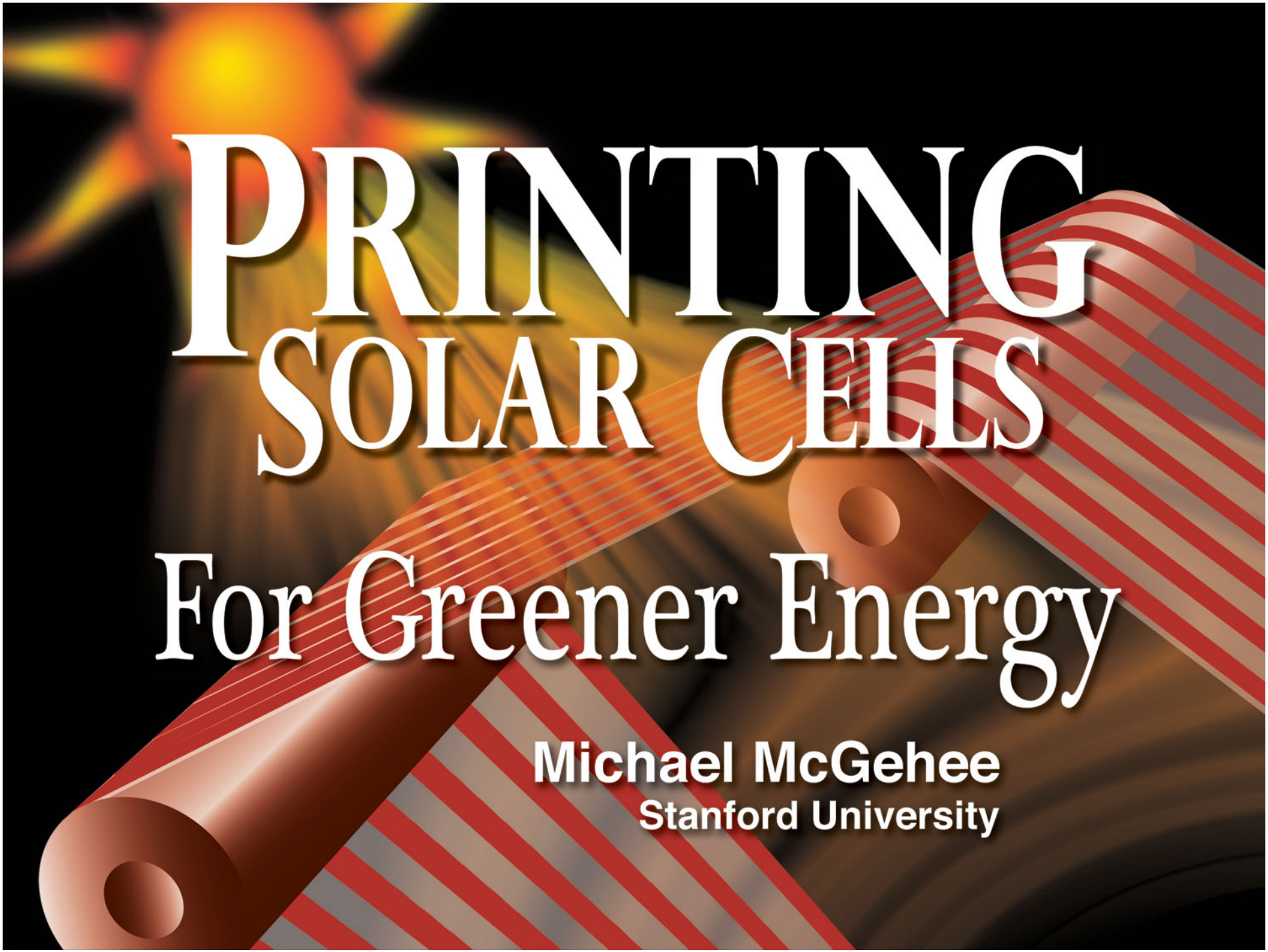
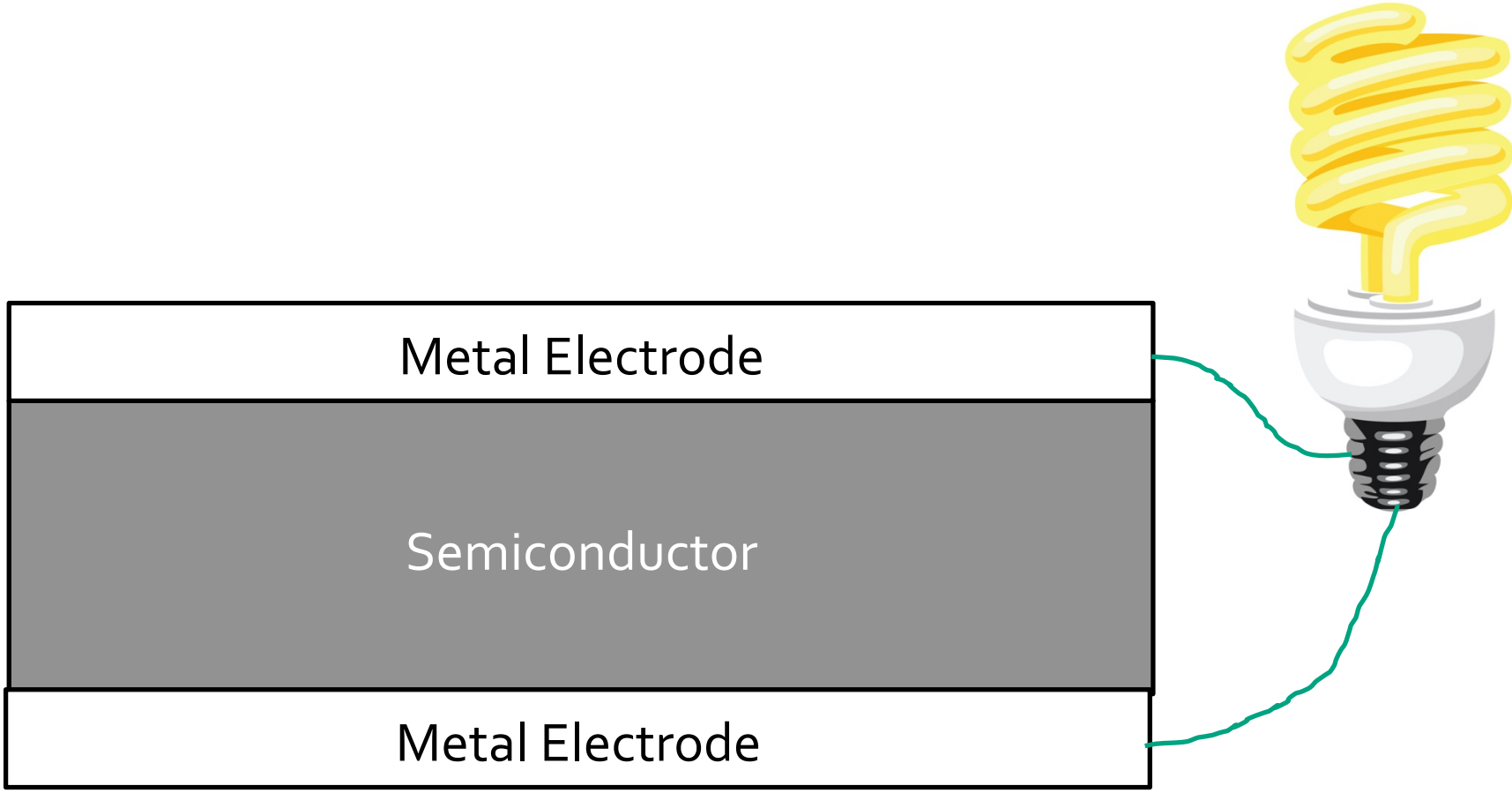

PRINTING
SOLAR CELLS
For Greener Energy
Michael McGehee
Stanford University

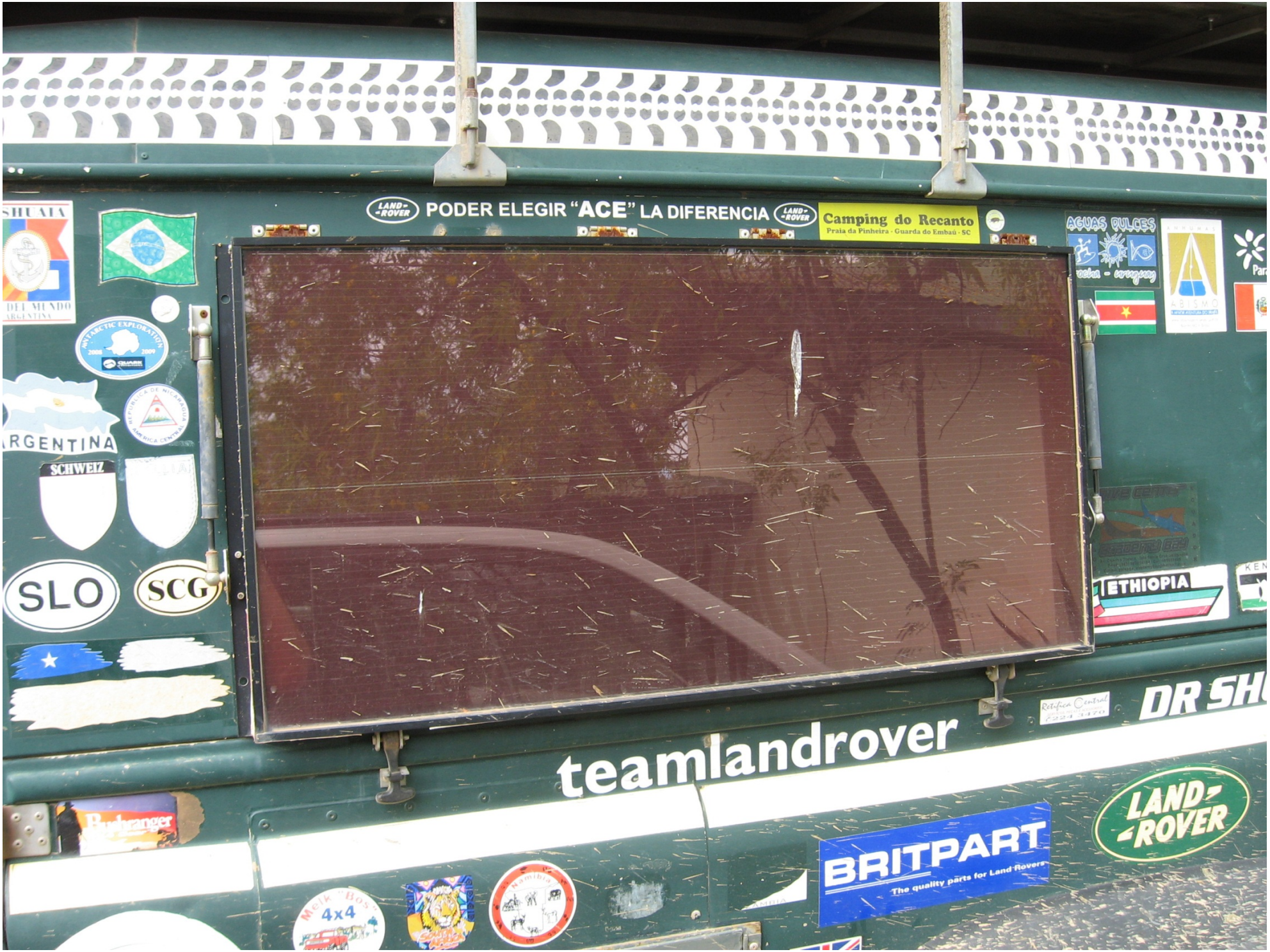
Questions I will answer

- What is a solar cell?
- How are solar cells used?
- Where do they compete economically with coal-fired power plants?
- How are solar cells made?
- How do they work?
- How efficient can they be?
- How can we print solar cells to bring the cost down?

