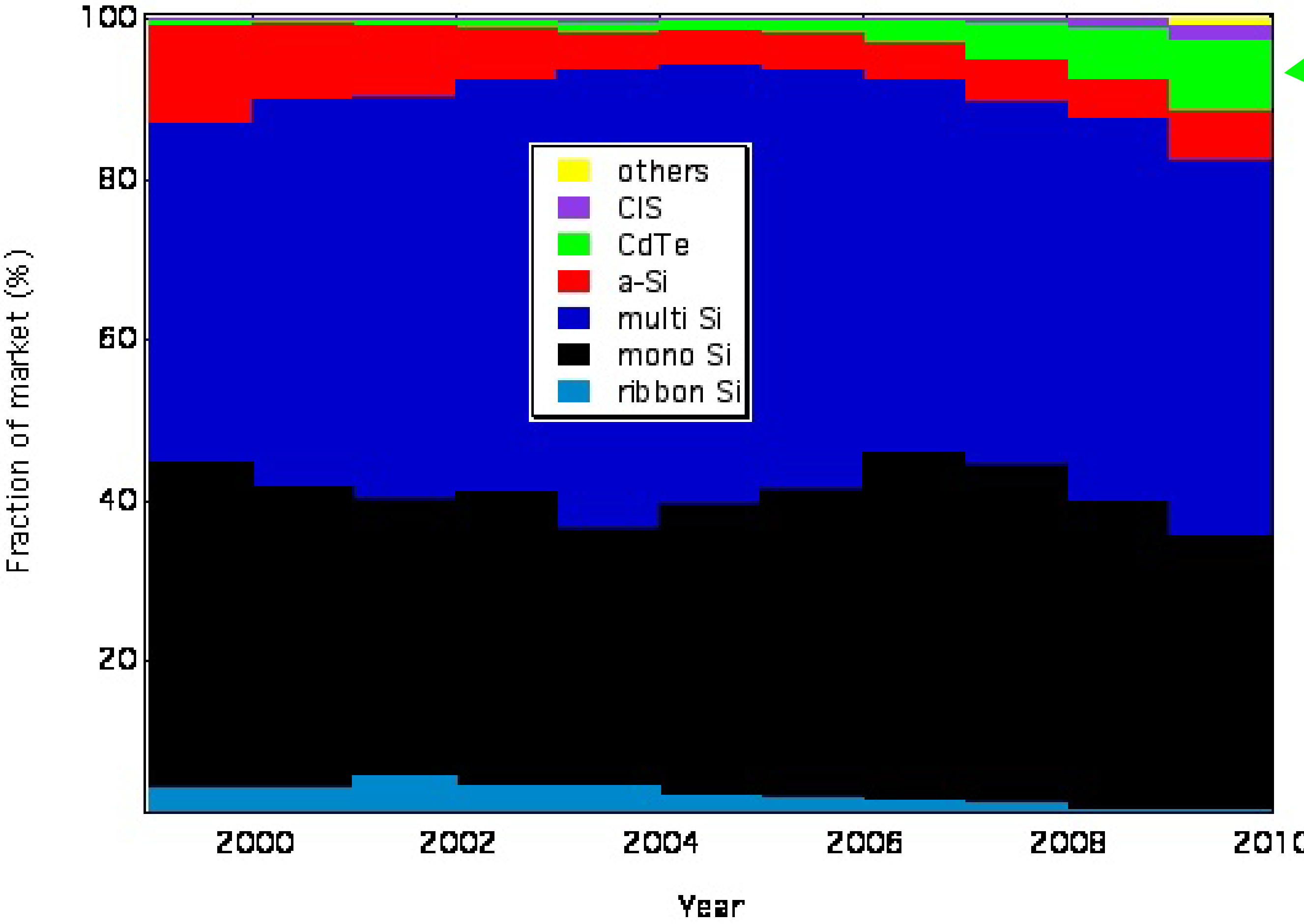
- Growth on inexpensive substrates limits efficiency
- Sensitivity to moisture leads to glass/glass laminate
- Infrastructure is not as well developed as for silicon
- Building integration increases operating temperature

