The Status of PV in 2008
and
a Look Ahead

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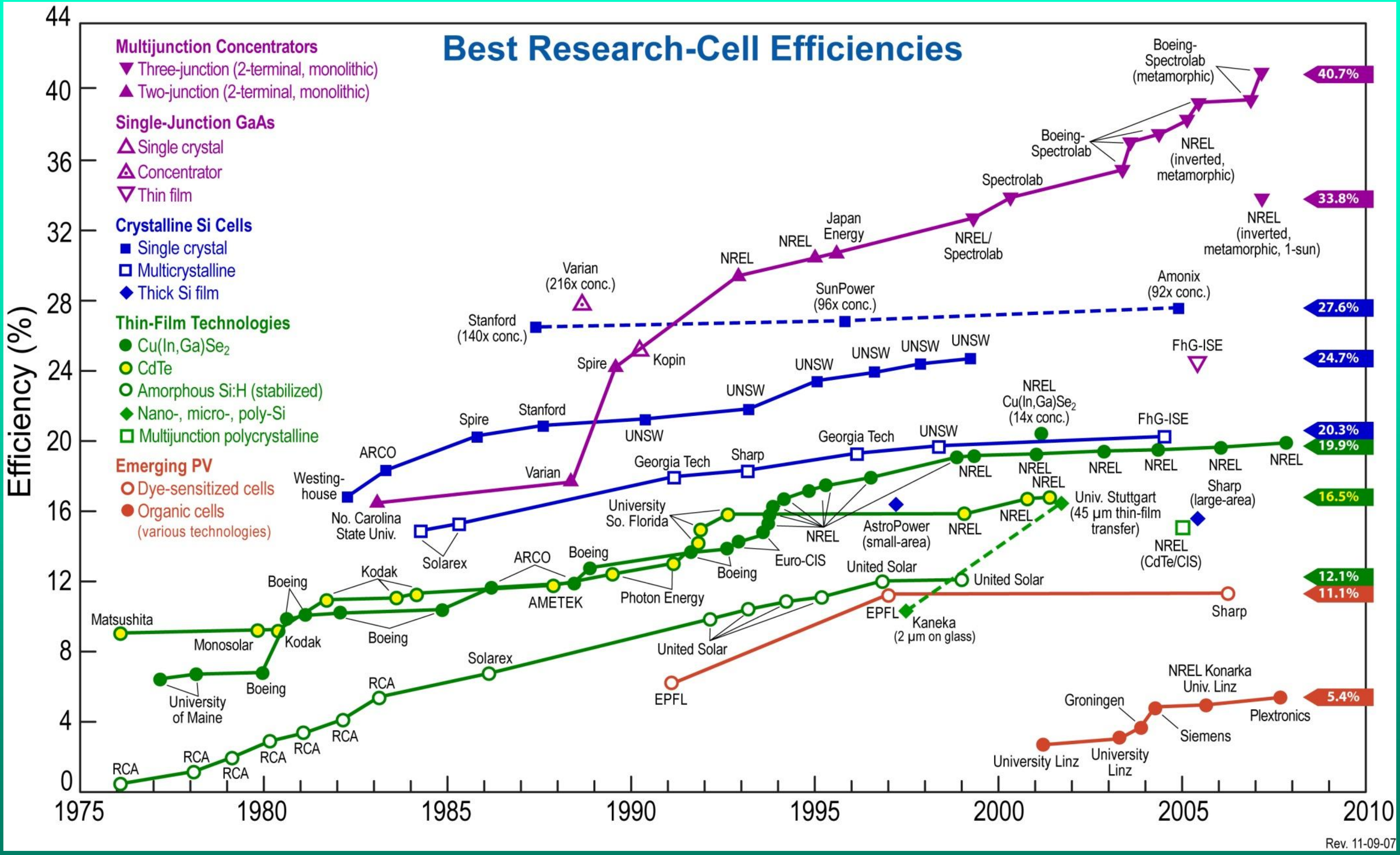
Outline

1. Survey of photovoltaic materials and small cells
2. Three generations of PV
3. Manufacturing technology for solar modules and systems -- thin films rising…
4. Commercial growth of PV in the U.S. and the world
5. Long-term potential for PV (>20% ?)

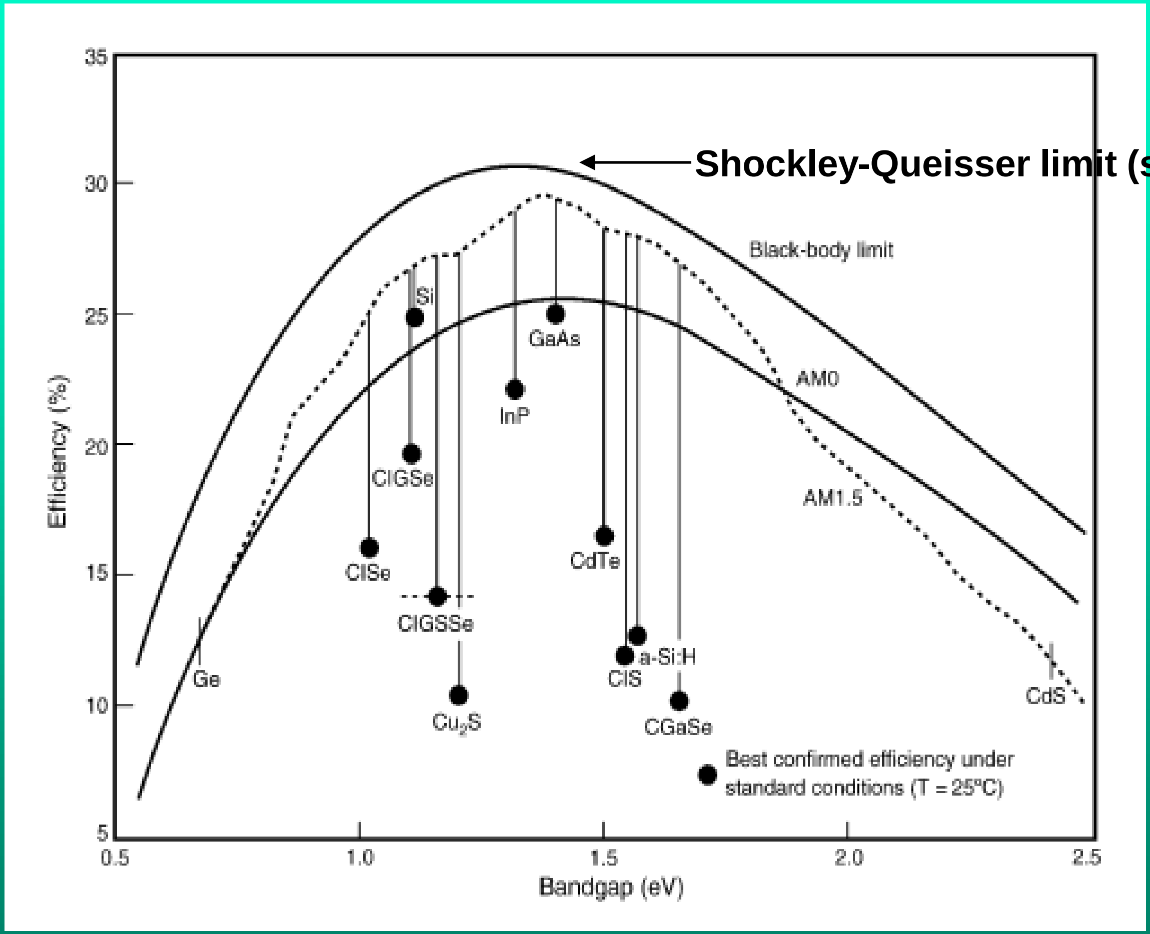
Champion Cell Efficiencies



from 5/28/08 presentation at U. Toledo by L. Kazmerski, Dir. NCPV, U.S. DOE

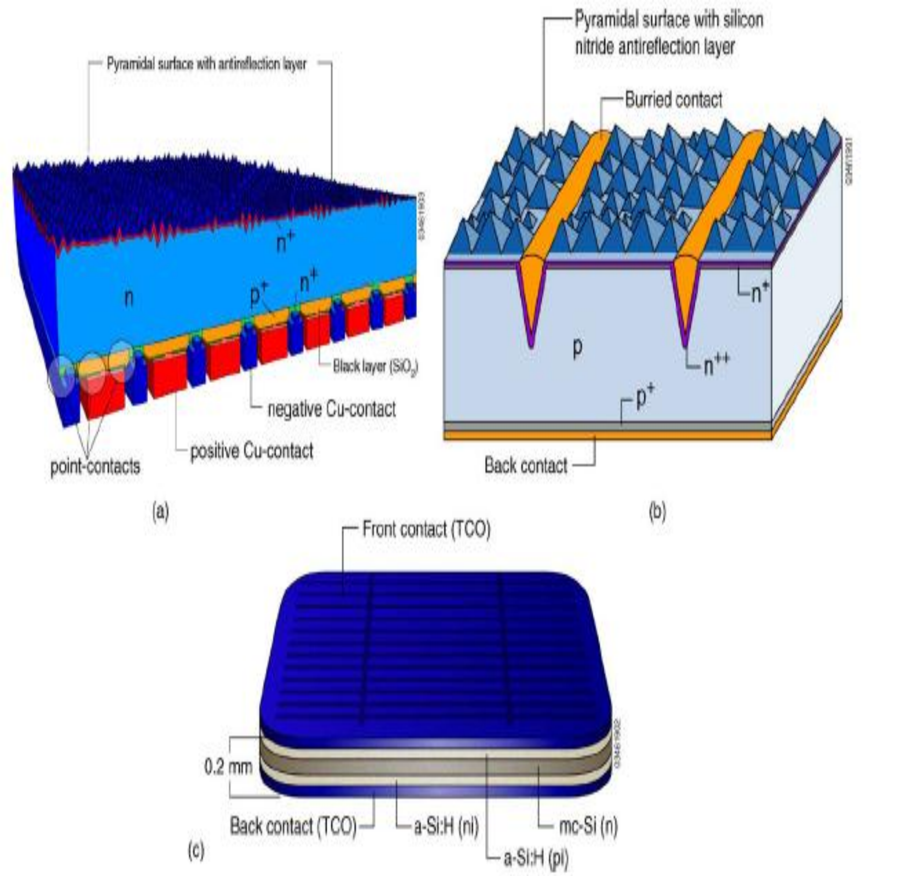
actual and attainable single junction cell efficiencies

(inorganic materials)