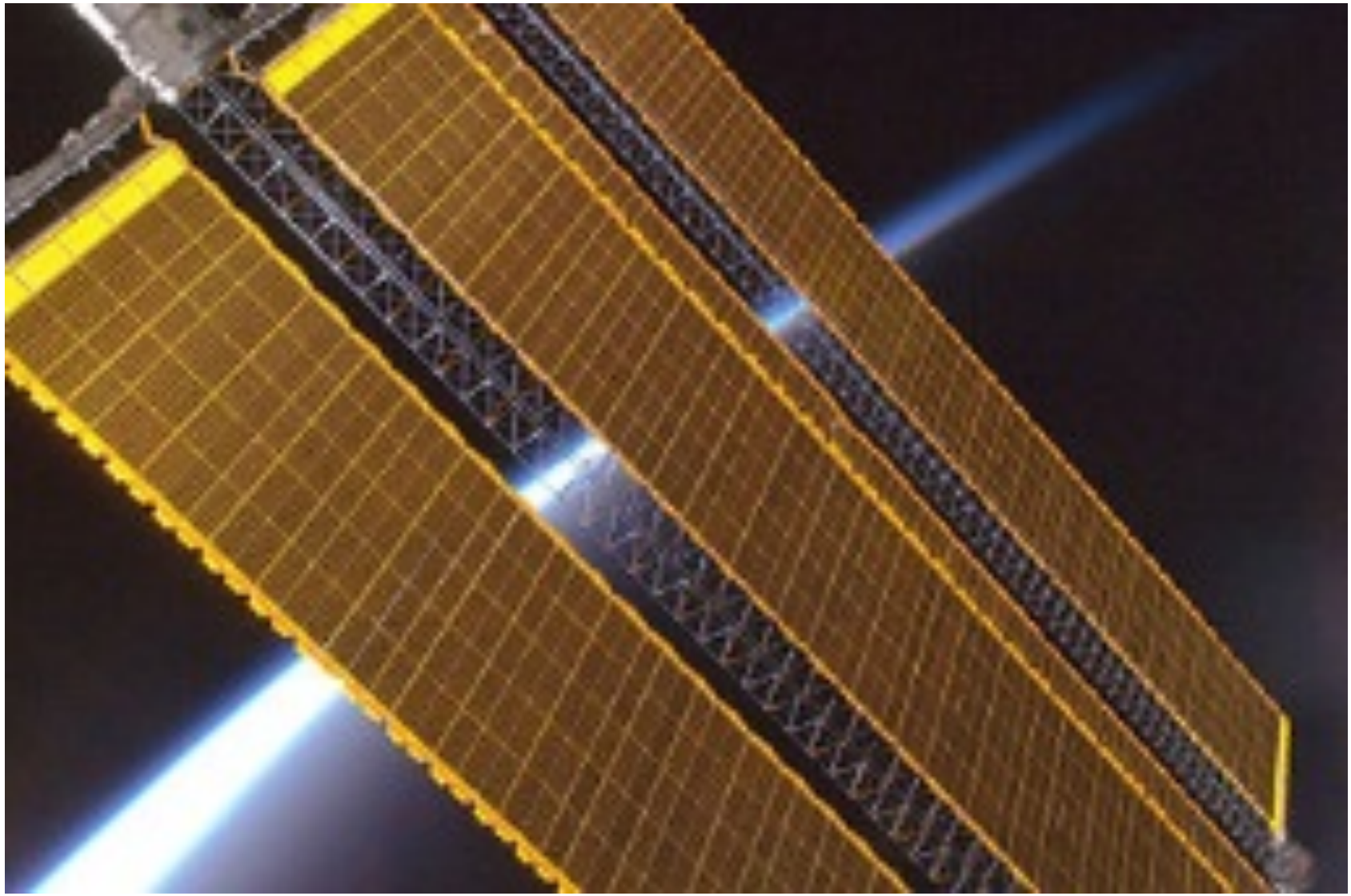
Solar (photovoltaic) cells absorb sunlight and generate electricity



Solar cells are the main source of electricity off the electrical grid


PODER ELEGIR "ACE" LA DIFERENCIA
Camping do Recanto
Praia da Pinheira - Guarda do Embaú - SC
AGUAS DULCES
ARGENTINA
SCHWEIZ
SLO
SCG
ETHIOPIA
teamlandrover
BRITPART
The quality parts for Land Rovers
LAND ROVER
4x4

Solar panels on the International Space Station



(150 km)^2 of Nevada covered with 15 % efficient solar cells could provide the whole country with electricity.

J.A. Turner, *Science* **285** 1999, p. 687.

Why solar cells are likely to provide a significant fraction of our power

- We need ~ 30 TW of power, the sun gives us 120,000 TW.

- Solar cells are safe and have few non-desirable environmental impacts.

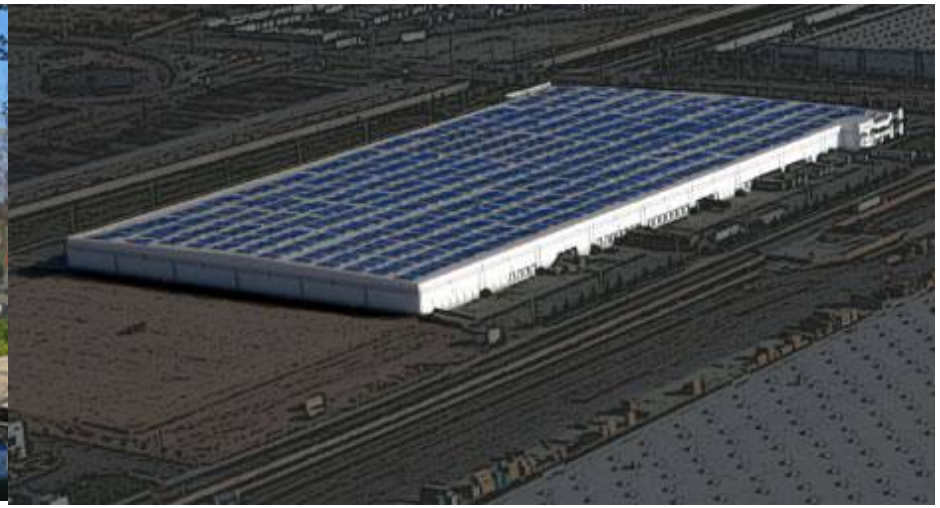
- Solar cells can replace coal, which generates lots of CO_2.

- Solar cells provide electricity exactly when we need it the most.