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

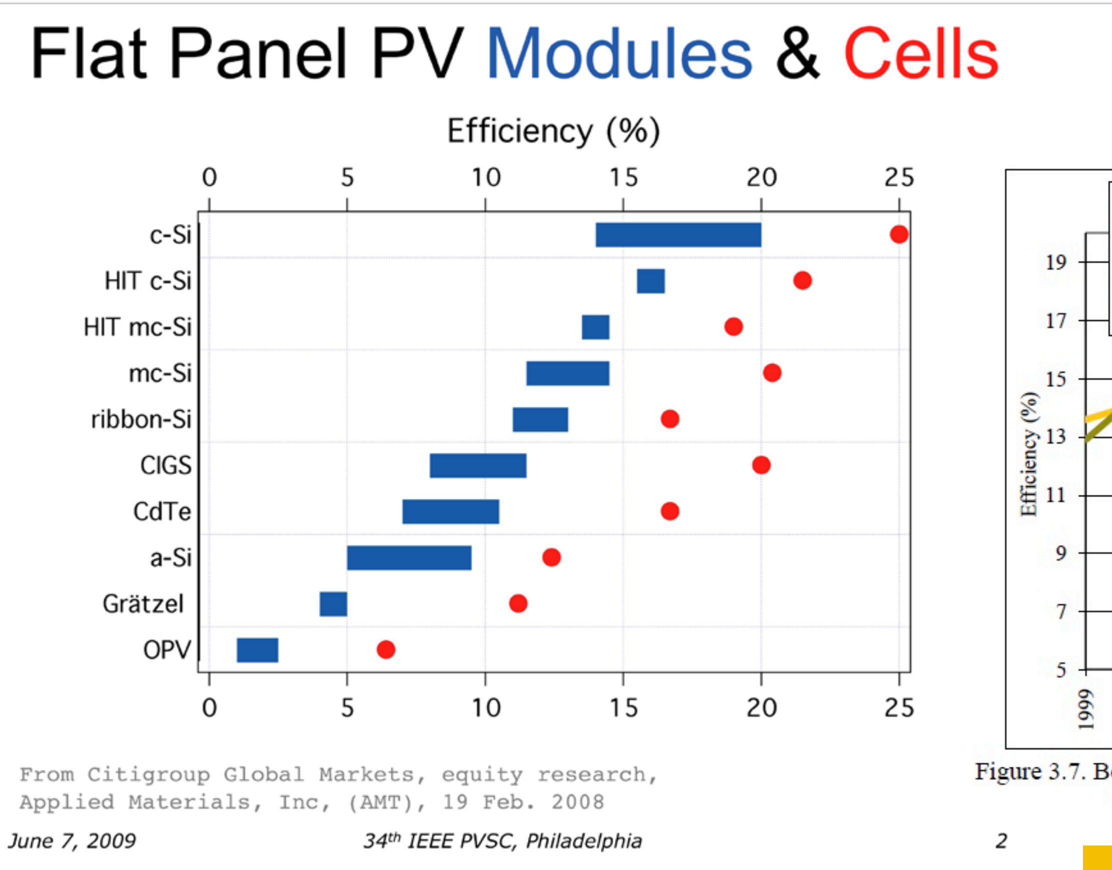


First Solar

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



Miasole just announced

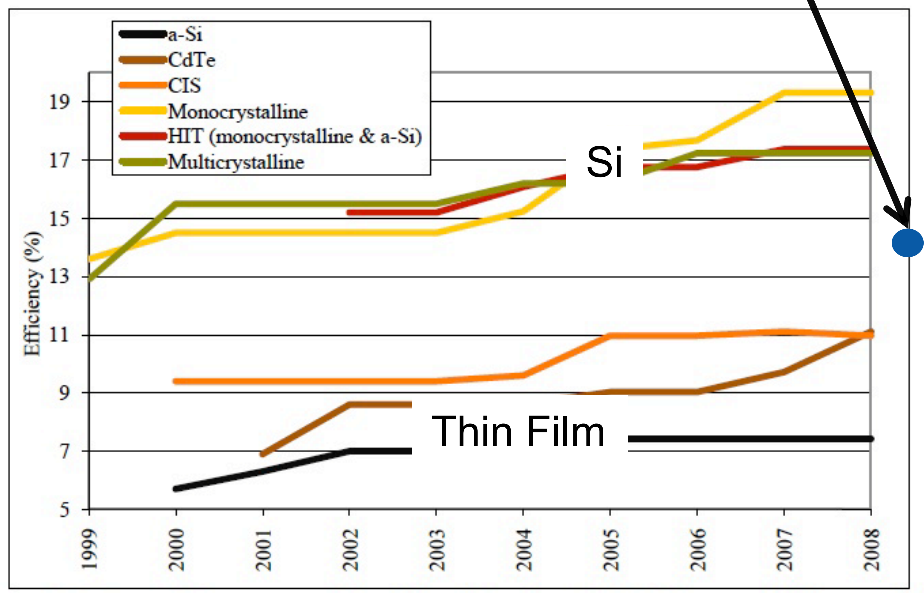
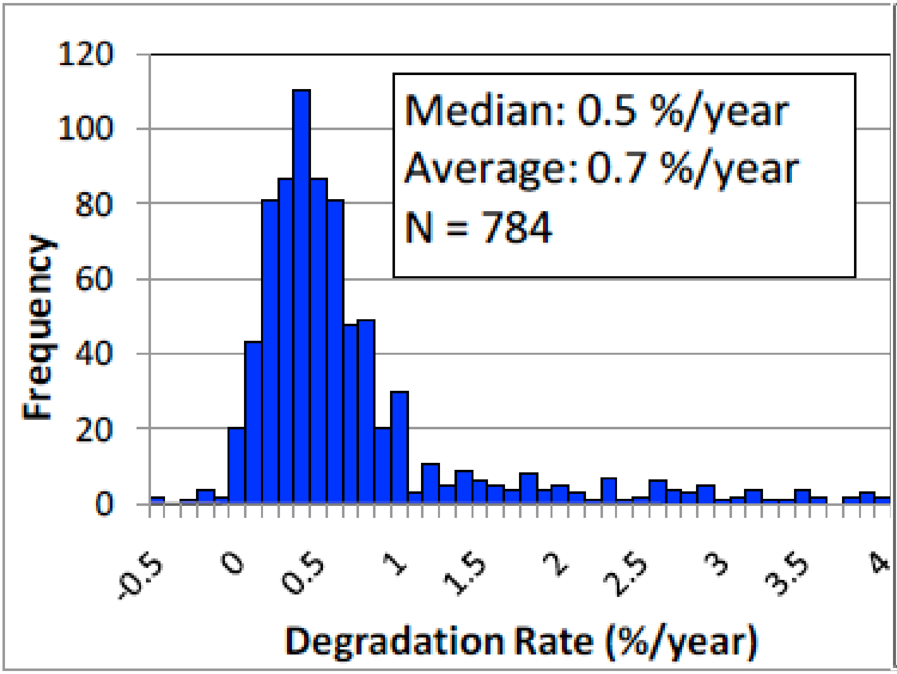