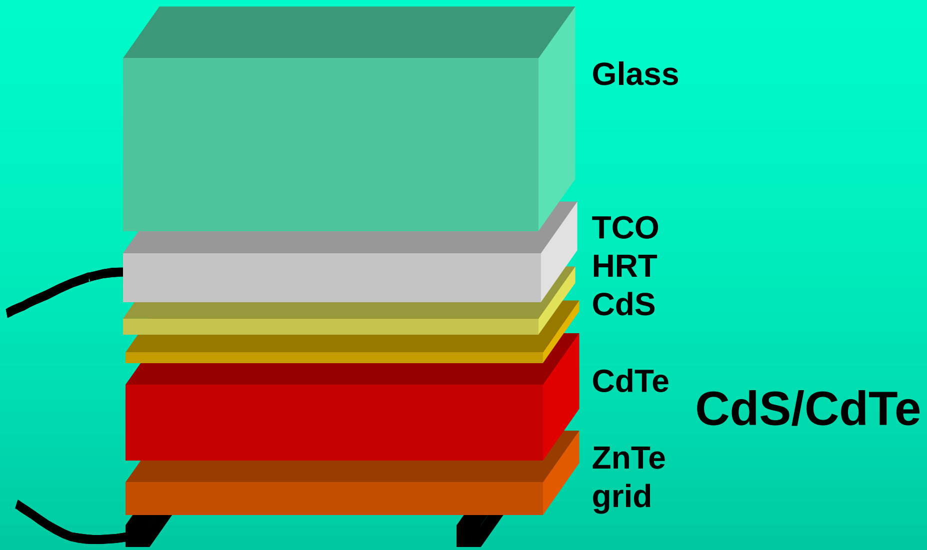
Attainable cell efficiencies for AM0 (solid line) and AM1.5 spectra (dashed line) and best efficiencies achieved for several materials as single junctions. (Kazmerski 2006)

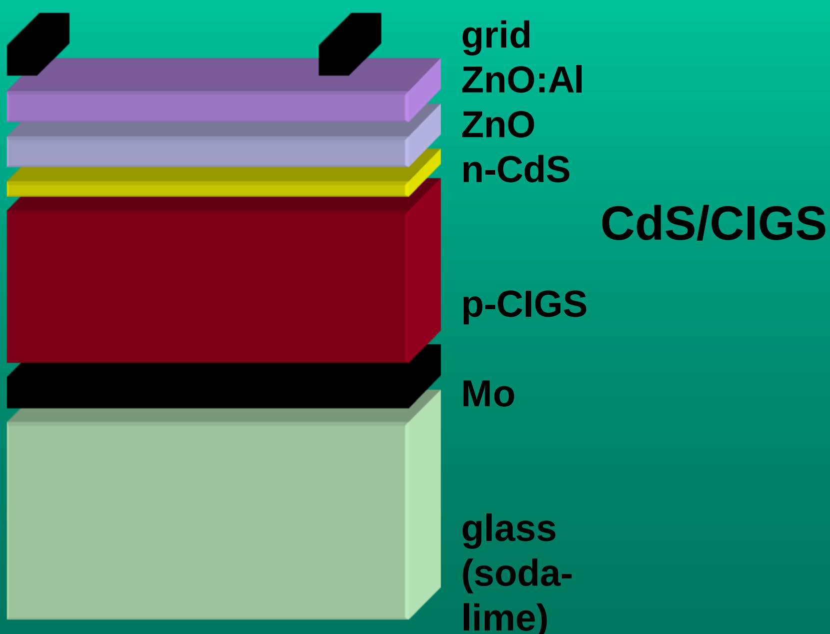
First generation:
wafer silicon modules



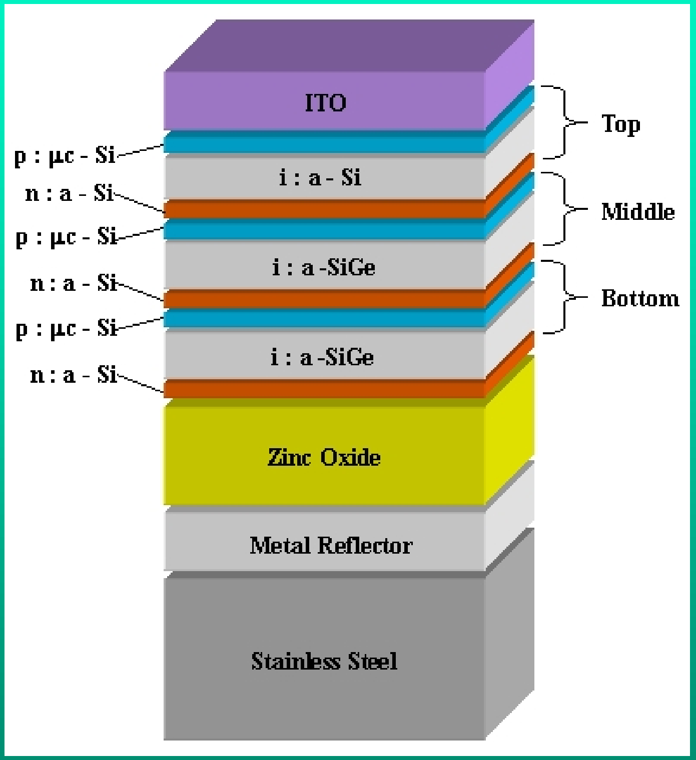
Three types of commercial silicon wafer cells as described in the text. From Kazmerski 2006.a) Sun Power, b) BP Solar, c) Sanyo HIT cell

Second generation (thin-film) cells





a-Si triple junction



Grain boundaries:

the challenge of polycrystalline thin-film cells

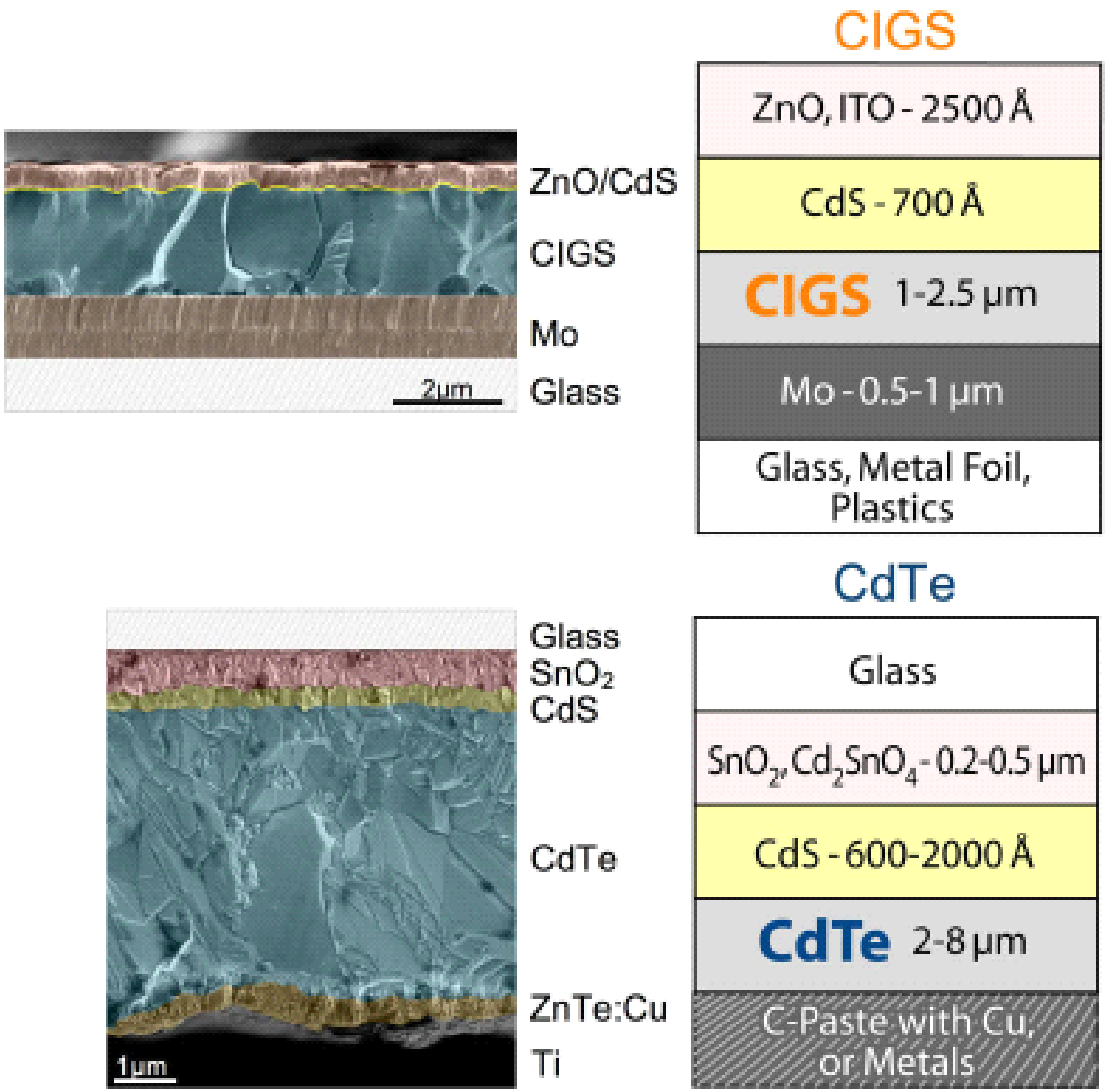


Fig. 4.2 Structure of the polycrystalline CIGS and CdTe cells. From Noufi 2006.