The Three Big Photovoltaic Markets

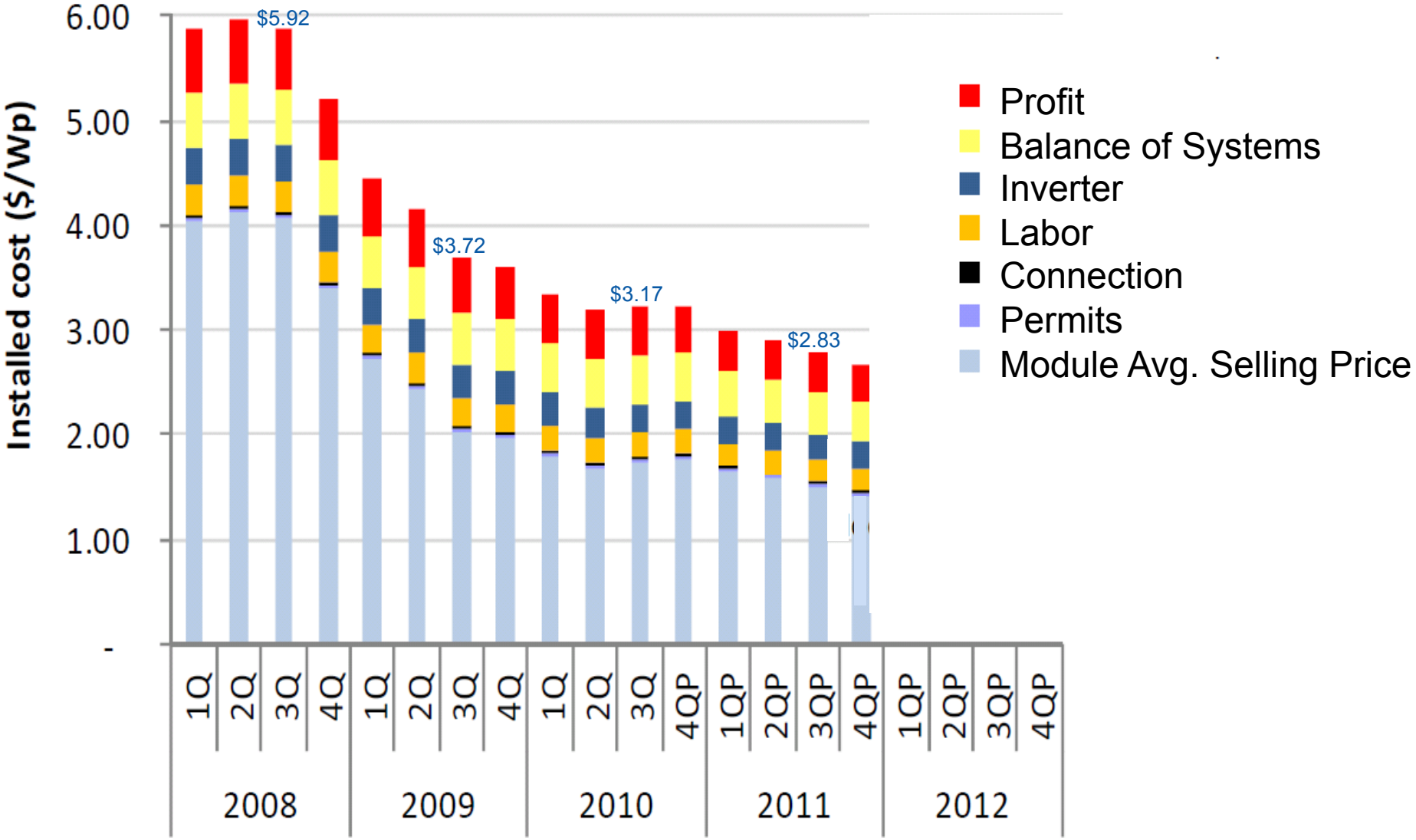
Residential

Commercial Rooftop



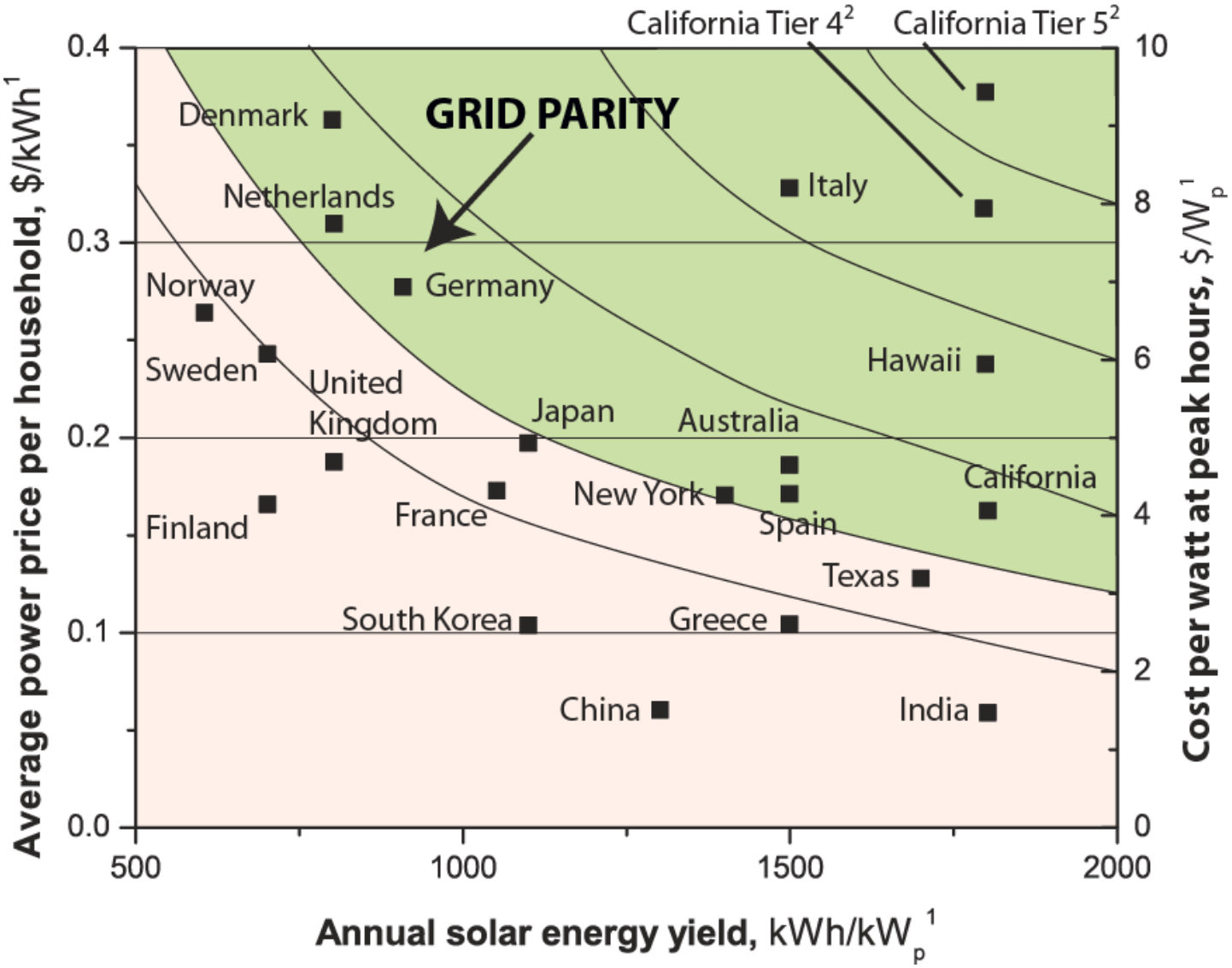
Utility scale power plants

Installed System Price per Watt



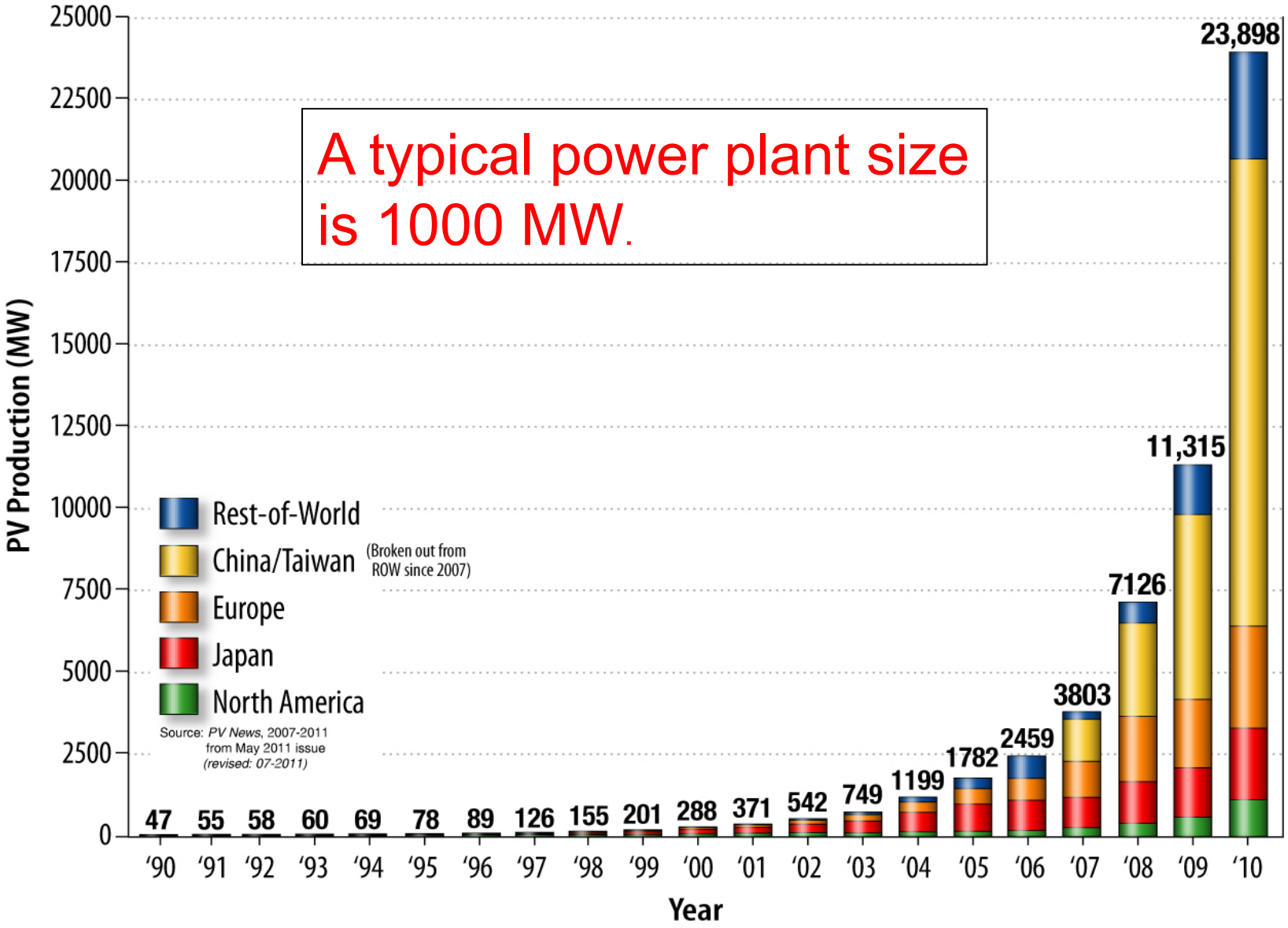
Original Source: Deutsche Bank, January 2011; Systems are global (i.e., blended across geographies)
My source: R. Swanson, IEEE PV Specialists Conf., June 2011

How cheap does PV need to be to compete w/ coal?



Source: CIA country files; European Photovoltaic Policy Group; Eurostat; Pacific Gas & Electric (PG&E); Public Policy Institute of New York State; McKinsey Global Institute analysis

The solar industry grows by about 40 % each year



How far will the industry go?

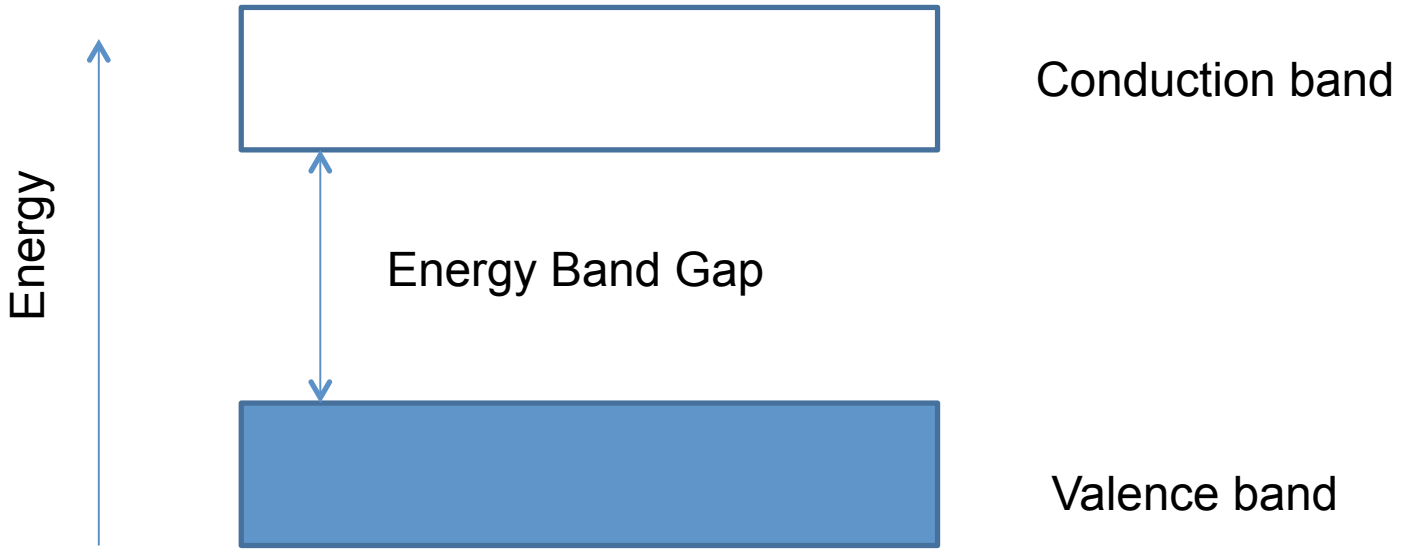
•By 2050 the world will need ~ 30 TW of power.

•Some think PV could provide 20 % of that.

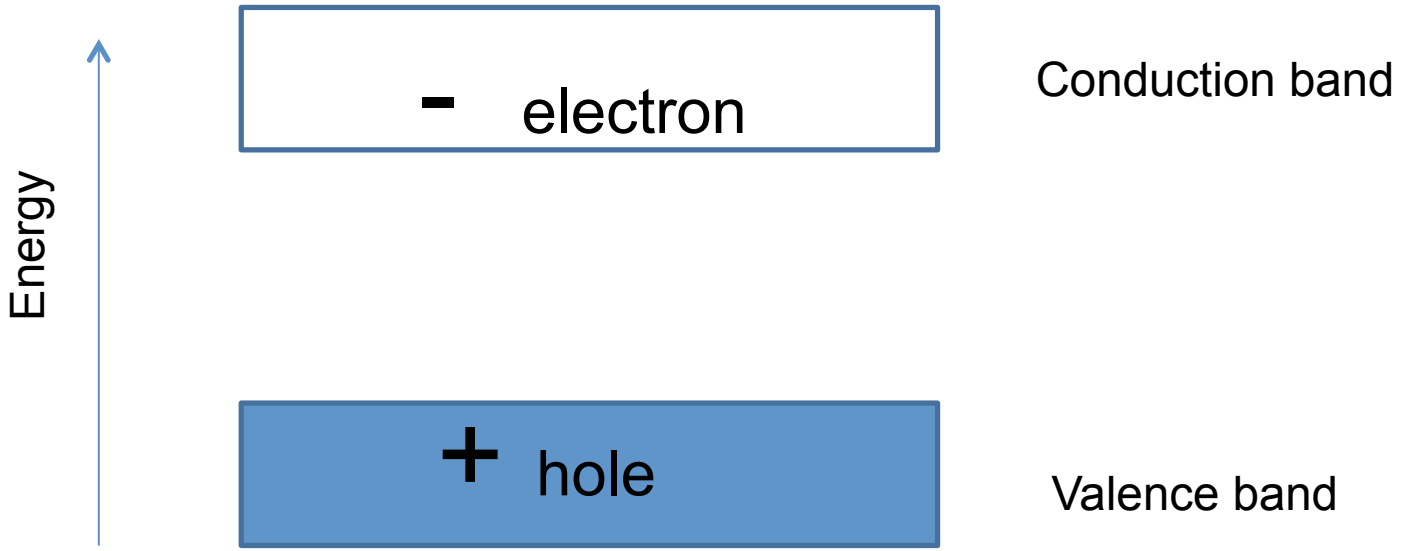
• It takes a panel rated at 5 W, to average 1 W of power through the day and year, so we would need 30 TW of PV capacity.

•If cells lasted 30 years, about 1 TW would be installed each year. In 2010 we installed 0.024 TW.

Semiconductors



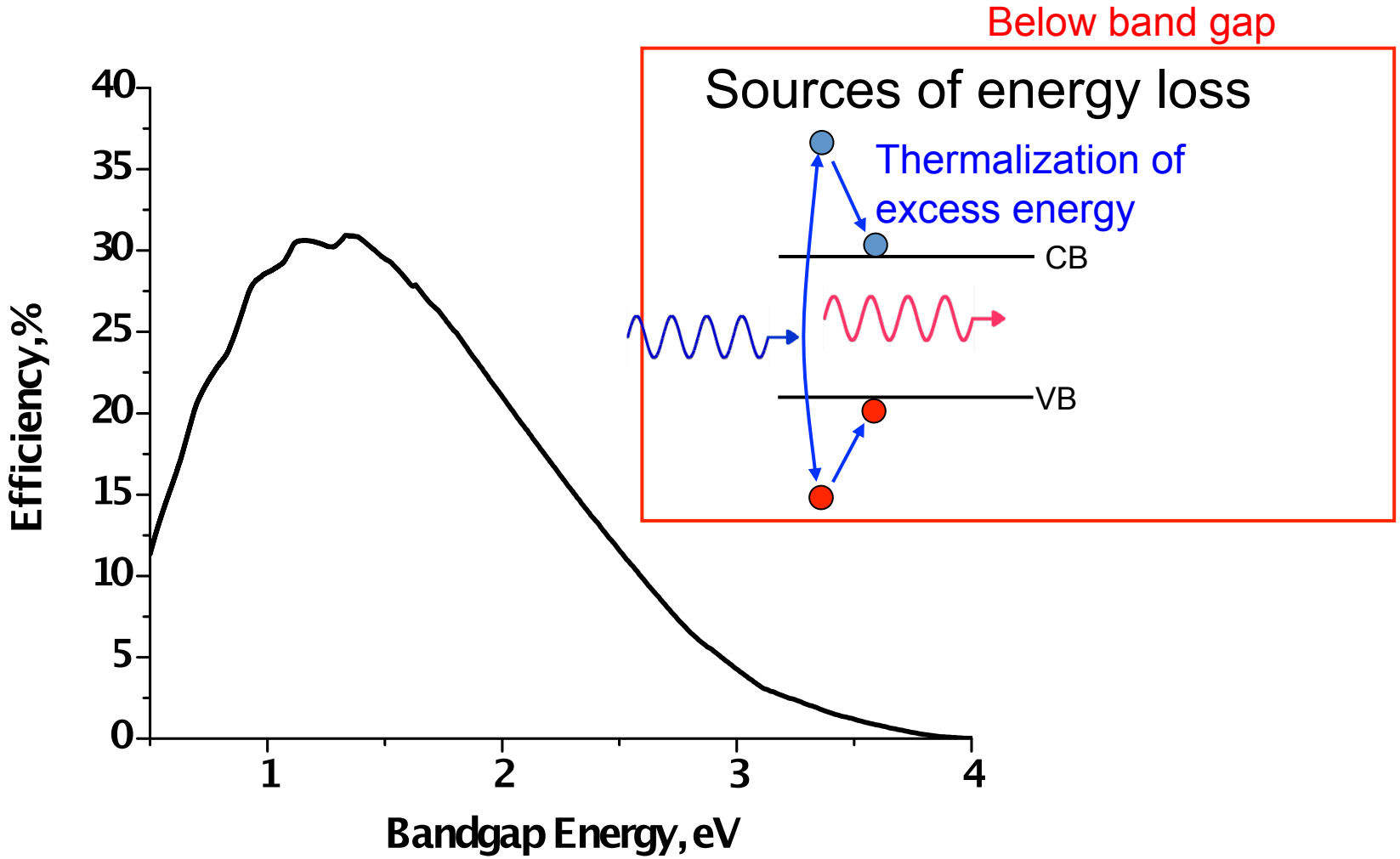
Energy is stored when light is absorbed



A hydropower analogy

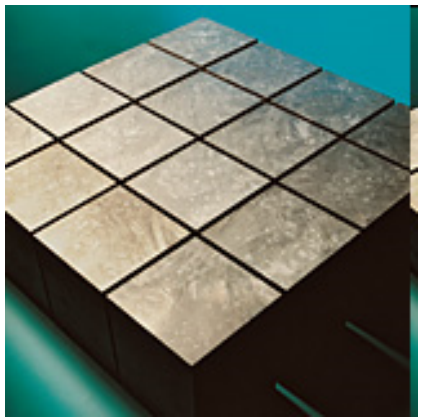
A reservoir must be low enough to collect a lot of water, but high enough to generate a lot of power.