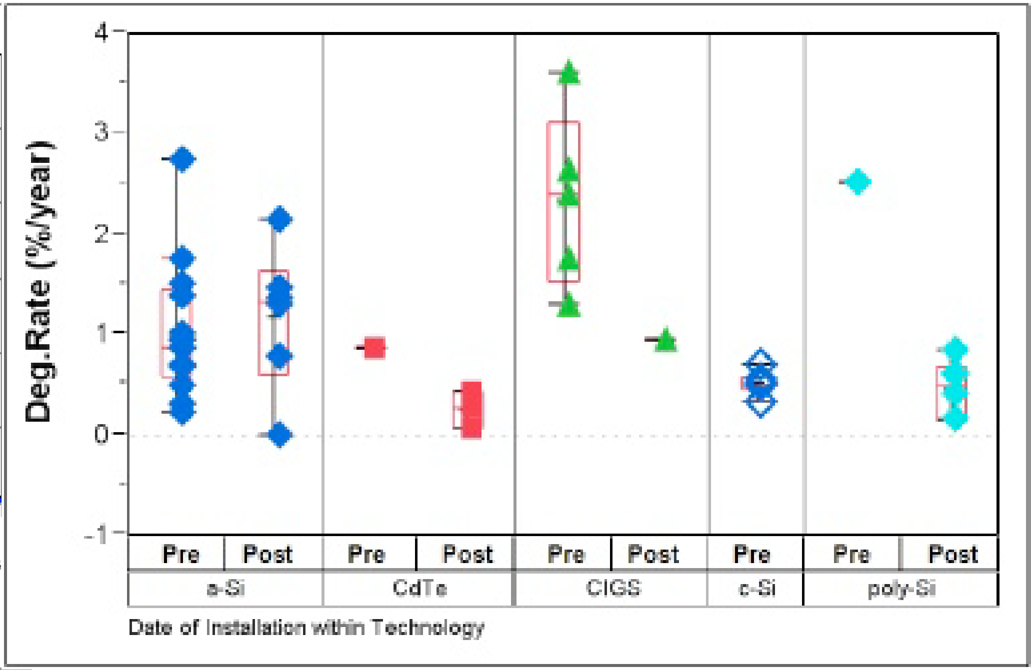
Figure 3.7. Best-in-class commercial module efficiencies, 1999–2008, compiled from modul survey data (Kreutzmann 2008, *Photon International* 1999–2008)

Source: DOE EERE 2008 Solar Technologies Market Report

In general, silicon outperforms thin film in terms of efficiency
Thin film is catching up!