Third generation concepts

- multijunction III-V
- organic
- dye sensitized
- hybrid cells

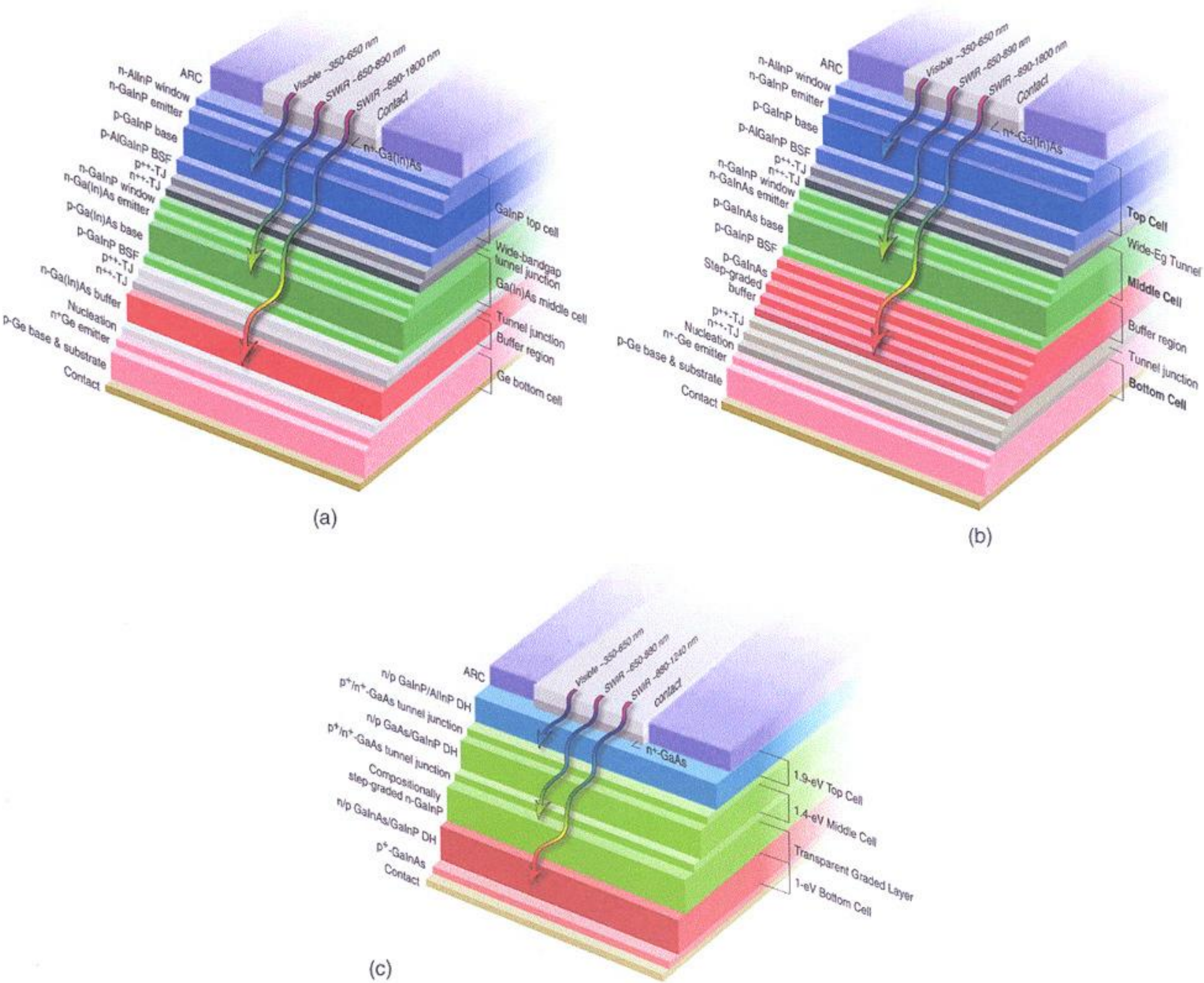
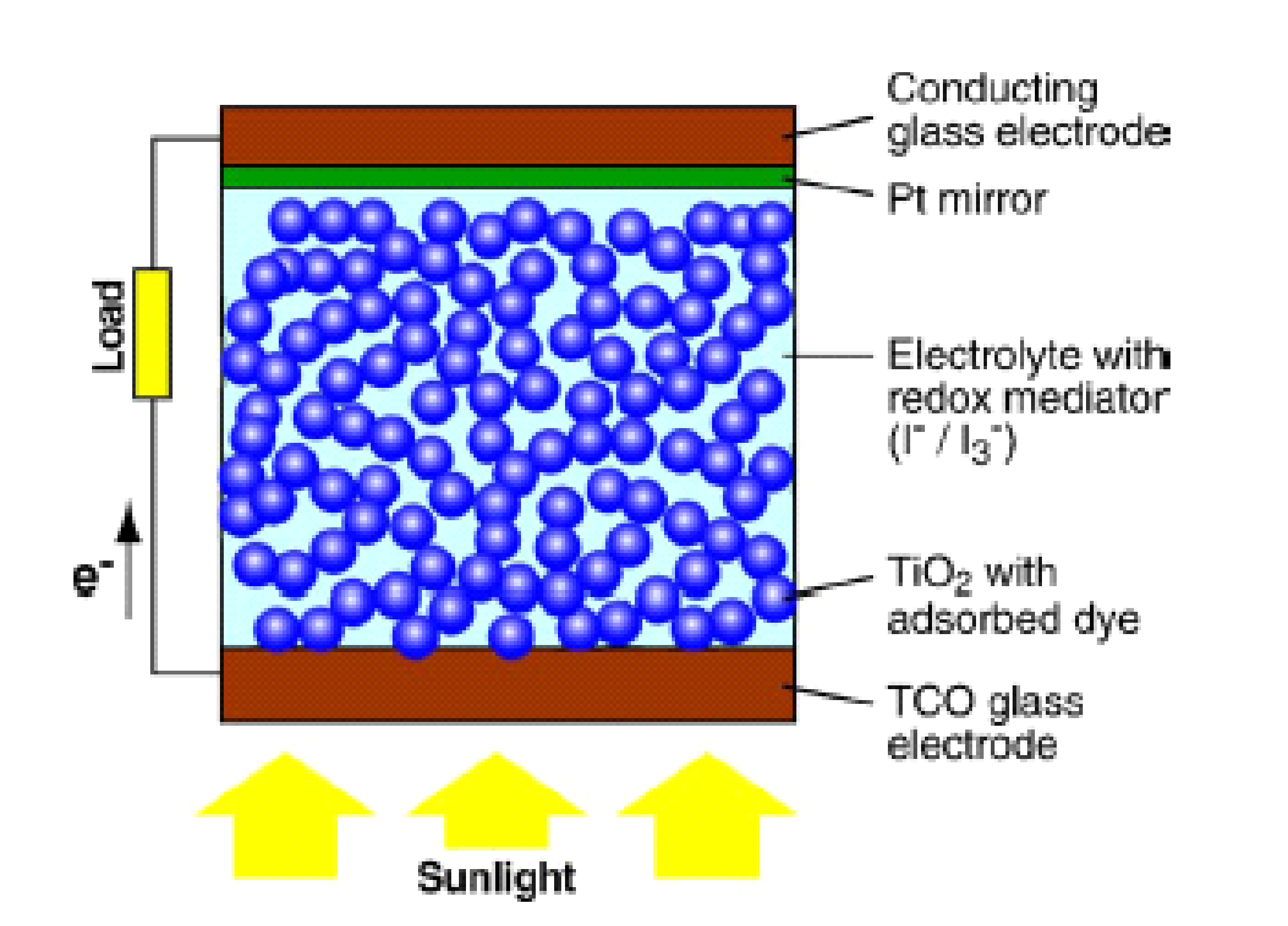


Fig. 17. Cross-sections of triple-junction, high-efficiency solar cells: (a) lattice-matched design, (b) lattice-mismatched (metamorphoric), and (c) latt mismatched, thin, inverted structure. ARC is the antireflection coating.

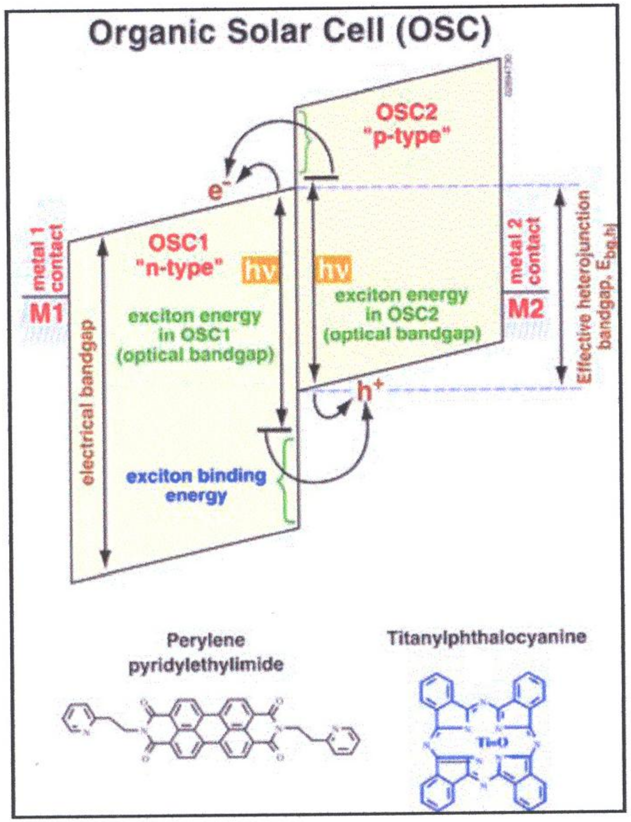
concentrators:

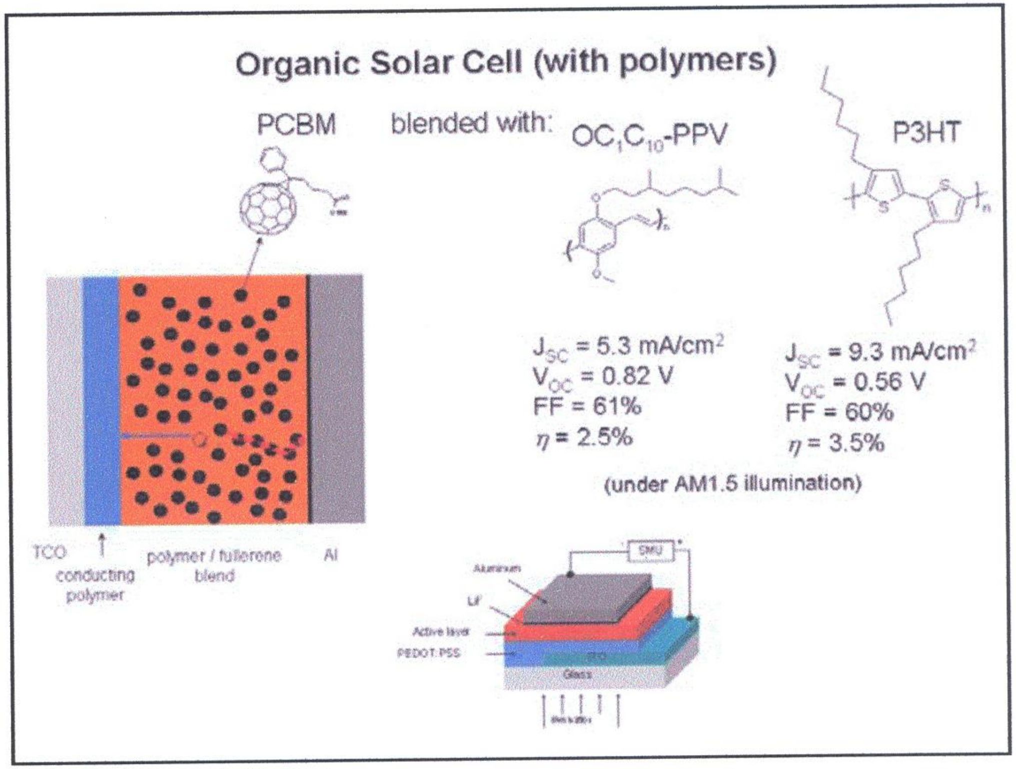
terrestrial implementation of high efficiency cells