Optimizing the band gap to maximize the efficiency

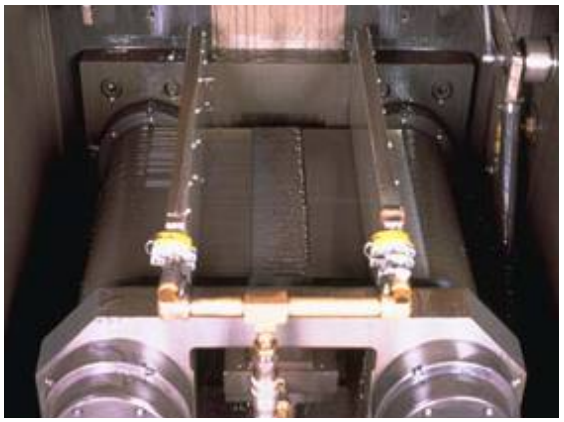


Silicon photovoltaics

Silicon Feedstock



Ingot Growth

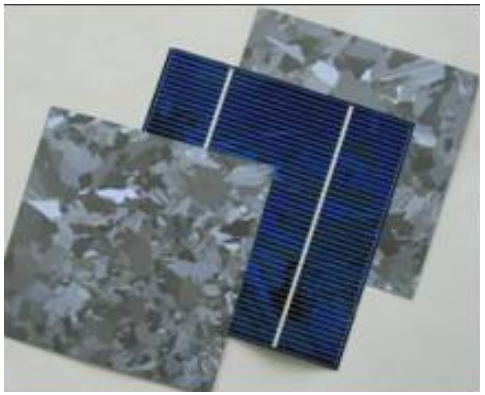


Slicing Wafers

Cell Fabrication

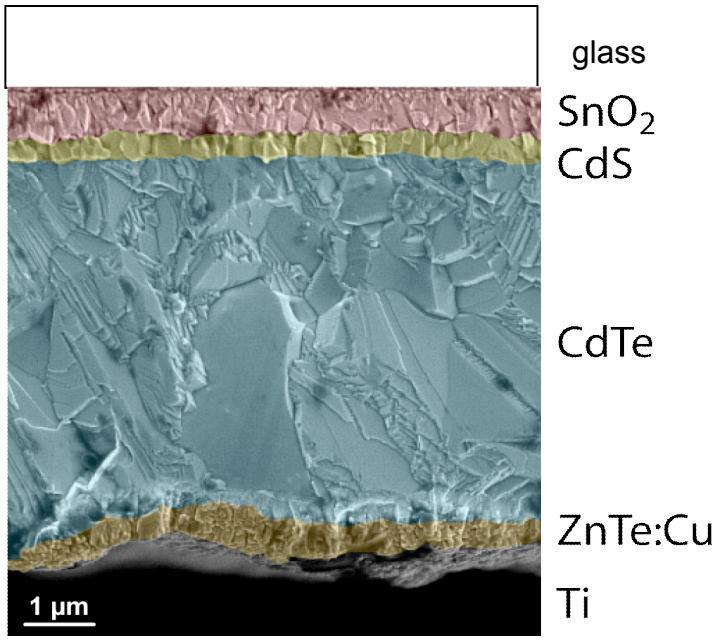
Module Encapsulation

Photovoltaic System



Traditional Thin Film (2nd Gen) Solar Cells

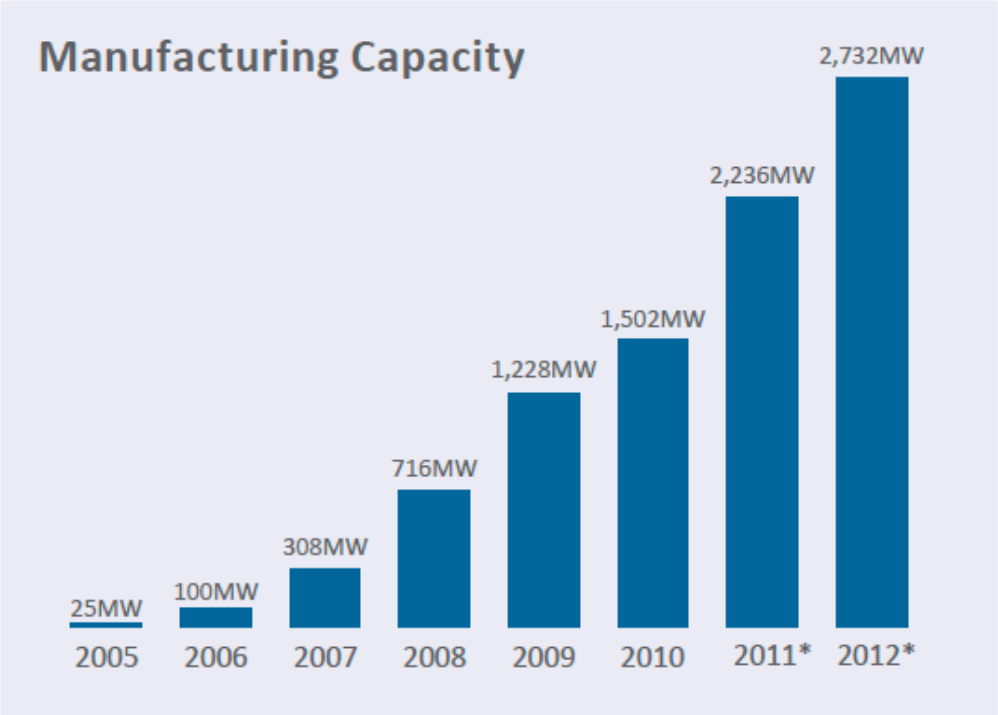
- A thin film of semiconductor is deposited by low cost methods.
- Less material is used.
- Cells can be flexible and integrated directly into roofing material.



CdS/CdTe

CdTe: Industrial Status

First Solar is the leader. It takes them 2.5 hours to make a 11 % module.

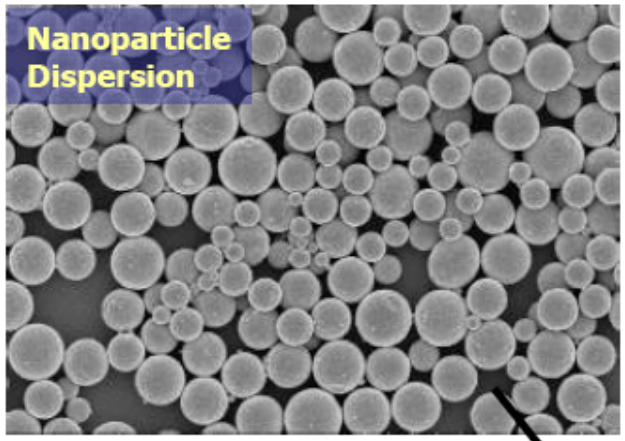


Average Manufacturing Cost

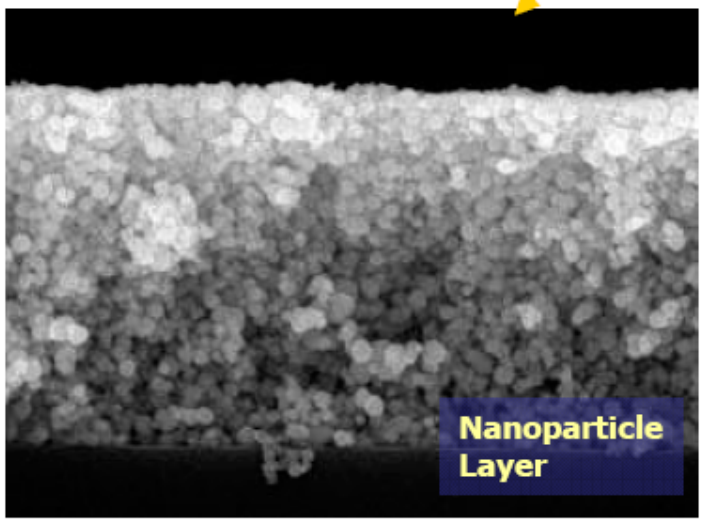
2006: $1.40/watt
2007: $1.23/watt
2008: $1.08/watt
2009: $0.87/watt
2010: $0.77/watt

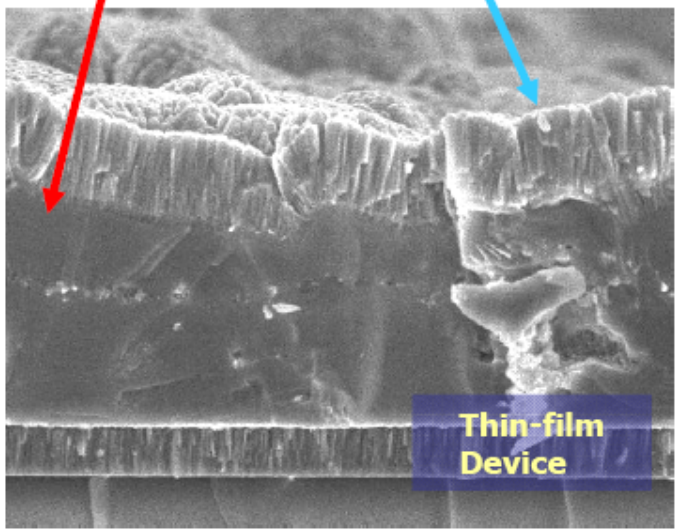
The energy payback time is 0.8 years.

PRINTED SEMICONDUCTOR



Printed Semiconductor +
Rapid Thermal Processing (RTP)





www.nanosolar.com

Nanosolar’s Roll-to-Roll Coating

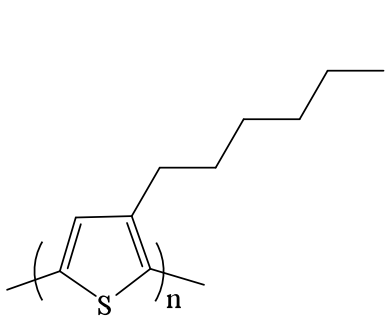
See videos of the coating machine and module packaging on Nanosolar’s website.

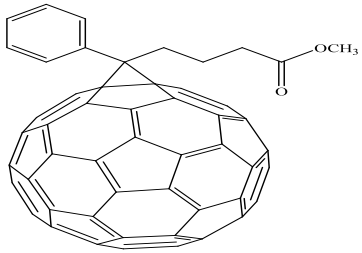
Summary of traditional PV materials

Material	Record efficiency	Typical module efficiency	Typical Cost	Leading companies	Issues
Silicon	25.0 %	16 %	$1.15/W	Suntech, Sunpower	
CdTe	17.3 %	11 %	$0.75/W	First Solar	Cd toxicity, Te scarcity
CIGS	20.0 %	12 %	$ 1/W	Nanosolar, Miasole	In scarcity

Organic Semiconductors

Donor **Acceptor**



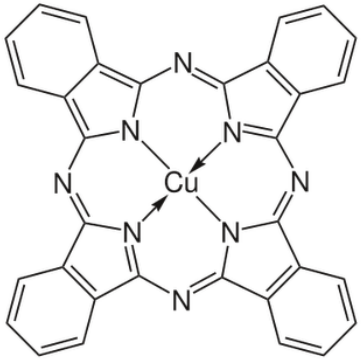


P3HT **PCBM**

By organic, I mean these molecules are carbon compounds.

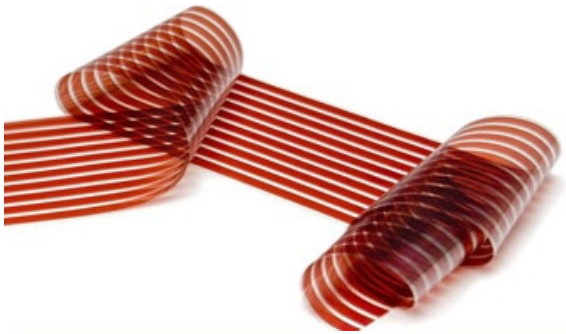
Organic Solar has Potential to be a Low Cost Source of Clean Energy