Comparison of degradation rates



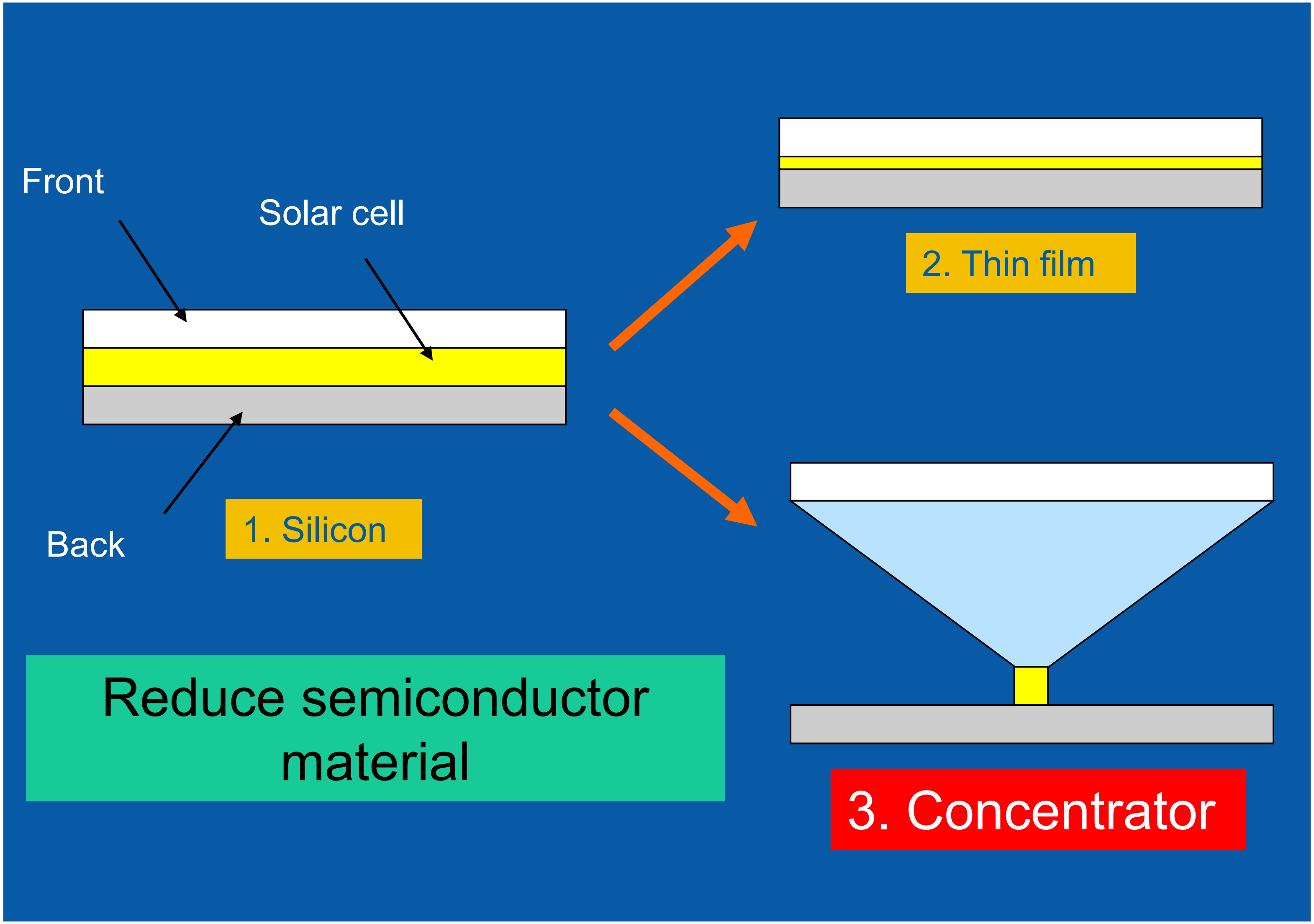


Statistically, observed degradation rates are about 0.5%/y

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

Source: Jordan, et al. PVSC 2010

Three approaches to PV

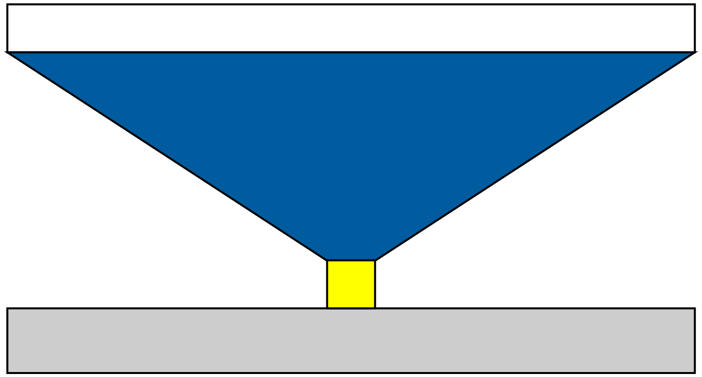


Reduce semiconductor material

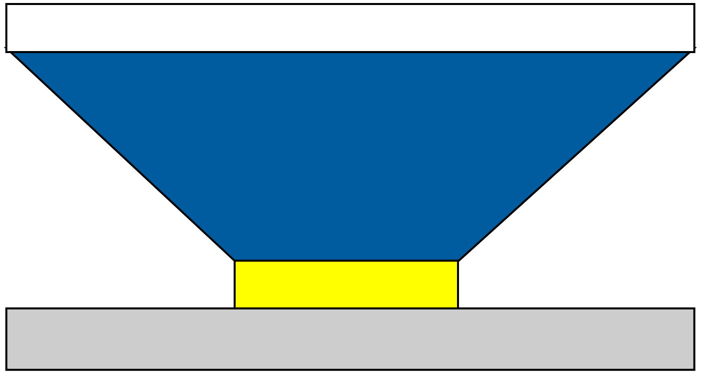
Two primary concentrator approaches

Amonix

JX Crystals

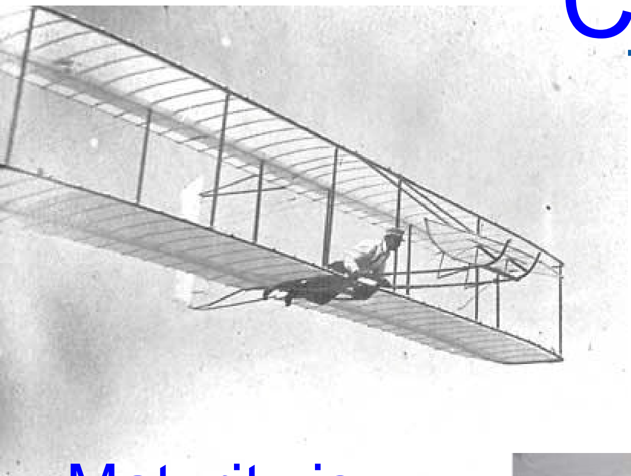


High concentration
• 35% - 40% III-V cells
• 400X – 1500 X



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

Returning to the question of cost

Practical ways to look at (real) cost:

- Energy payback
- $ payback

Rule of thumb: 1 kW can generate 1000-2000+ kWh/y

(At 10 cents/kWh, that's $100-200 in first year;

At 10% efficiency, 1 kW covers 10 sq m)

For payback in one year: cost target is $10-$20/sq m

Note: installation and permitting costs can exceed this budget

Strategies for tomorrow's PV

- Breakthrough
  - Higher efficiency
  - Lower cost
  - Cost avoidance
- Incremental reductions in cost and improved efficiency
- Lifetime as a path to low cost

‘Breakthrough’ or ‘Revolution through Evolution’?