Device representation of a dye-sensitized solar cell



Band diagram and processes for polymer organic solar cells



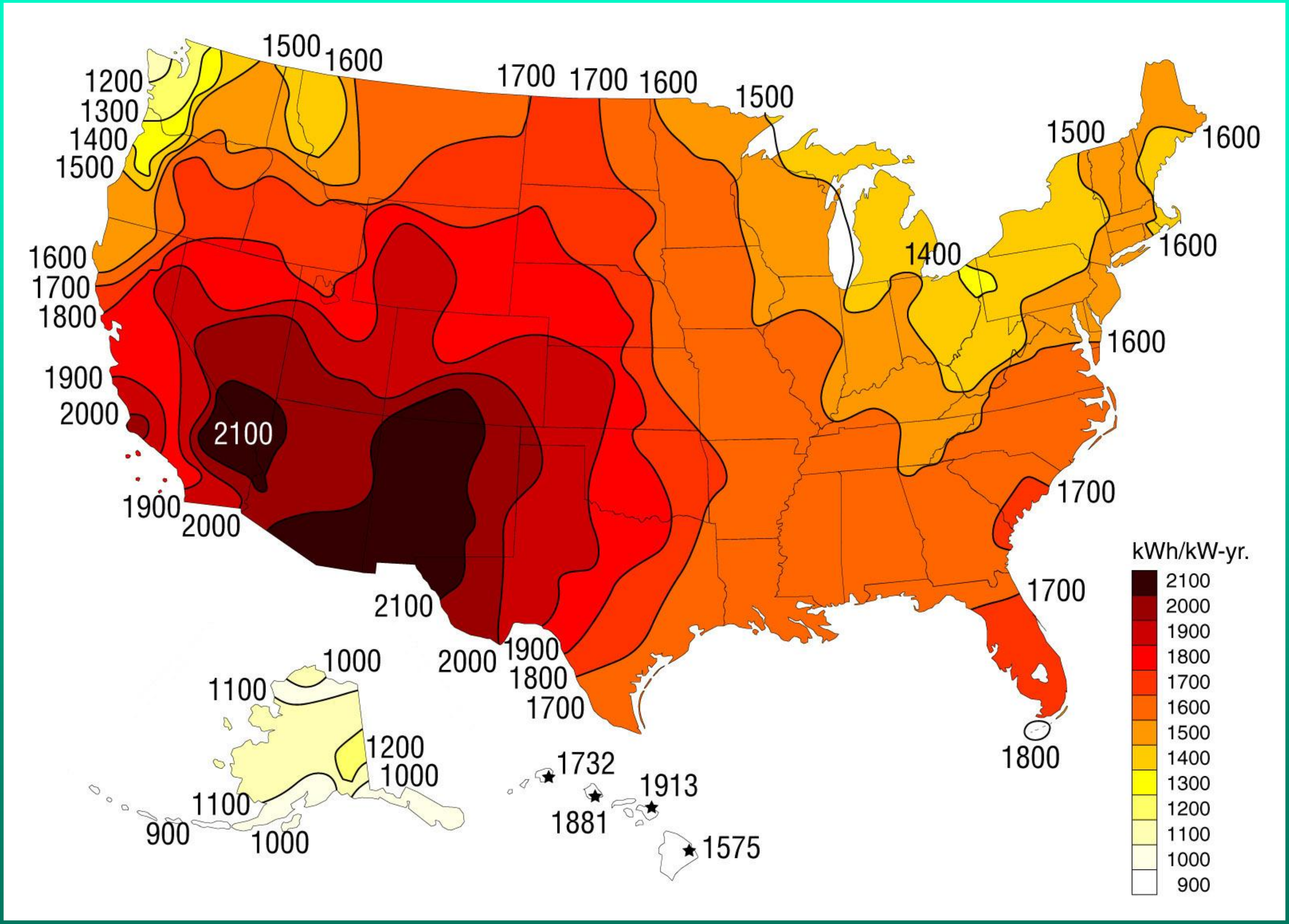


PV modules

- solar resource (U.S.)
- history of cost reductions
- manufacturing technology

PV Energy kWh/kW-yr

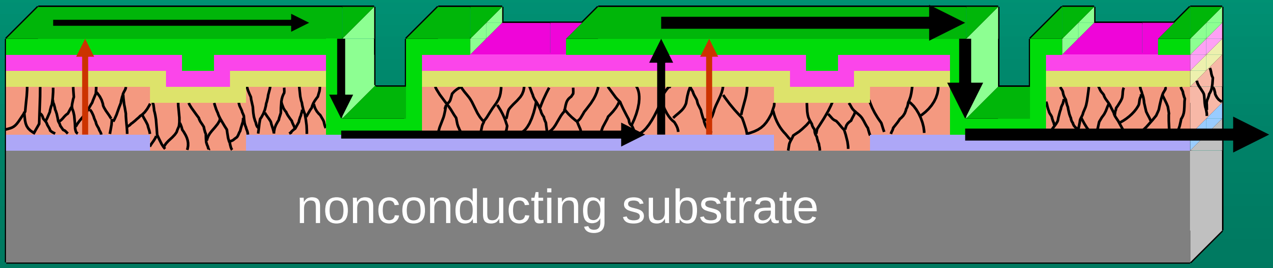
(for any flat solar module)



from cell to module--
series integration

assembly from smaller cells

monolithic integration



First Solar—the largest U.S. module producer

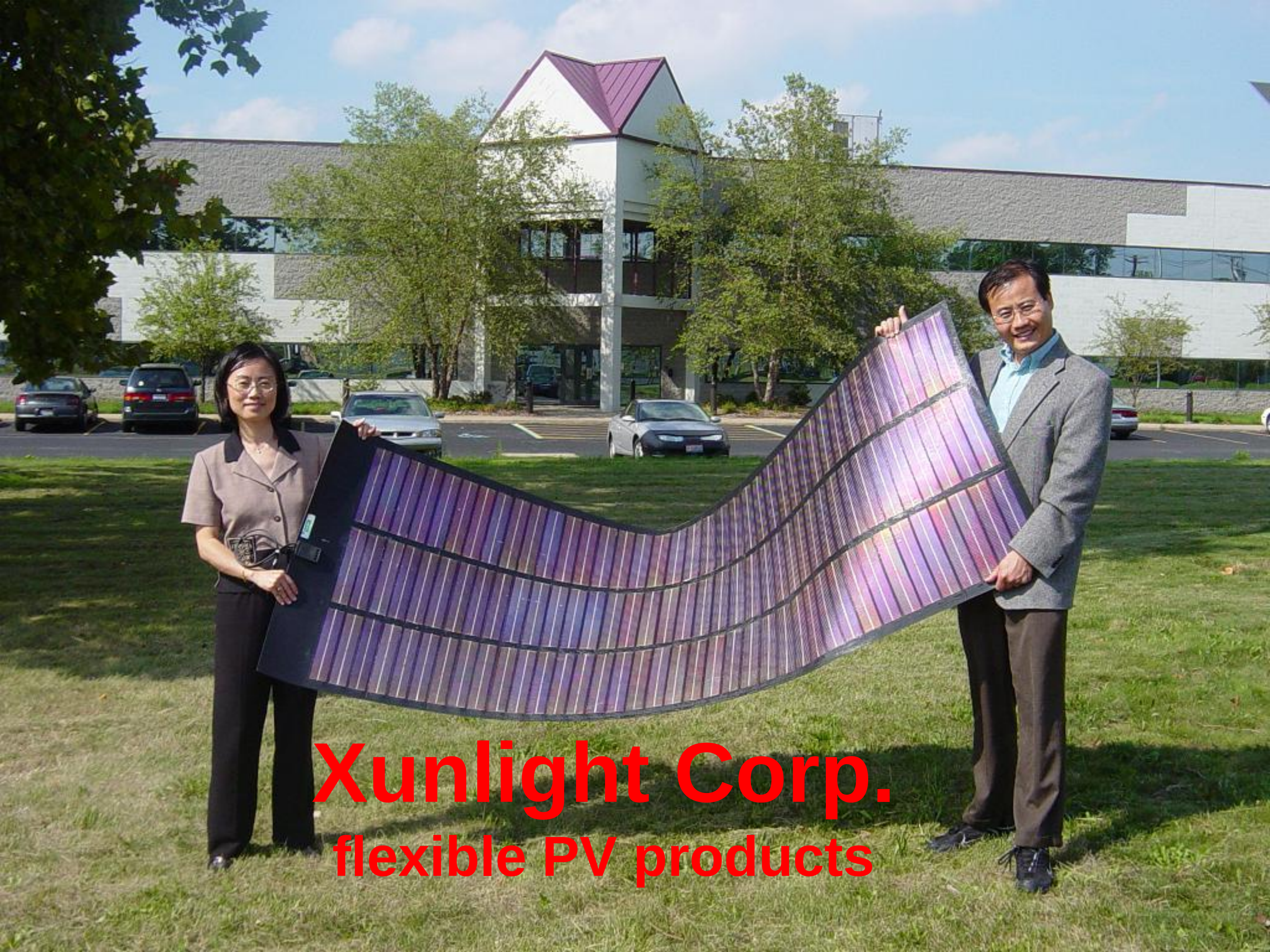
(Began as Solar Cells Inc on the U.T. campus)

Module Production Capacity:

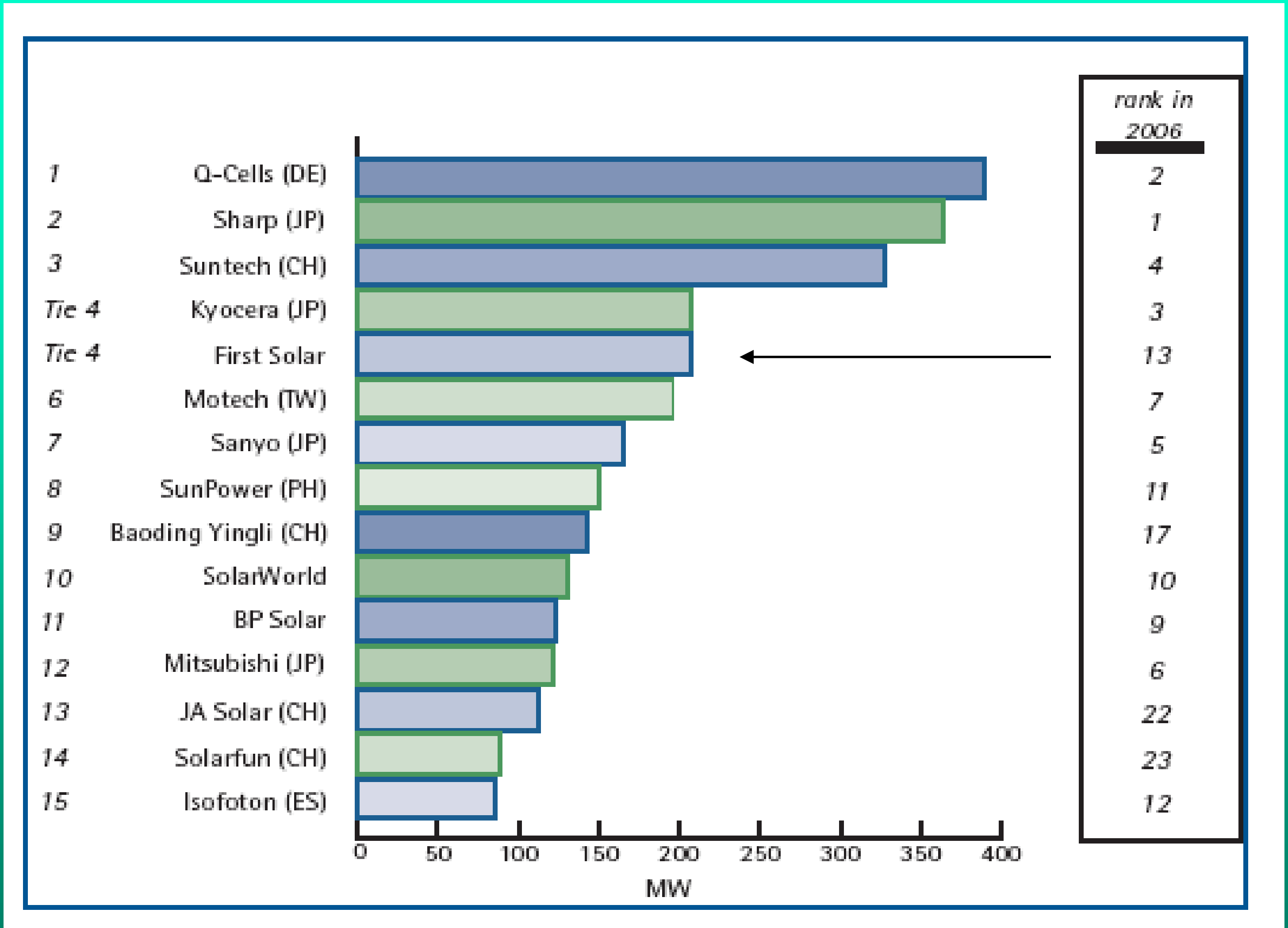
Ramped the first 25MW module production line in Perrysburg, Ohio to its steady state volume in 2005