Low-Cost Materials

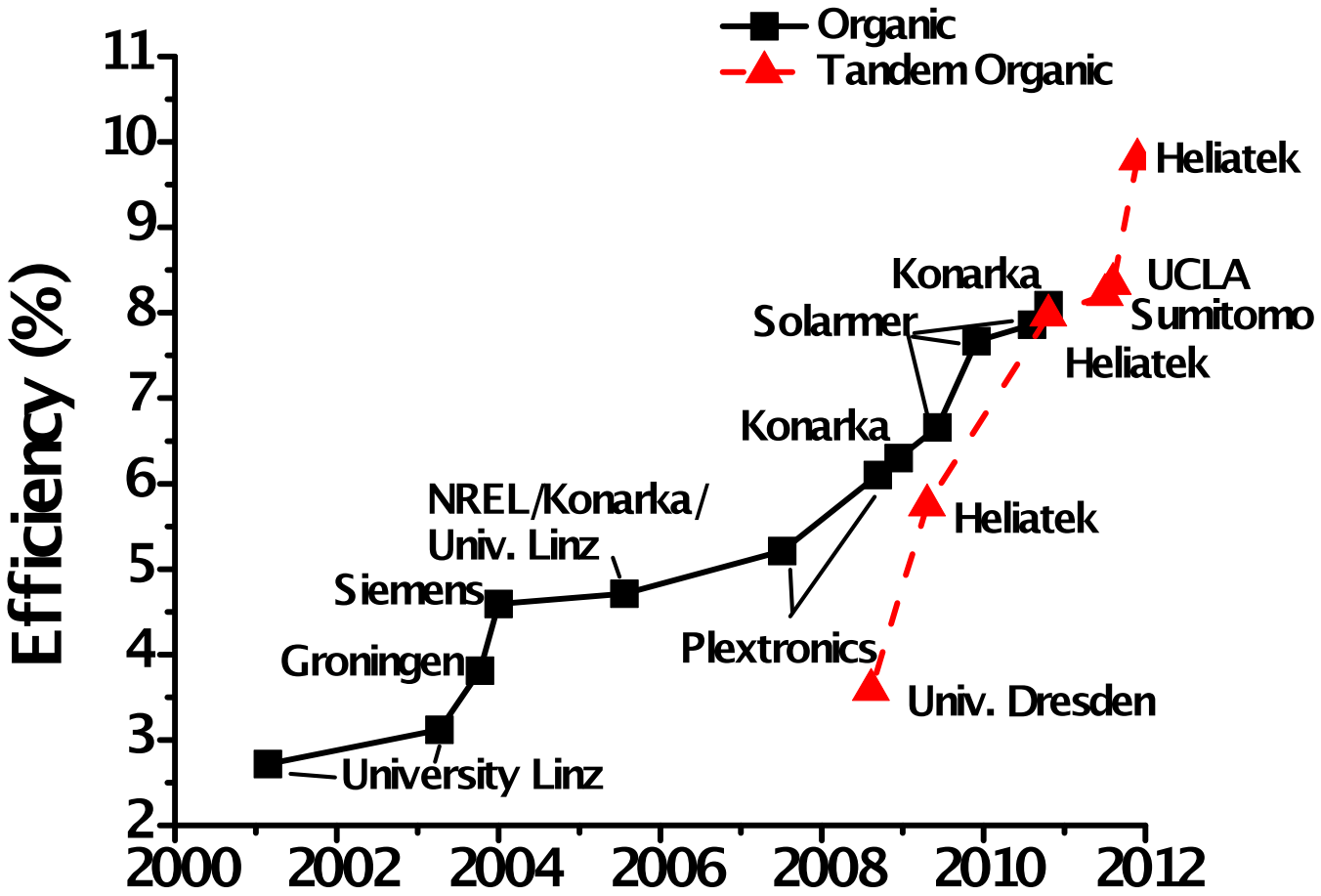


Low-Cost Manufacturing

Low-Cost Installation



Organic solar cells are rapidly improving

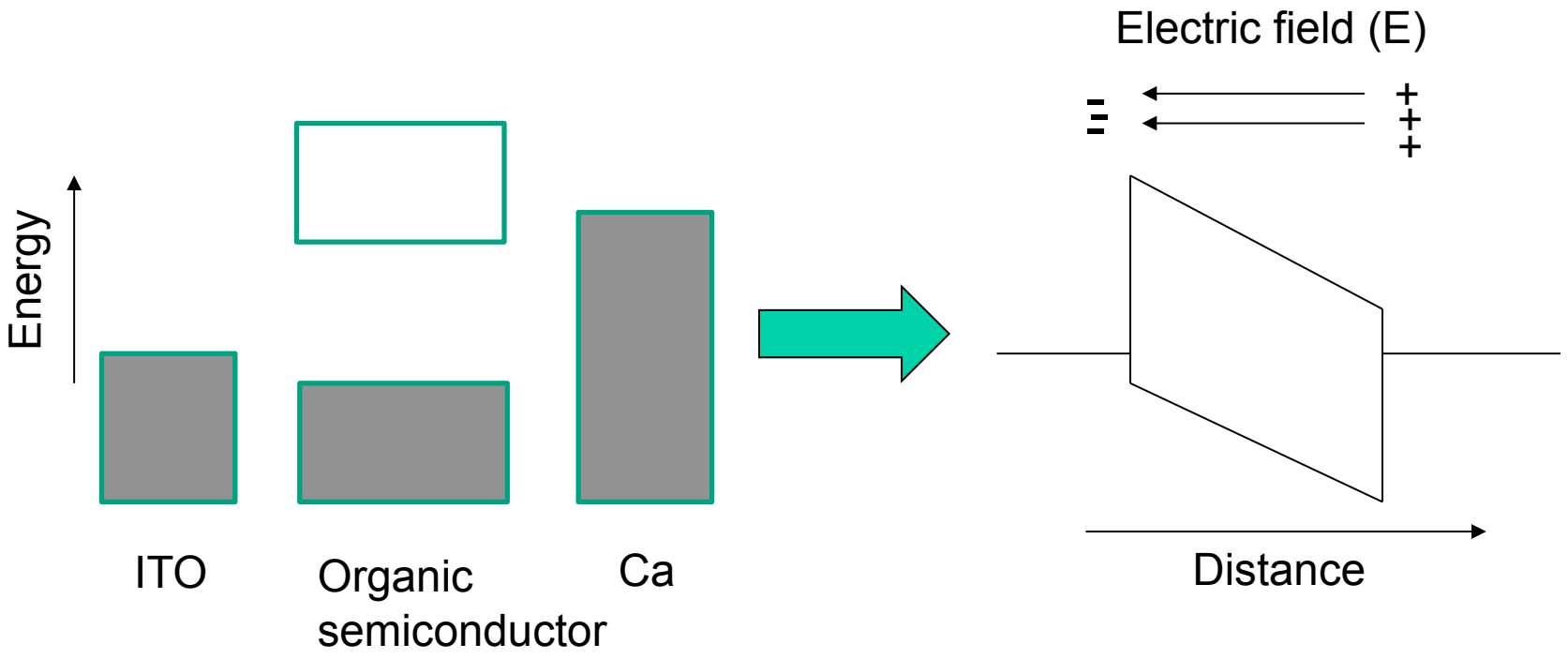


Source: NREL

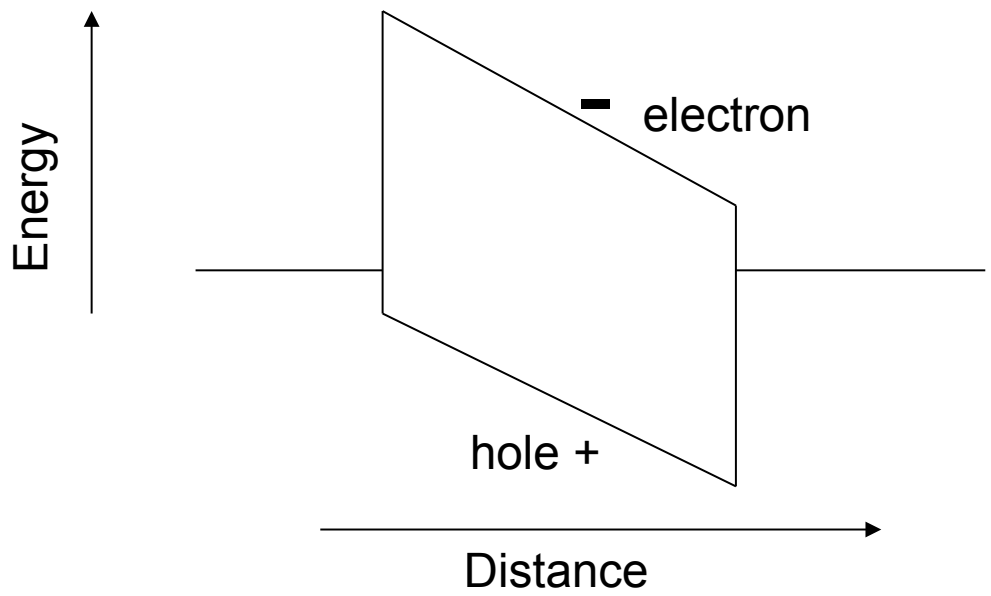
A fair comparison of efficiency

- Cells are rated at 1 sun, normal incidence and 25 °C.
- Organic PV holds it performance better than Si at low light, low angles and high temperature.
- Averaged over the year an organic PV system will get 30 % more power than a Si system with the same rating.

Using two different metals to create an electric field

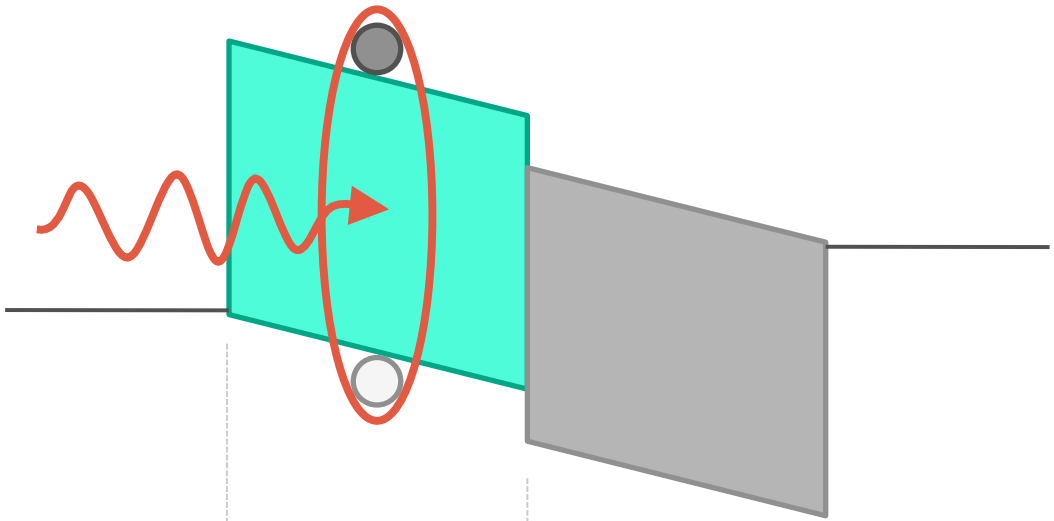


Single semiconductor organic PV cells



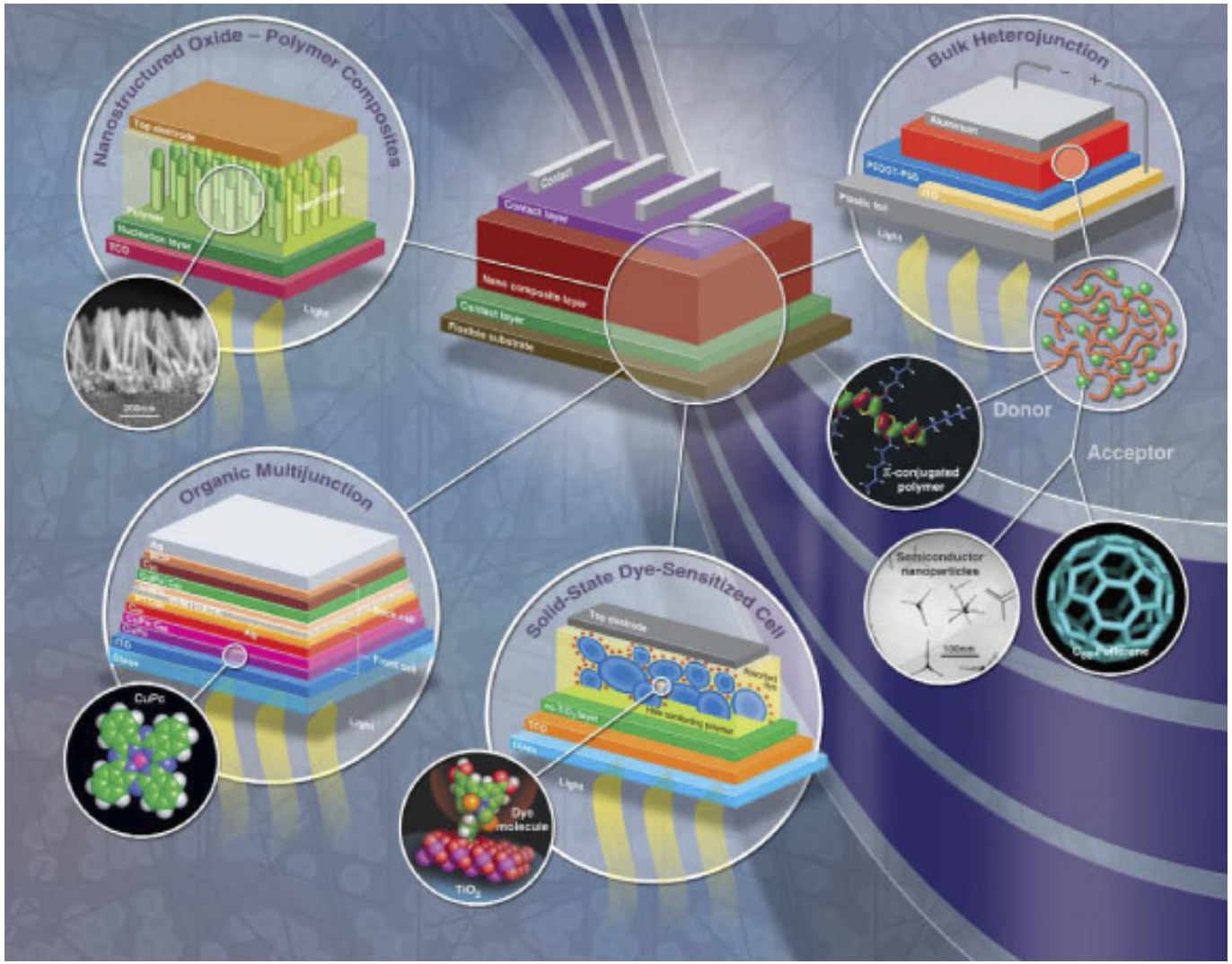
The electron and hole are bound to each other in an exciton.