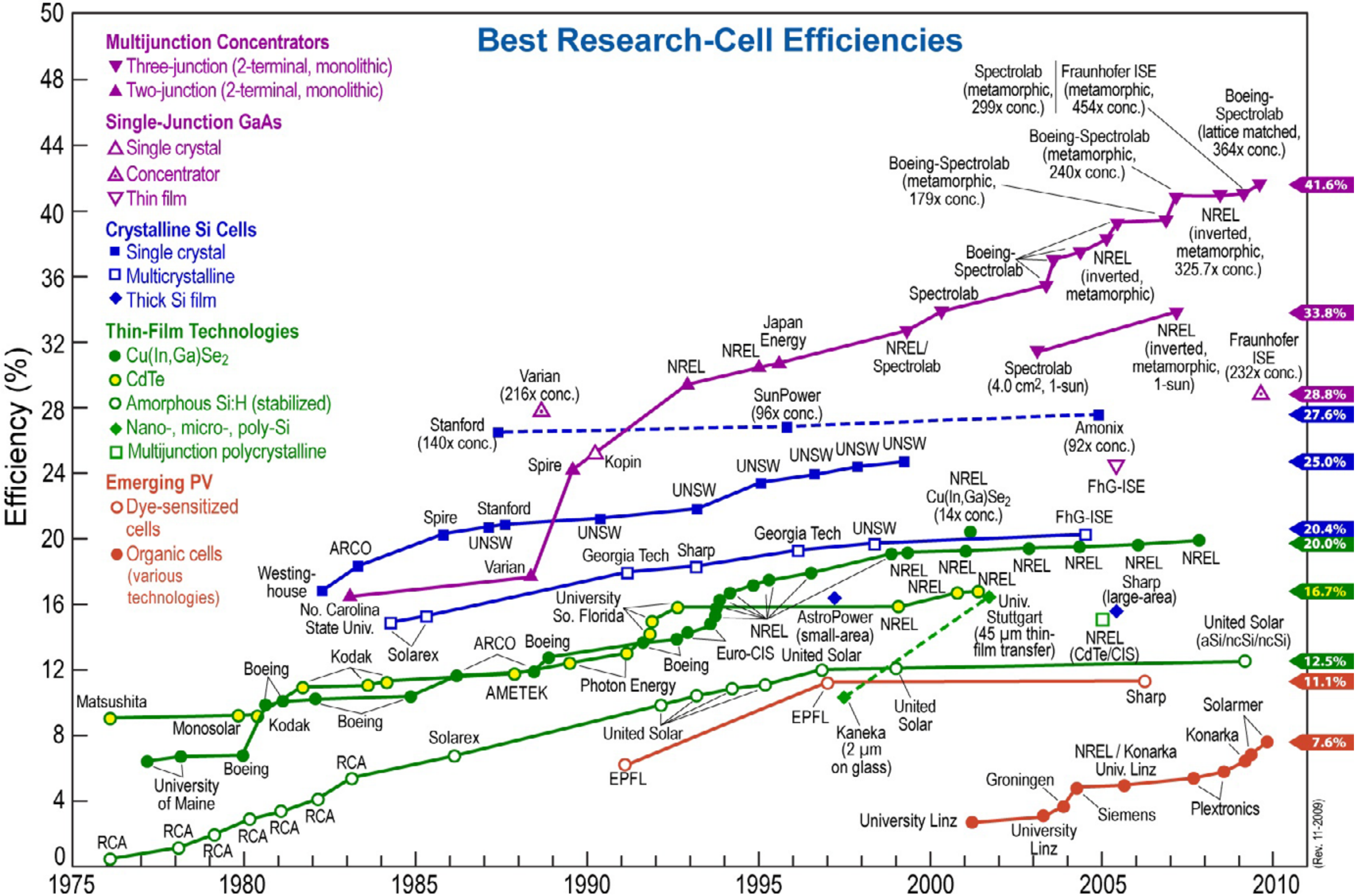
Two camps predicting future of PV:

- Need revolutionary breakthrough
- Achieve revolution through evolution

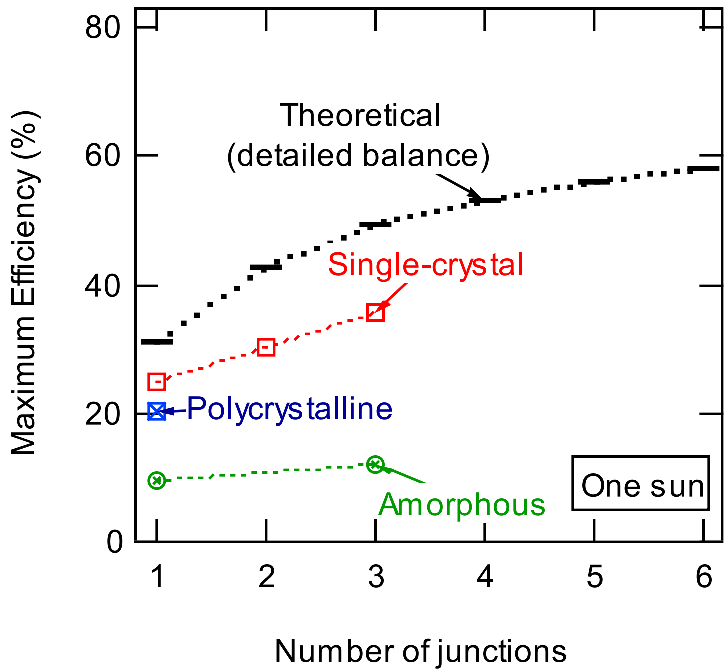
Potentially high-efficiency breakthrough approaches have been explored for decades:

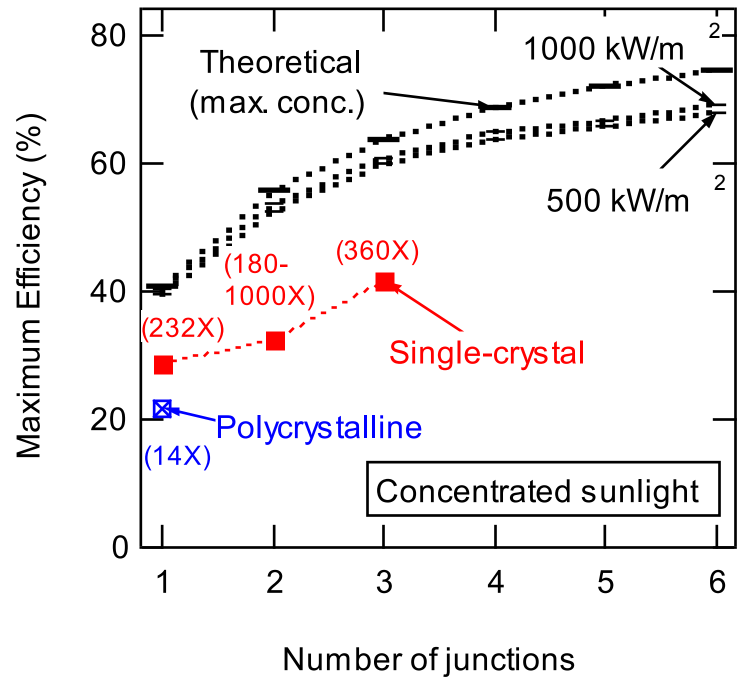
- Intermediate band,
- Hot carrier,
- Multiple exciton.

Efficiency differentiates technologies



Efficiency opportunities





Kurtz, Prog. In PV, 2008.

Three ways to achieve higher efficiencies:

1.more junctions, 2. excellent material quality, 3. use concentration

Efficiency can give incremental improvement

Reduce cost of PV modules

Strategies avoiding glass:

- PV plastic wrap
- PV spray-on paint

(must solve moisture problem and improve efficiency)

Avoid cost by incorporating into building material

- Shingles, etc. replaces building material, so now compete with cost of that building material.

(in most cases higher operating temperature means lower efficiency: can be 10% to 15% relative effect)

Reduce cost through longer lifetime

Rule of thumb: 1 kW can generate 1000-2000 kWh/y

(At 10 cents/kWh, that's $100-200 – fundamental rub;

At 10% efficiency, 1 kW covers 10 sq m)

Payback of 1 yr @10% efficiency requires <$10-20/sq m

Payback of 1 yr @20% efficiency requires <$20-40/sq m

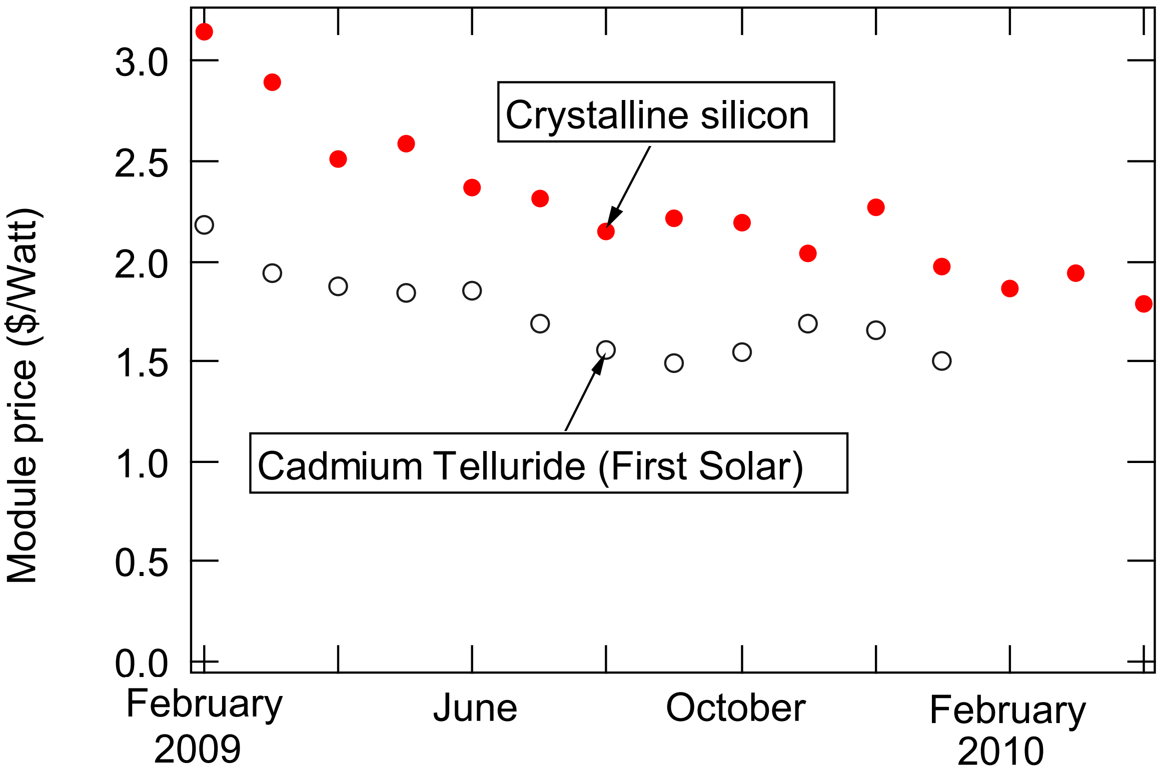
Payback of 50 yr @20% efficiency requires <$1000-2000/sq m (assuming no maintenance costs)

Current costs demonstrated at ~ $3000 / sq m

Are 100 year lifetimes possible? If so, we're 'there'!