Added two additional 25MW production lines in the U.S. in 2006

Annual Capacity = 75MW by end 2006 (raised to 90 MW in 2007)


Xunlight Corp.
flexible PV products

Top 15 Global Producers of PV in 2007

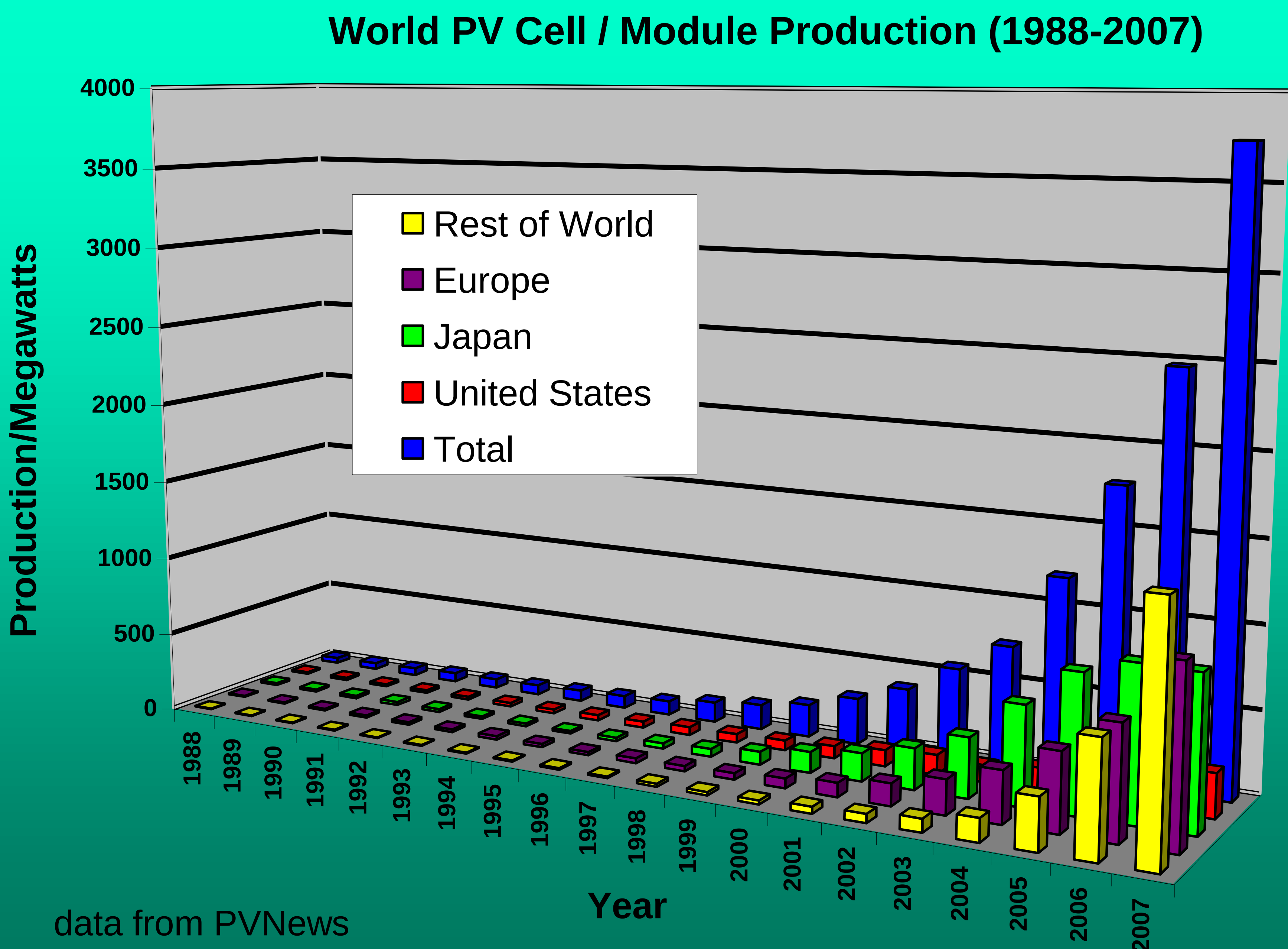


3/08 data from PVNews

Production of solar modules in the U.S.

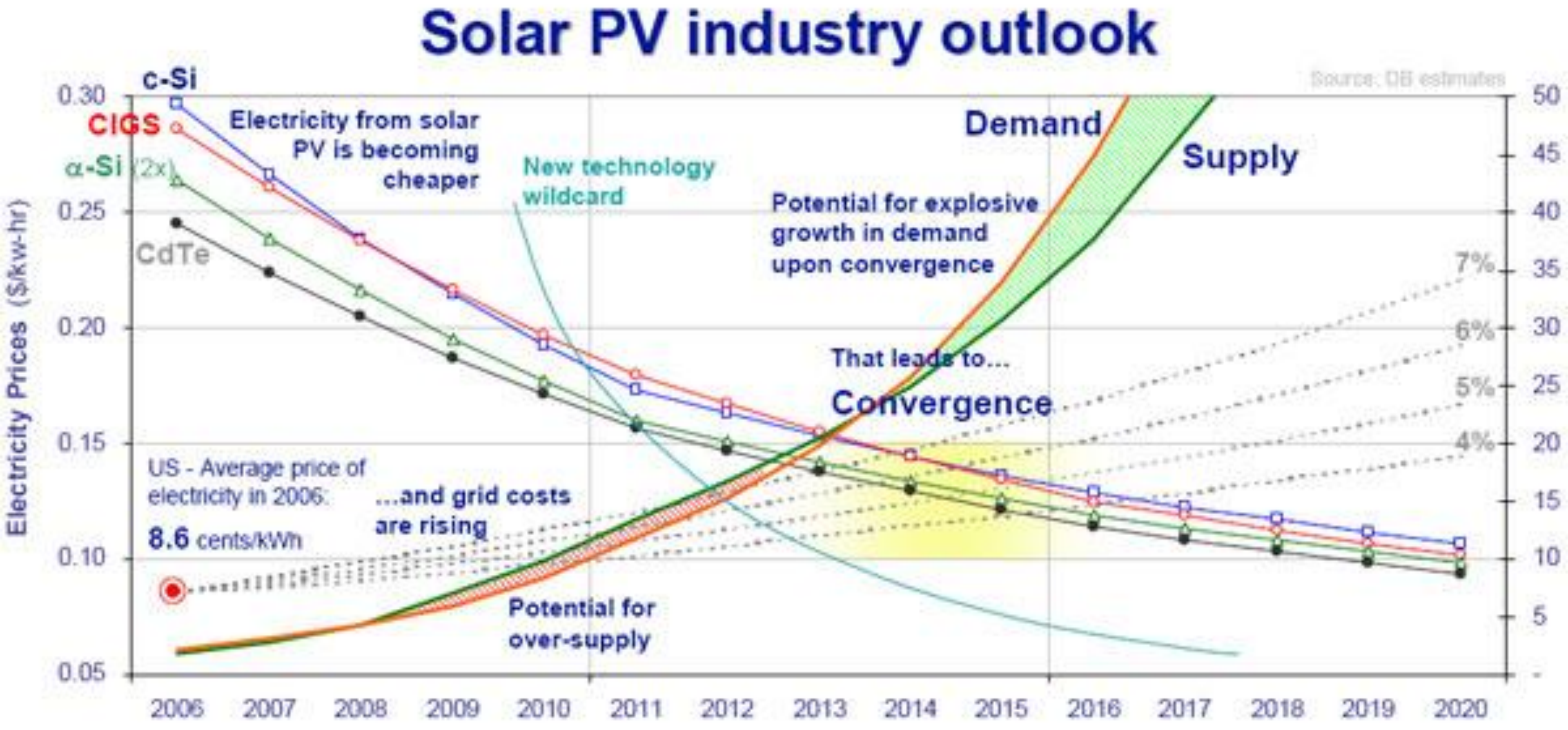
Company	2000	2001	2002	2003	2004	2005	2006	2007
Shell Solar/ Solarworld	28	39	47	52	62	42	35	35
BP Solar	21	25	31	13	14	22	25.6	27.7
United Solar*	**3**	**4**	**4**	**7**	**14**	**22**	**28**	**48**
First Solar*				**3**	**6**	**20**	**60**	**120**
GE					25	18	22	
AstroPower	18	26	30	17				
Schott Solar	4	5	5	4	10	13	13	10
Evergreen Solar			2	3	6	14	13	16.4
Global Solar				**2**	**1**	**1**	**2.5**	**4**
Other	2	1	3	2	1	1	2.5	5
TOTAL	**75**	**100**	**121**	**103**	**139**	**153**	**201.6**	**266.1**

***First Solar (Perrysburg, OH), UniSolar (Auburn Hills, MI) and Global Solar (Az) are exclusively thin-film PV mfgrs** (3/08 data from PVNews)


World PV Cell / Module Production (1988-2007)
Production/Megawatts
4000
3500
3000
2500
2000
1500
1000
500
0
Rest of World
Europe
Japan
United States
Total
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year
data from PVNews

Electricity price convergence – 5 to 6 years

(Source: Deutsche Bank 2007)



Definitions:

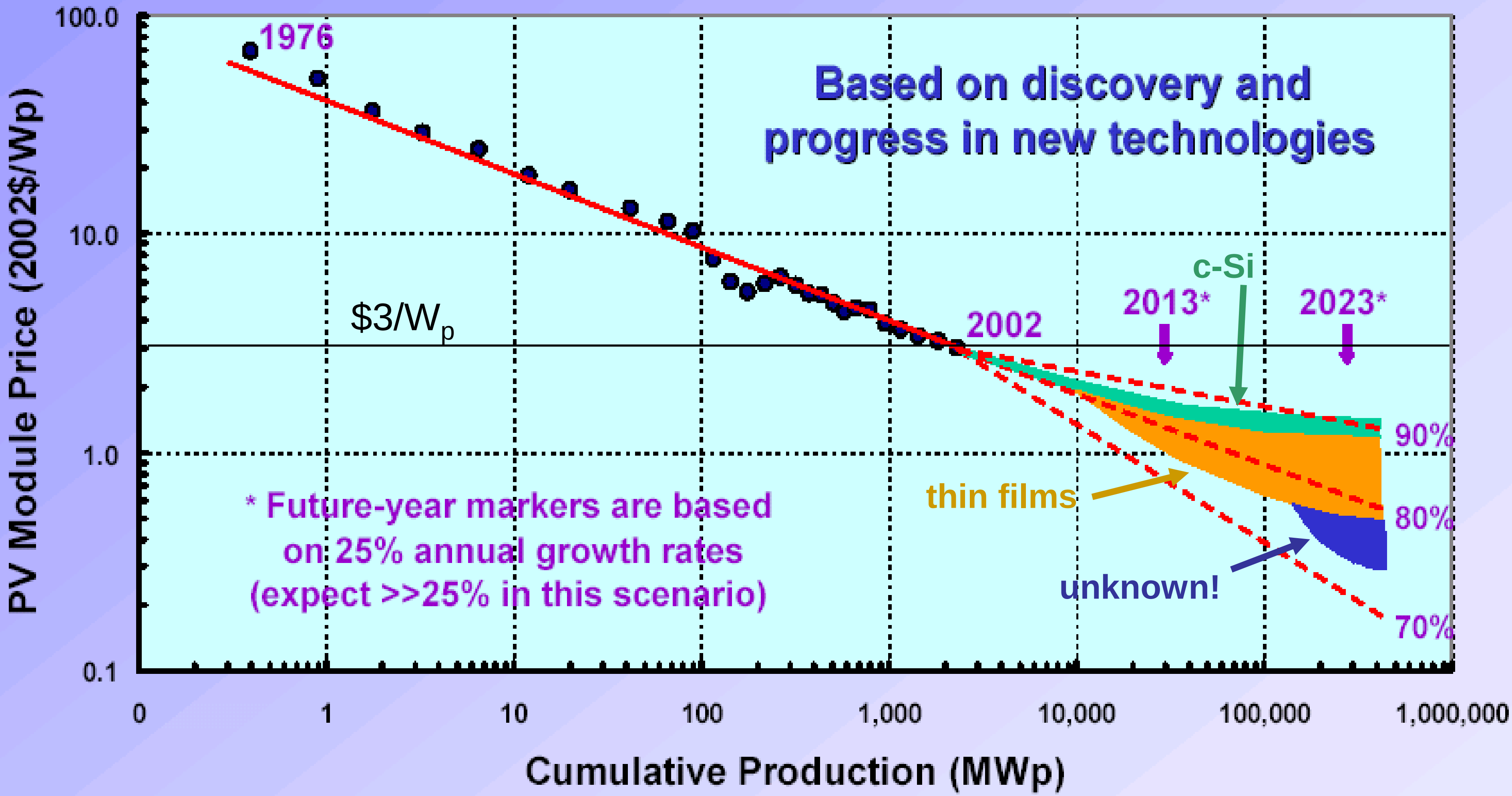
First Generation PV: bulk crystalline silicon (monocrystalline, multicrystalline)

Second Generation PV: inorganic thin films (CdTe, a-Si:H, nc-Si:H, CIGS)

Third Generation PV: nanostructures, organic/hybrid, advanced concepts

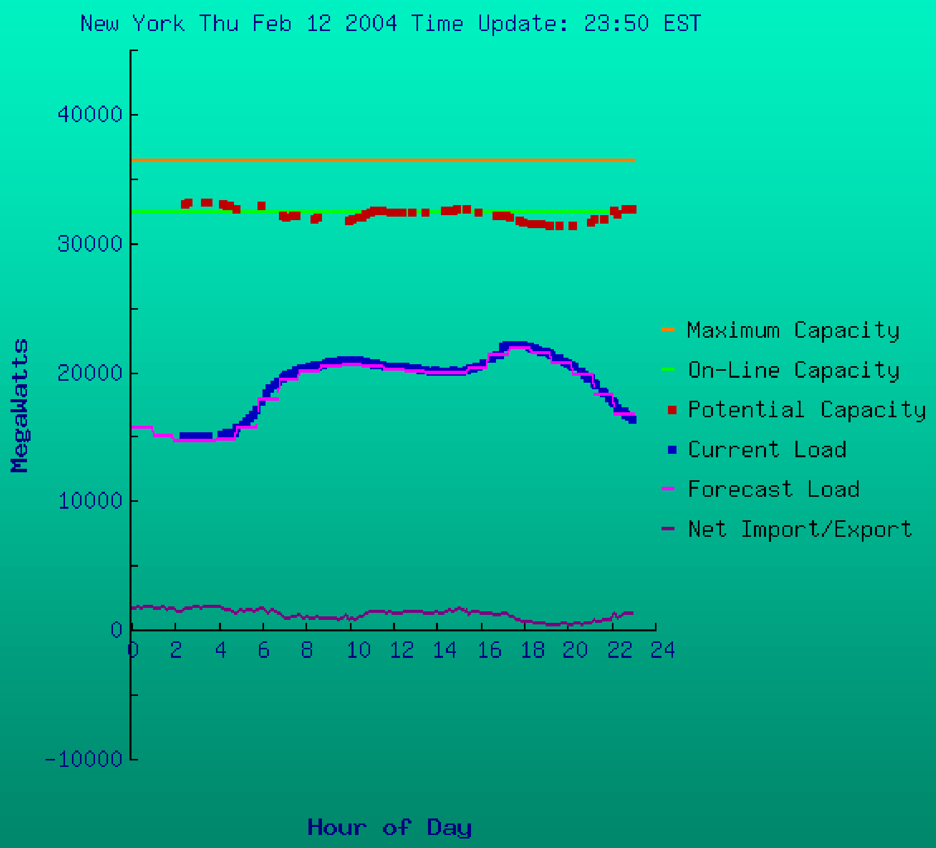
PV Module Production Experience (or "Learning") Curve

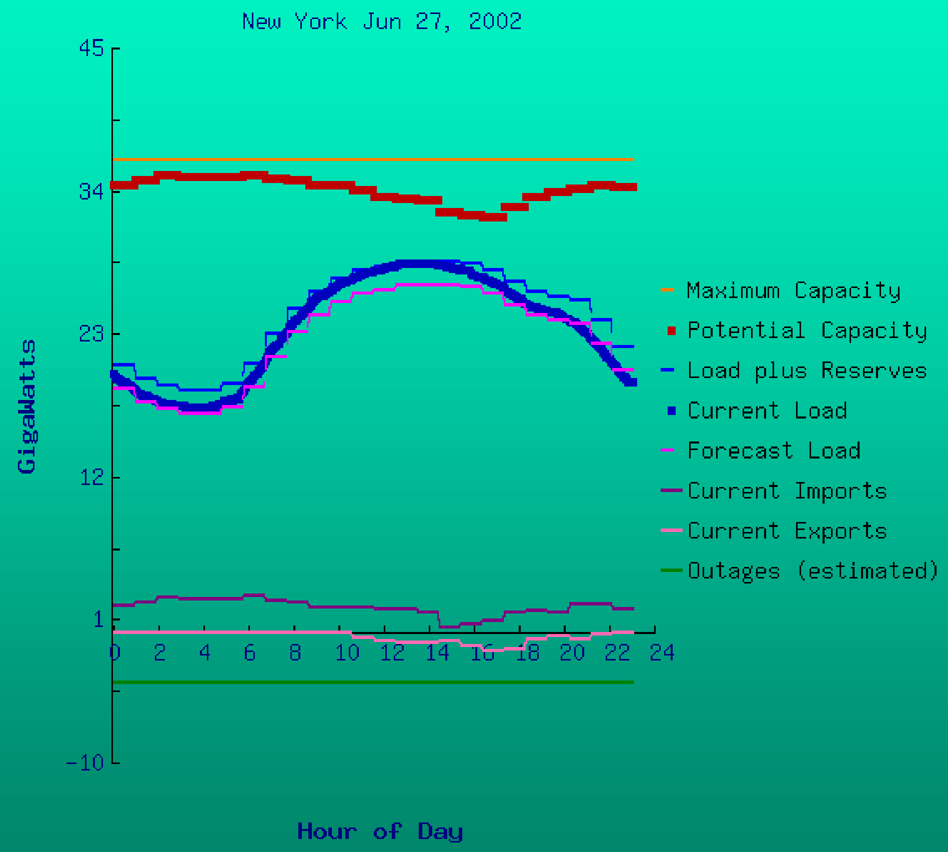
from Tom Surek & Robt Margolis, Third World Conf. on PV Energy Conversion, Osaka, May, 2003



(First Solar module production cost Q4 2007 = $1.13/W$_p$)

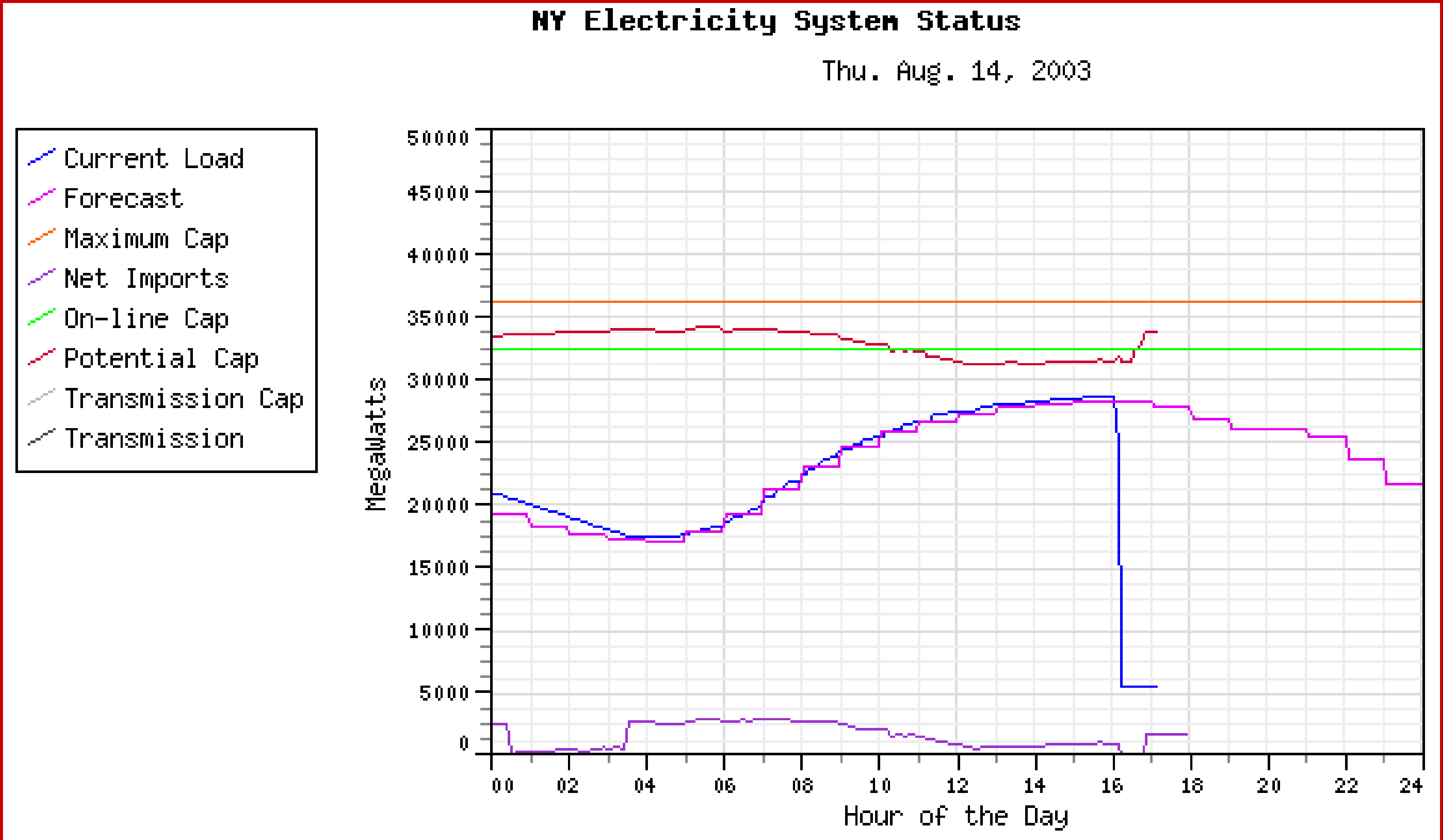
PV produces electricity just when it is most needed!
electricity usage (NY State) vs. time of day





source: http://currentenergy.lbl.gov/ny/

…and sometimes grid electricity fails!