Splitting the exciton with a second semiconductor



1. Light absorption
2. Exciton diffusion
3. Exciton splitting
4. Charge extraction

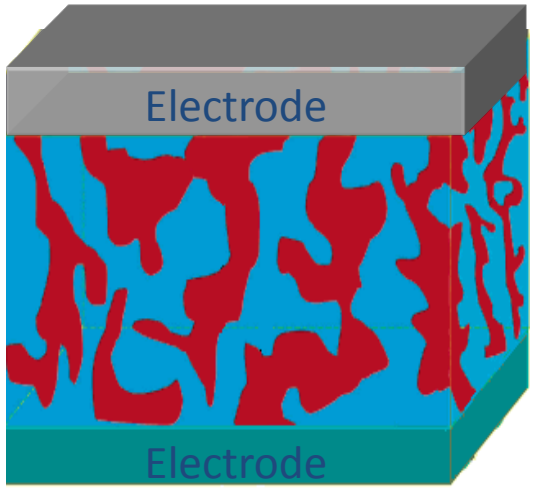
Bulk Heterojunctions



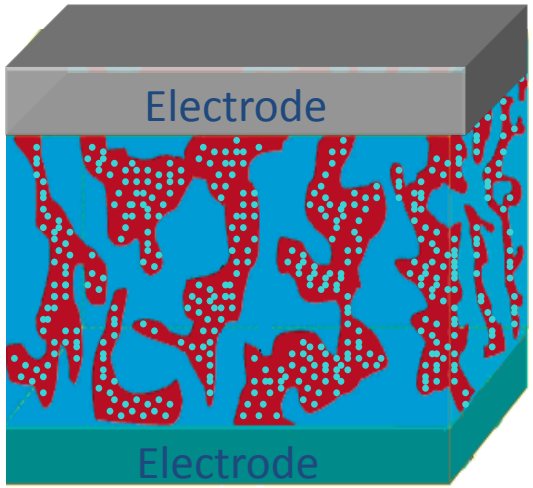
January 2005 *Materials Research Society Bulletin*

Possible structures

Bulk Heterojunction



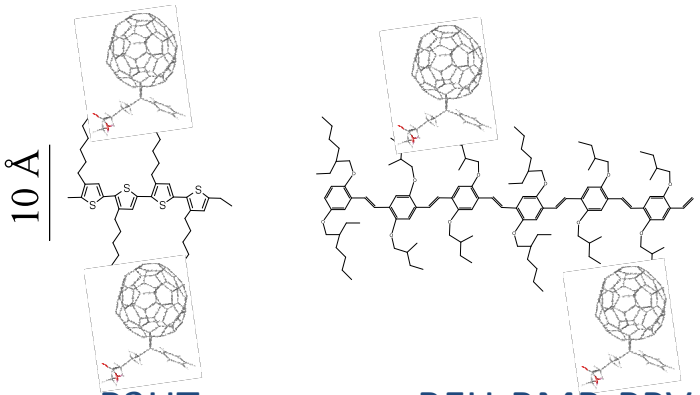
Bulk Heterojunction with Mixed Phases



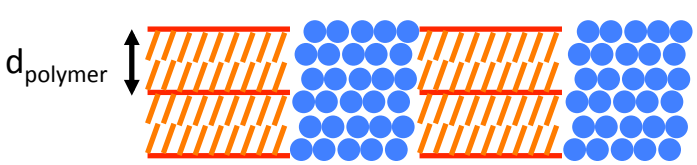
- Donor (Polymer)
- Acceptor (PCBM)

Effect of acceptors (fullerenes) mixing with the donor (polymer)

Dense Side Chains
No Intercalation



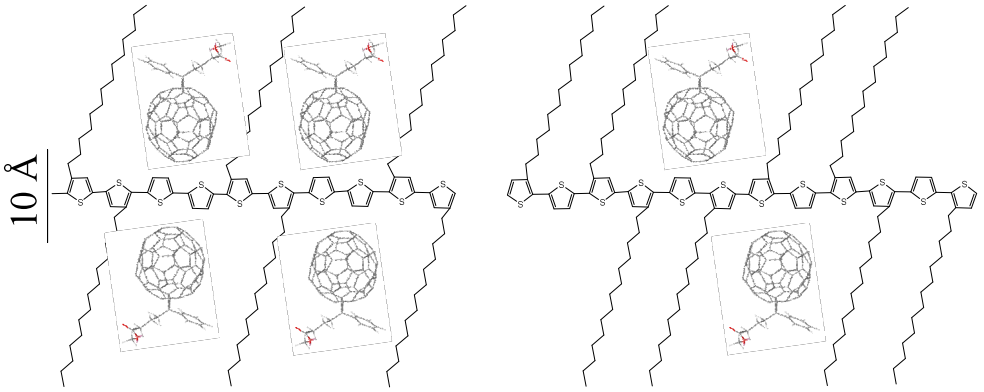
P3HT BEH-BMB-PPV



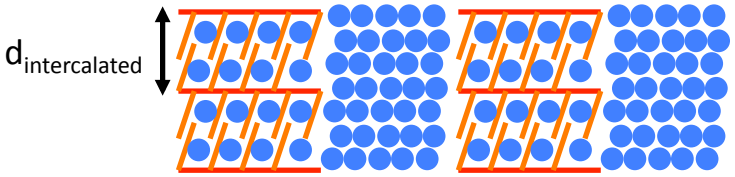
Optimum Blend Ratio ~1:1

polymer:fullerene (w:w)

Sparse Side Chains
Intercalation is Possible



PQT PTT



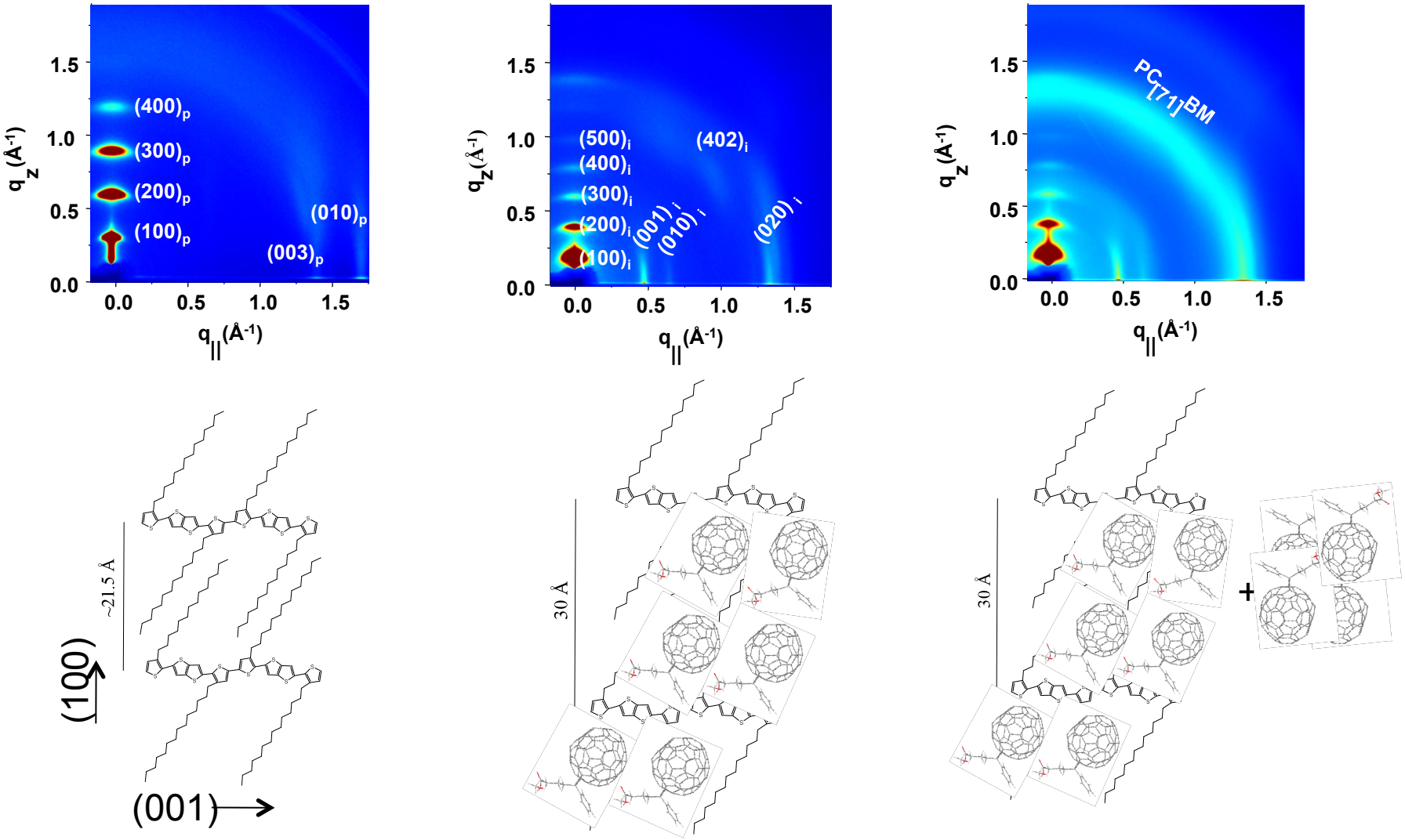
Optimum Blend Ratio ~1:3-1:4

polymer:fullerene (w:w)

A.C. Mayer, et al., *Advanced Functional Materials* 19 (2009) 1173.

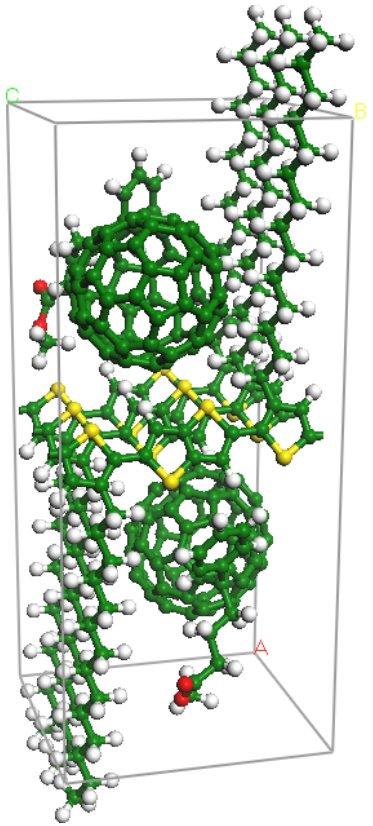
X-ray Diffraction polymer:fullerene Blends

0 wt% fullerene 50 wt% fullerene 80 wt% fullerene



A.C. Mayer, et al., Advanced Functional Materials 19 (2009) 1173.

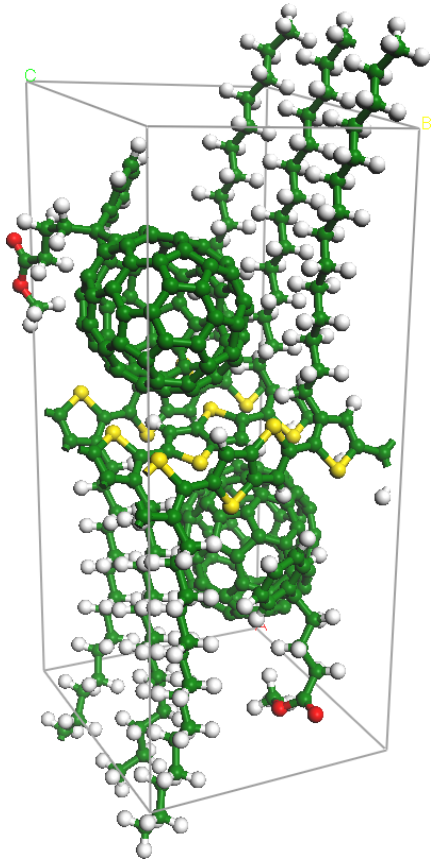
Molecular Mechanics Simulations



Initial
10861 kcal/mol

after 1 iteration:
4898 kcal/mol

Several Iterations



final
2497 kcal/mol

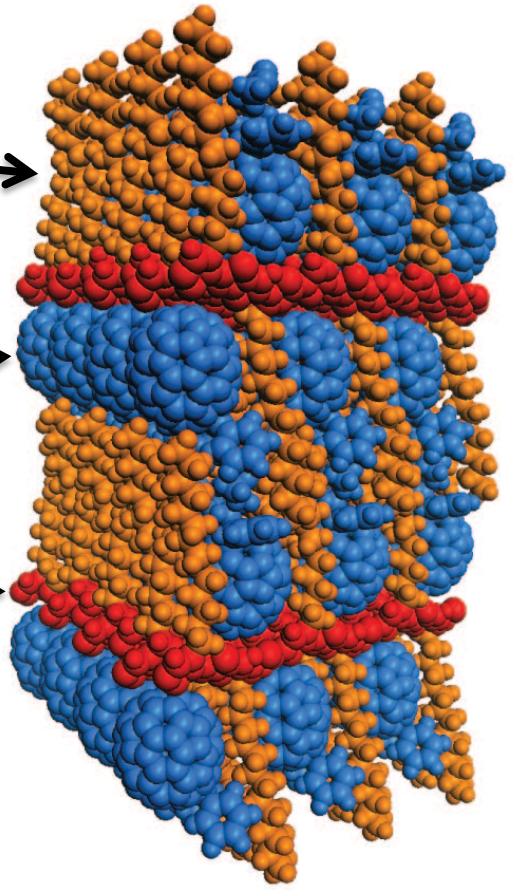
Eunkyung Cho, Chad Risko, Jean Luc Bredas at Georgia Tech