Long lifetime may be practical way to reach cost-effective PV

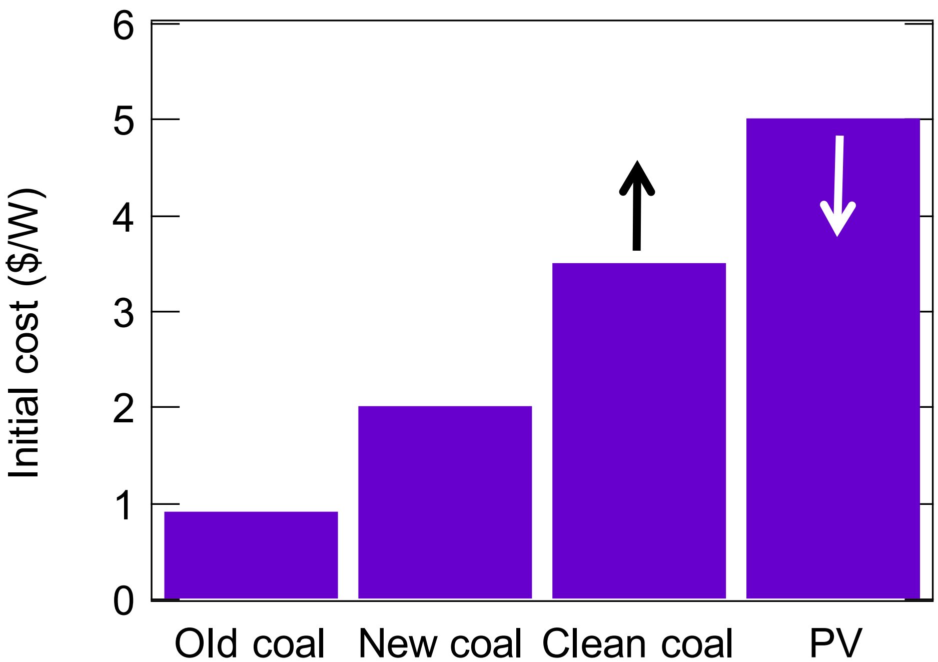
PV prices have decreased



Prices have been coming down; how much more?

Source: PHOTON International

Moving cost target?



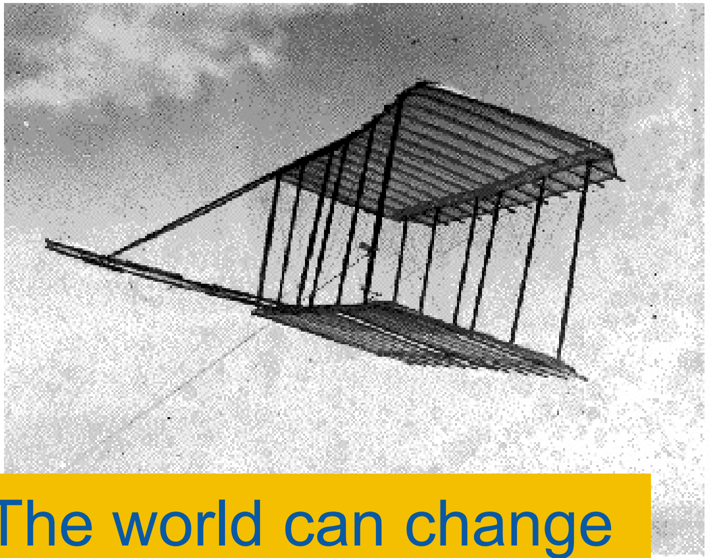
*Fortnightly's SPARK, p. 10, May 2008

Assumption of 10 cents/kWh may or may not represent electricity costs of the future.

New coal plants are more expensive than older plants

Summary

- Three practical approaches:
  - Lower cost
  - Higher efficiency
  - Longer lifetime
- Silicon, thin-film, and concentrator approaches are all making progress
- In the future, practical strategies could include:
  - Dramatically reduce cost by removing glass
  - Replace other materials (e.g. shingles)
  - Lots of incremental improvements
  - Long lifetime



The world can change a lot in 100 years.

What will our world be like 100 years from now?