Sunday, August 08, 2004 Cleveland Plain Dealer--
About 50 million people were affected, and the economic impact was estimated at more than $6 billion in lost business and damages.

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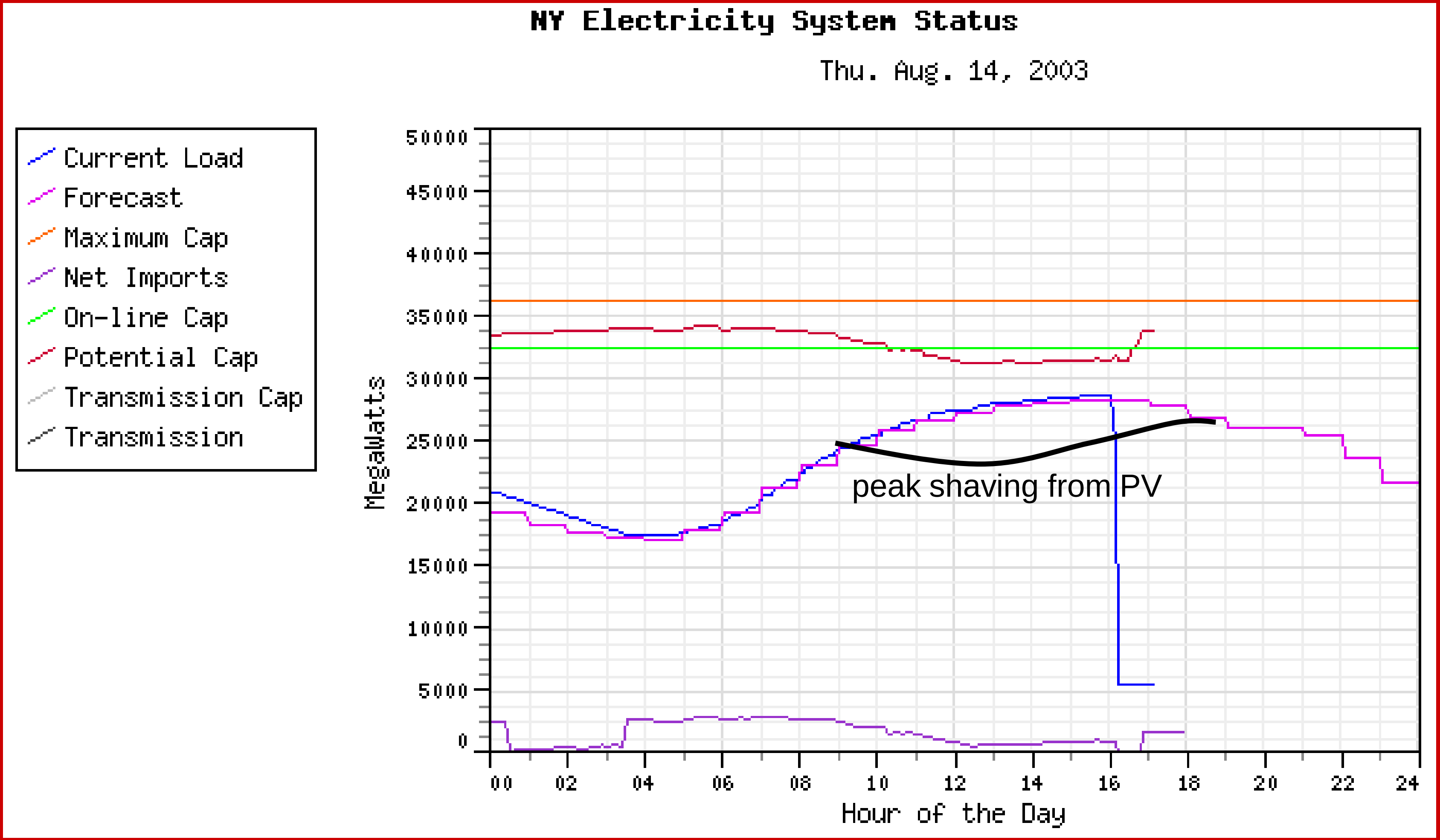

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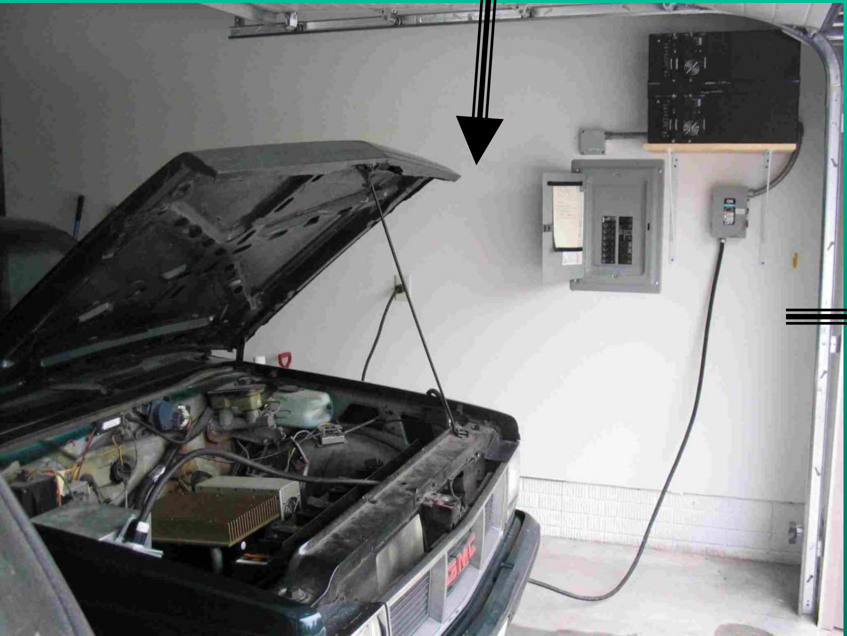
PV at the workplace
+
plug-in electric vehicles
=
off-peak power for the home



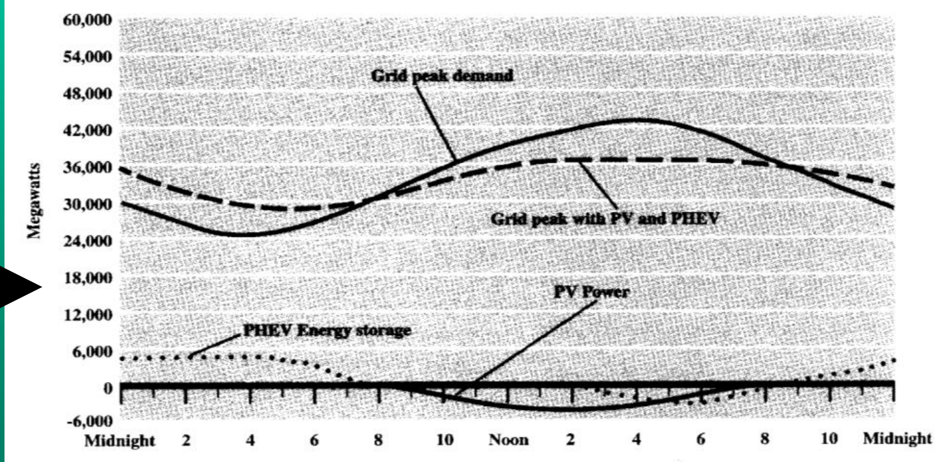
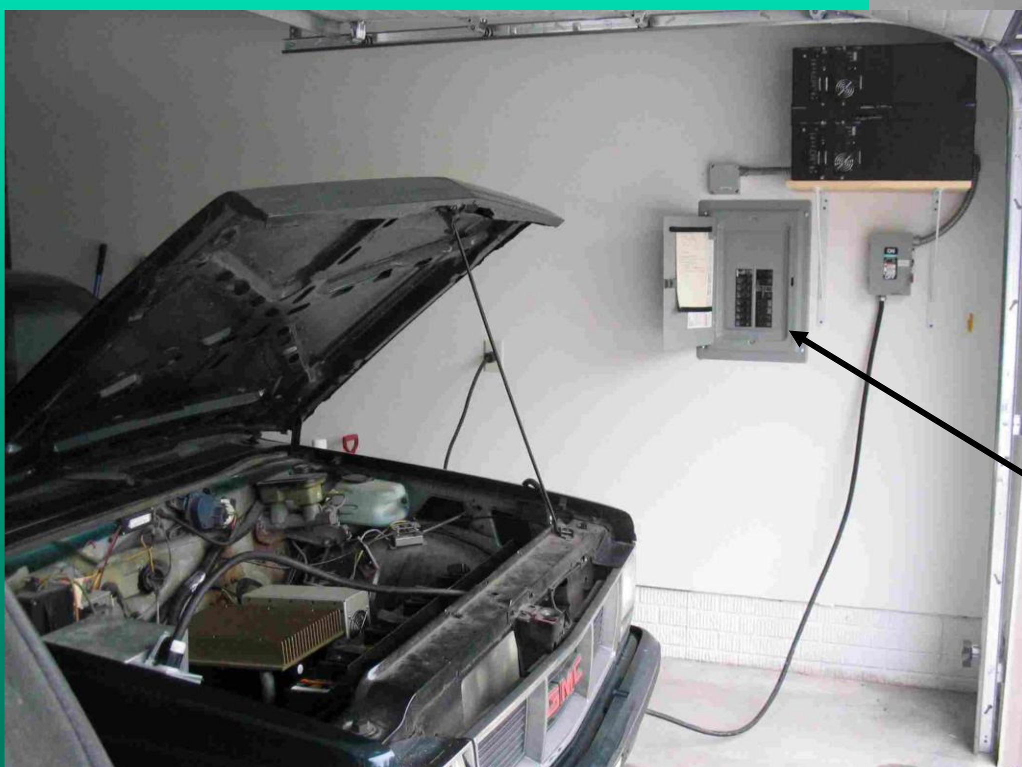