Polymer:Fullerene Molecular Structure and Its Impact on Charge Transport

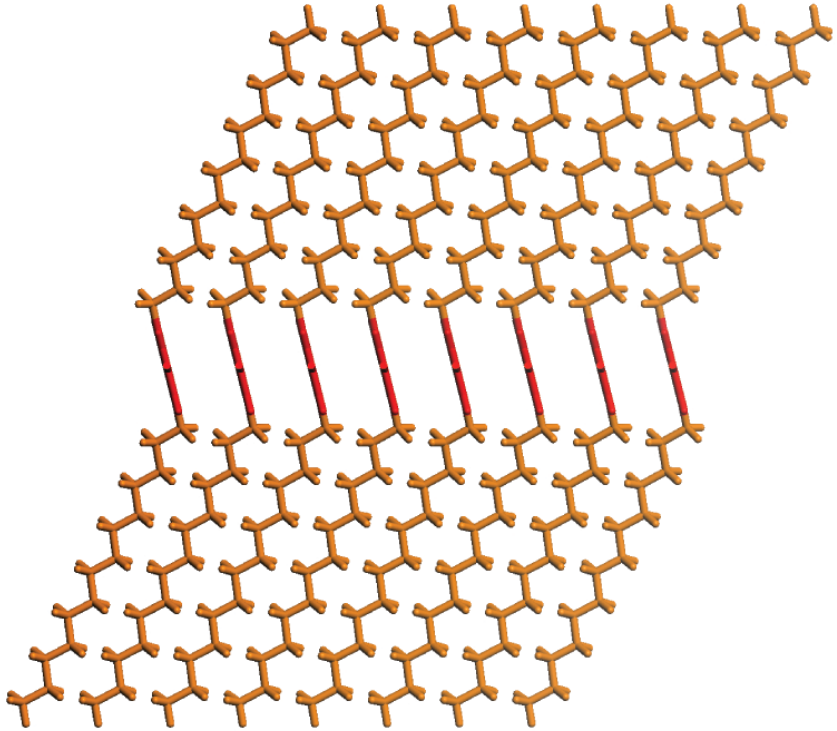
Curved, Insulating Side Chains

1D Electron-Conducting Fullerene Channels

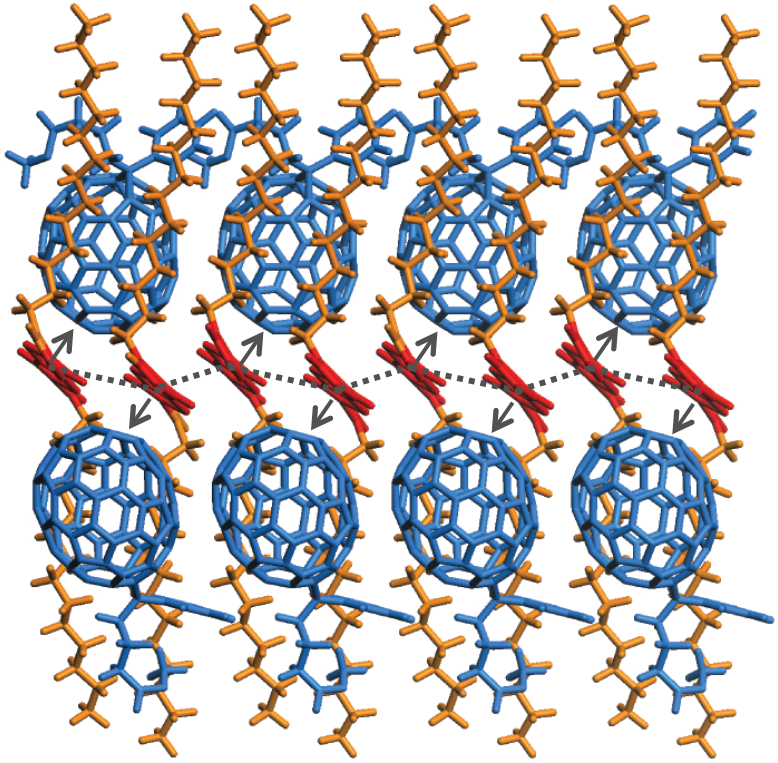
2D Hole-Conducting Sheets



Polymer

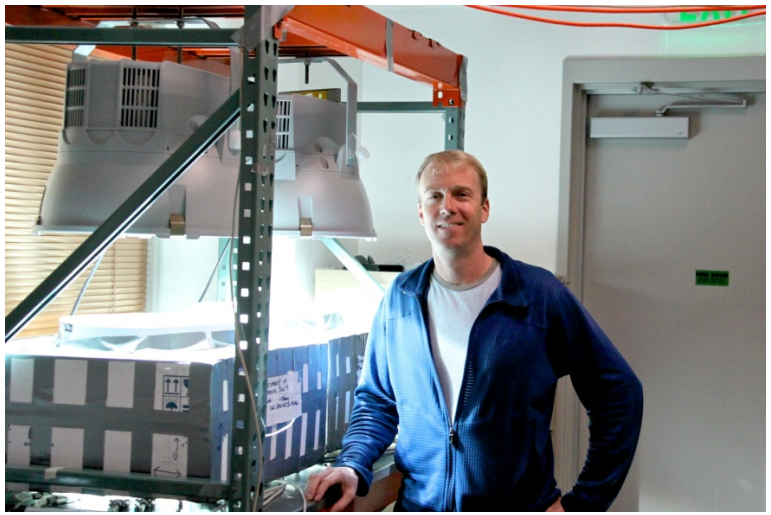


Polymer:fullerene



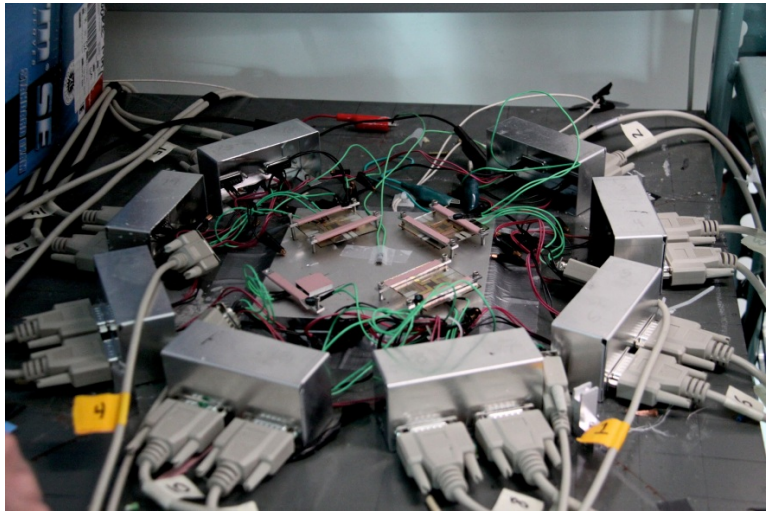
Can organic solar cells last 25 years?

Long-term Lifetime Measurements

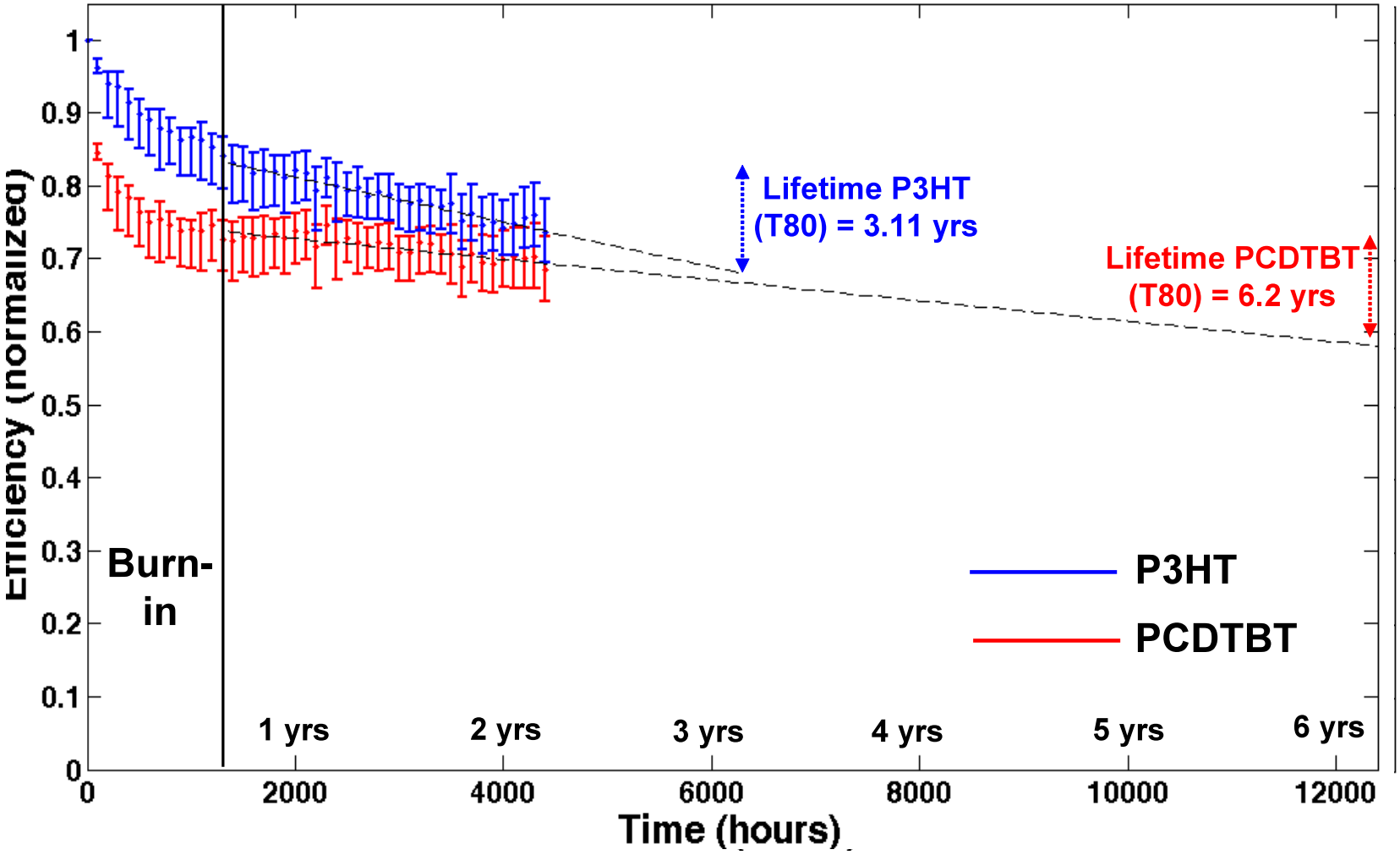


Devices held at:

- **37°C +/- 2°C**
- **One-sun intensity (no-UV)**
- **Max power point**



Average lifetime of devices (using 8 devices of each type)



Craig Peters, M.D. McGehee *et al.Advanced Energy Materials, 2011.*

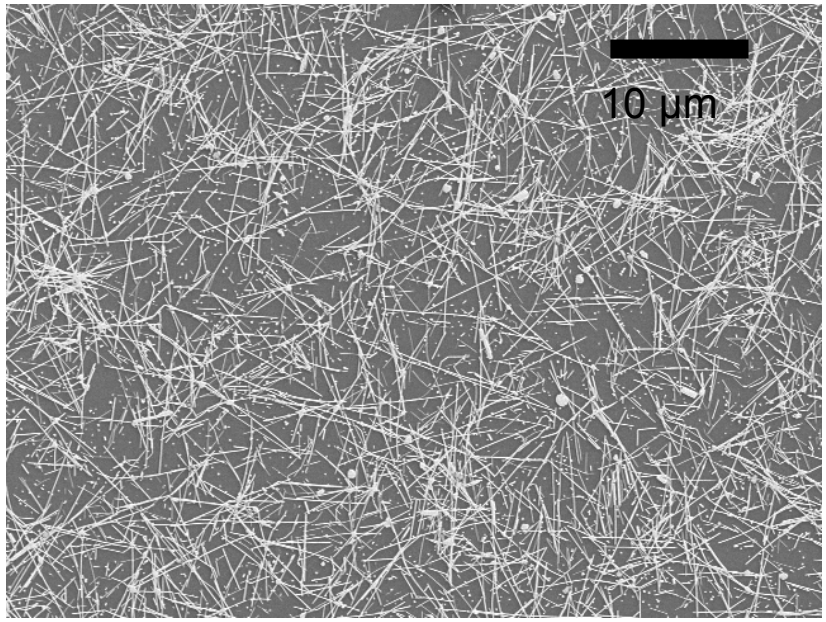
Outlook on reliability

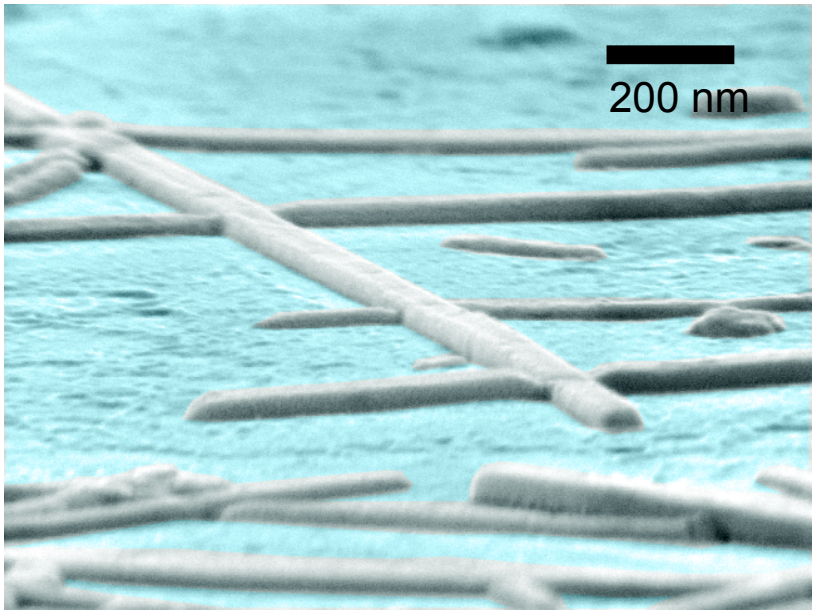
- Encapsulation will be needed.
- A UV filter will probably be needed.
- Many molecules are very stable in light.
- Organic light-emitting diodes are now very stable.
- It should be possible to make organic PV stable.

The conventional transparent electrodes is indium tin oxide (ITO)

- ITO is easy to get because the display industry uses it.
- It costs around $\$10/m^2$.
- It is sputtered in a vacuum chamber, not printed.
- It is conductive and transparent enough, but not on plastic.
- It is brittle.

Spraying Silver Nanowires

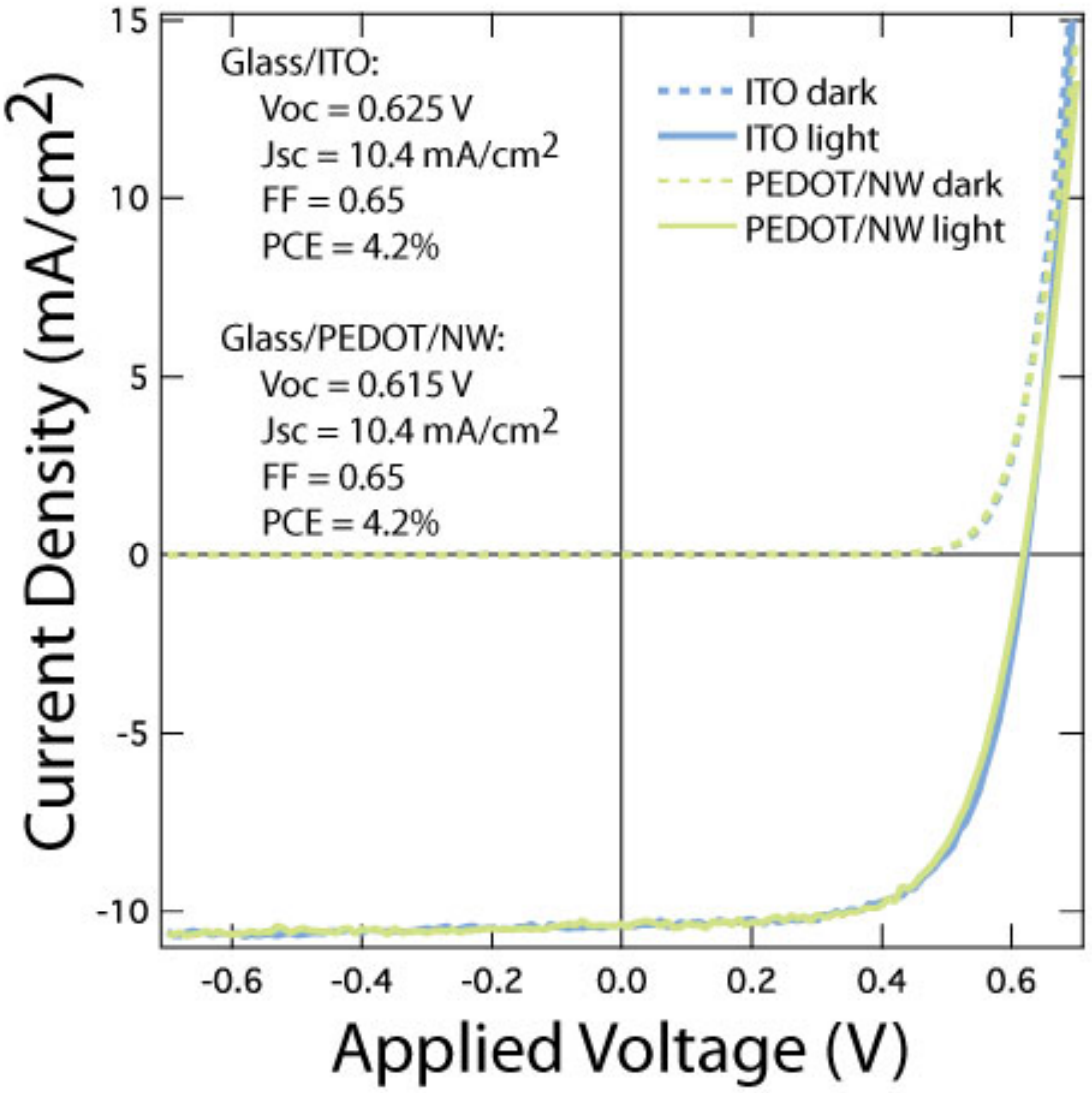




The wires are sprayed on glass on then pressed into a polymer film.

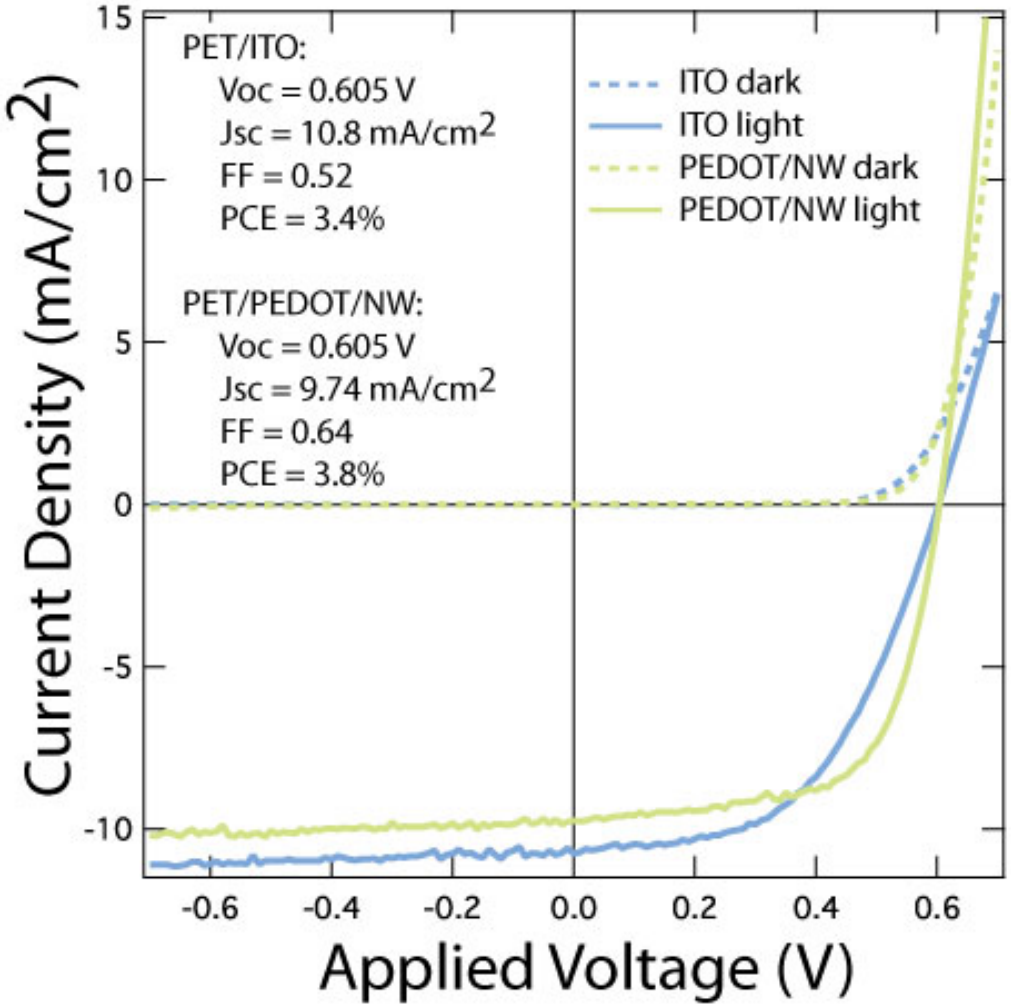
Whitney Gaynor, Peter Peumans et al, Advanced Materials, 23 (2011) 2905

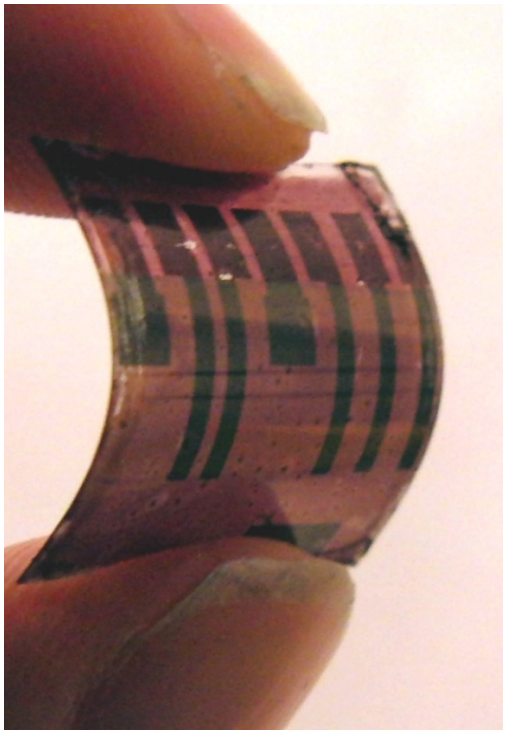
Polymer PV Cells with ITO or Silver NWs



Whitney Gaynor, Peter Peumans et al, Advanced Materials, 23 (2011) 2905

Flexible Polymer PV Cells



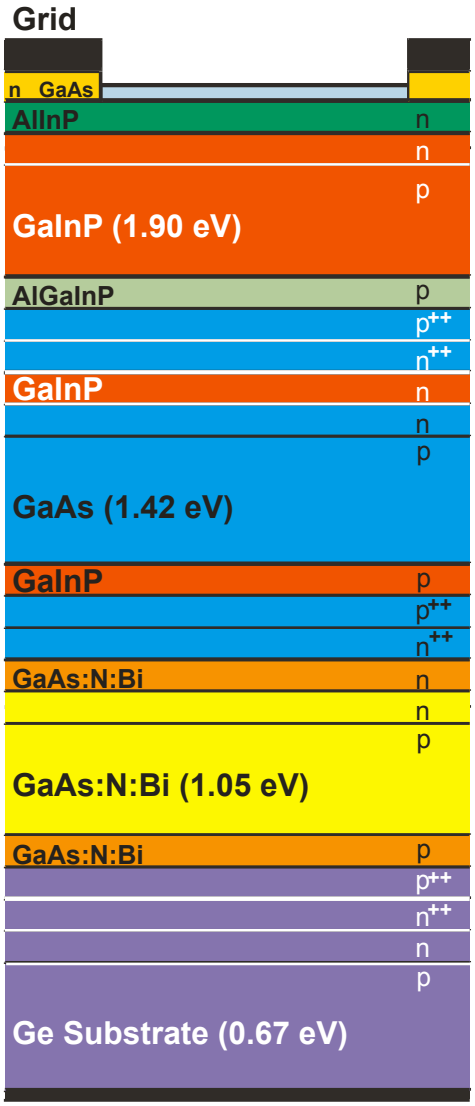


Whitney Gaynor, Peter Peumans

How can we beat the limit of 31 %?

Third Generation Photovoltaics

Multijunction (tandem) cells

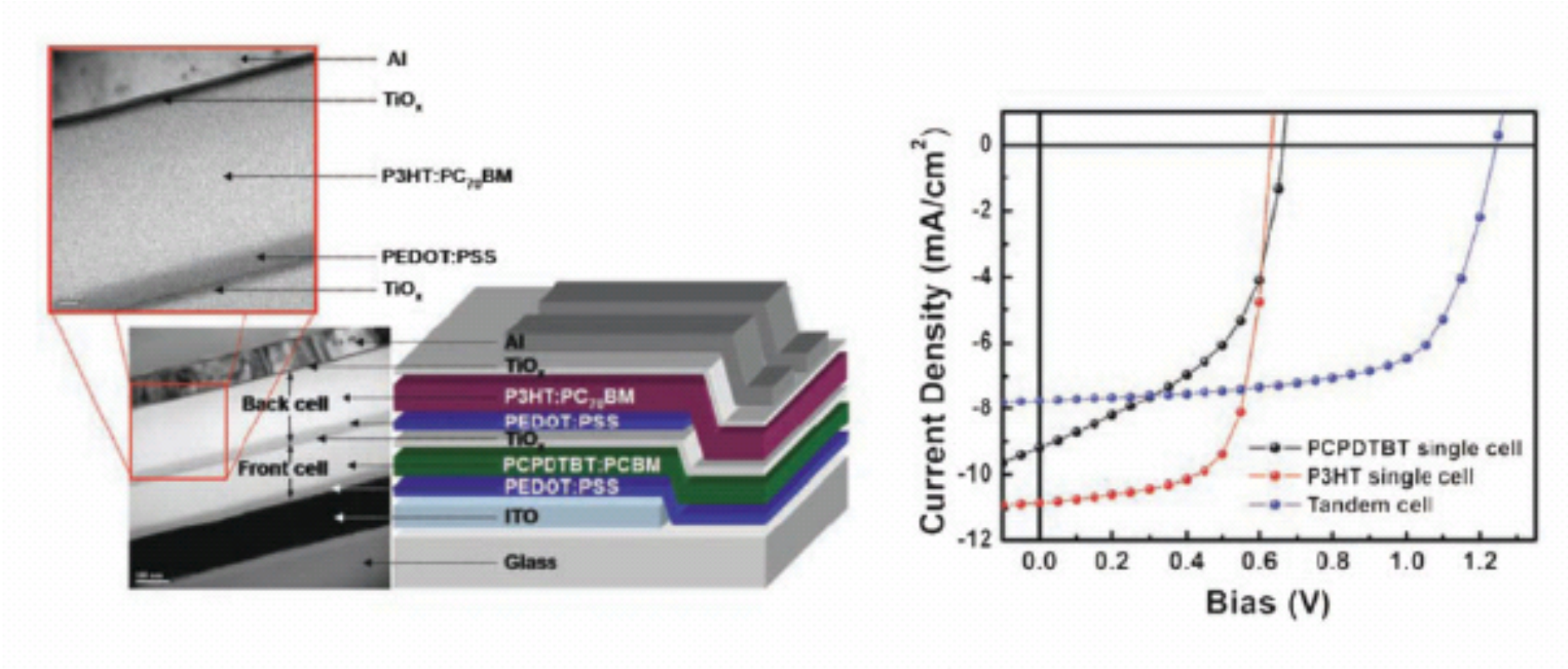


43.5 % efficiency has been achieved

Costs are estimated at $50,000/m^2, so concentrators must be used.

Concentrators need to point towards the sun to work, so trackers are needed.

Organic tandems



Heliatek has made tandems with 10 % efficiency.

Heeger et al. *Science* 317 (2007) p 222
See also a review article by Brabec et al. *Energy and Env. Sci.* 2 (2009) p. 347-363.
G. Schwartz et al., *Proc. of SPIE*, 7416 (2009) p. 74160K-1

Conclusions

- The solar industry is growing by 40 % each year.
- Grid parity has been reached in many places and will likely be achieved in most places by 2020.
- There is a race between silicon, CdTe, CIGS, a-Si, organic and tandem solar cells to capture a future $1 trillion/year market.
- Si has a commanding lead, but the race is far from over.
- Printing organics has huge potential.
- There is lots of fascinating science to do so solve this energy problem and many others.

More information and thanks

The Center for Advanced Molecular Photovoltaics
http://camp.stanford.edu