Figure 7.2 The Effect of a Few Million PHEVs and 9% PV Power on the California Electric Load in Mid-July

Dave Heidenreich, *Exponential Solar* (2007)


LECTRK

Not only is the e-truck charged with solar, it can power up the house for emergencies…



Exeltech inverters with transfer switch and subpanel circuits for:

furnace, water heater, sump pump, kitchen, master bedroom

PV, Wind and the Smart Grid

- Sensors and controls together with a communications backbone can support bi-directional power flow and help to reduce the need for base-load power generation and dispatchable power.
- The smart grid can increase the penetration of solar and wind and enable a lower carbon grid.
- Navigant Consulting is engaged in a major study of the potential for and impacts of a PV smart grid to be completed in October, 2008, involving:
  - Electric utilities
  - Equipment manufacturers and installers
  - Service providers
  - Lendors and investors

PHEVs and Vehicle-to-Grid

(with either wind or solar)

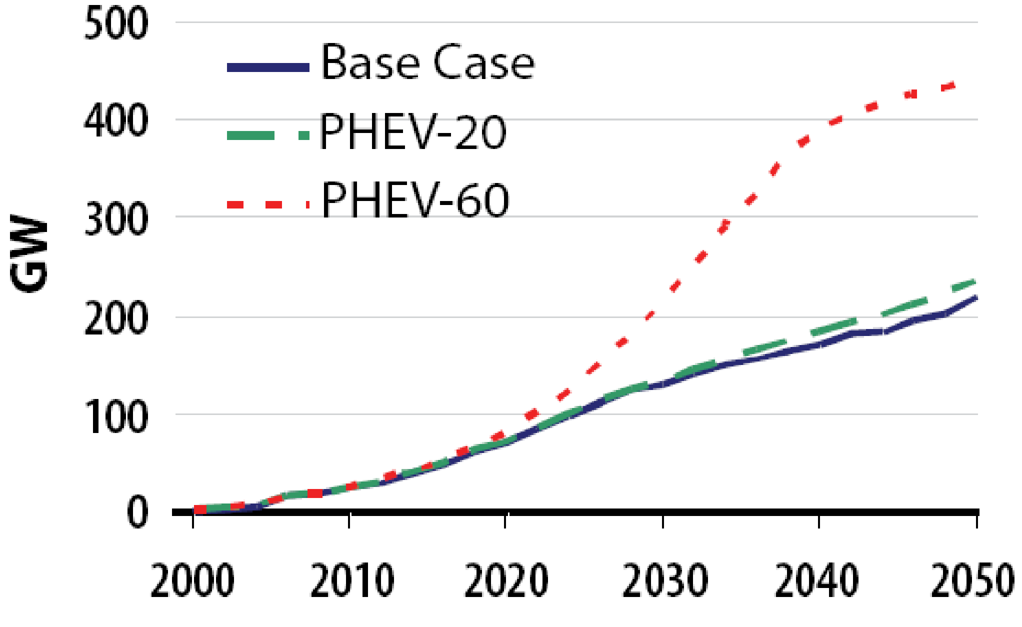


Figure 4: Wind Penetration with PHEVs

from: Short and Denholm, NREL

A Solar Grand Plan

Ken Zweibel, James Mason, Vasilis Fthenakis
Scientific American, Dec. 16, 2007

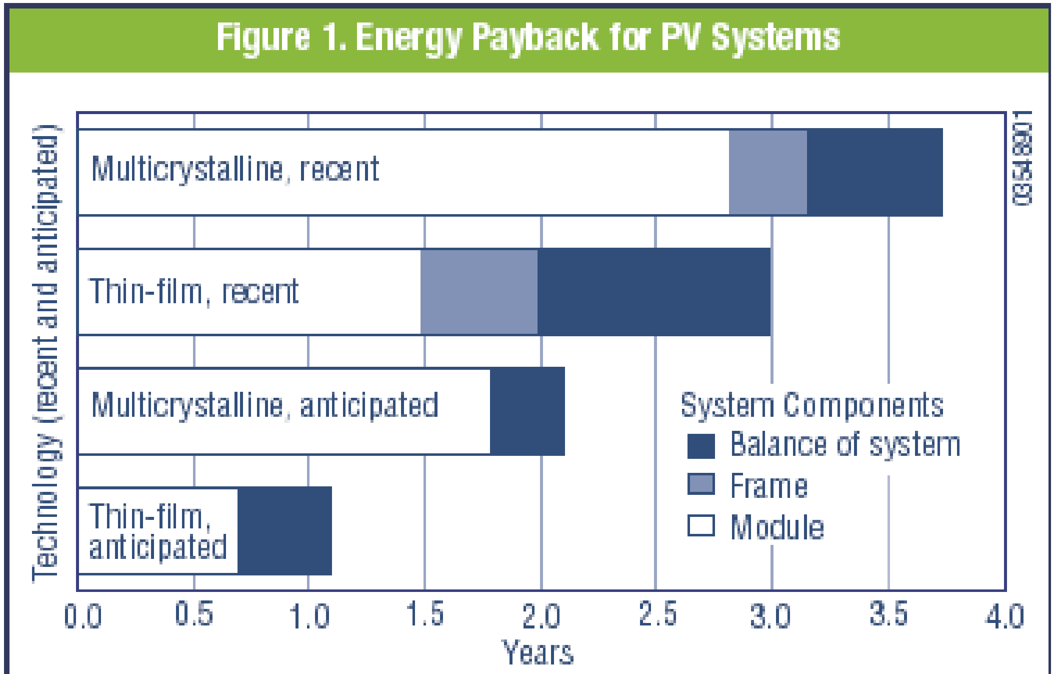
- PV farms in the U.S. Southwest
  [can use high efficiency, concentrating PV (CPV)]
- High Voltage Direct Current (HVDC) long-distance transmission lines throughout the U.S. deliver power to regional AC grid
- Compressed air storage (1100 psi) in natural gas reservoirs across the U.S.
- Natural gas turbines w/ compressed air used for off-peak power

recent developments

Battery storage--Xcel Energy has signed a contract to purchase a battery from NGK Insulators Ltd. The 20 50-kilowatt NaS battery modules will be able to store about 7.2 megawatt-hours of electricity, with a charge/discharge power of one megawatt.
The project will take place in Luverne, Minn., about 30 miles east of Sioux Falls, S.D., with the battery installation beginning this spring adjacent and connected to a nearby 11-megawatt wind farm owned by Minwind Energy, LLC. The battery is expected to go on-line in October 2008.

- **IBM** announced Monday a joint venture with Tokyo Ohka Kogyo to produce CIGS solar modules
- Miasolé, Nanosolar, HelioVolt and Global Solar Energy also are developing CIGS modules
- **GE Energy** last week announced it had raised its stake to a controlling interest in PrimeStar Solar developing CdTe modules
- other CdTe module developers: AVA, Calyxo

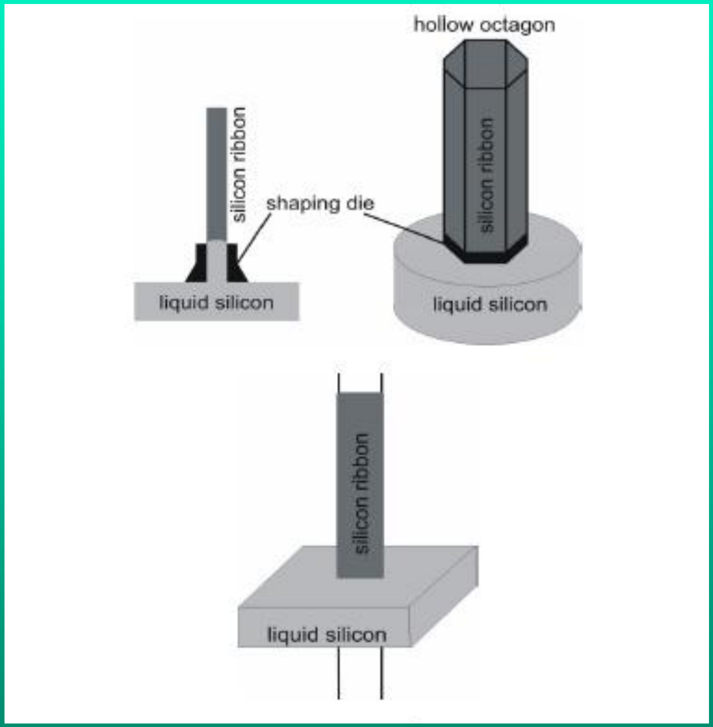
Energy payback time for various PV materials

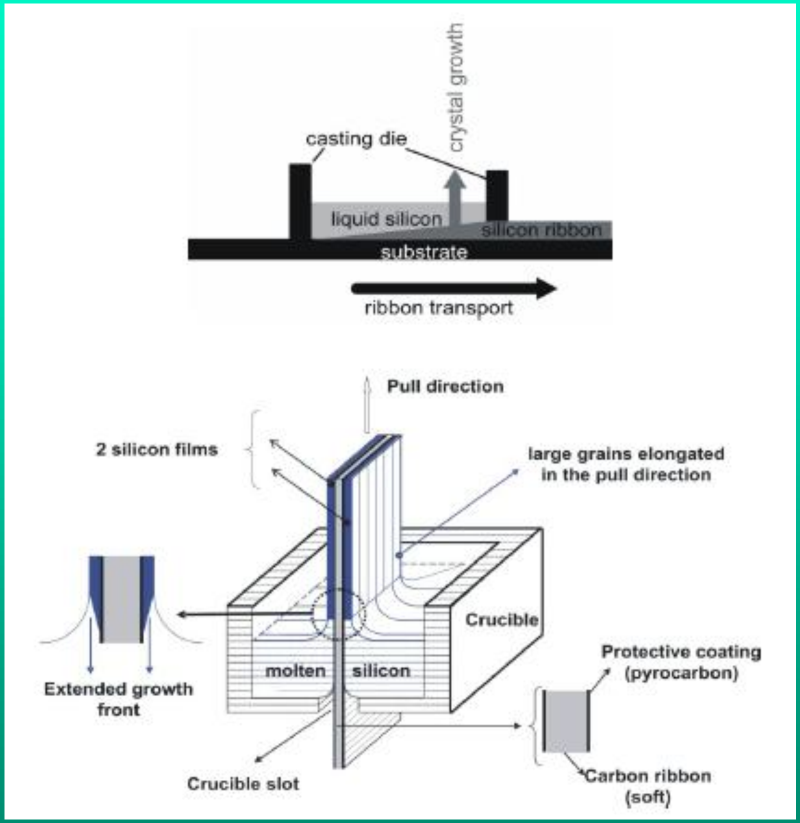


Reaping the environmental benefits of solar energy requires spending energy to make the PV system. But as this graphic shows, the investment is small. Assuming 30-year system life, PV systems will provide a net gain of 26 to 29 years of pollution-free and greenhouse-gas-free electrical generation.

from: PV FAQS US DOE Office of Energy Efficiency and Renewable Energy

Ribbon Si growth techniques





Upper: edge fed growth (EFG)
Lower: string ribbon (SR)

Upper: ribbon growth on substrate (RGS)
Lower: molded wafer (RST)

self-assembled multijunctions

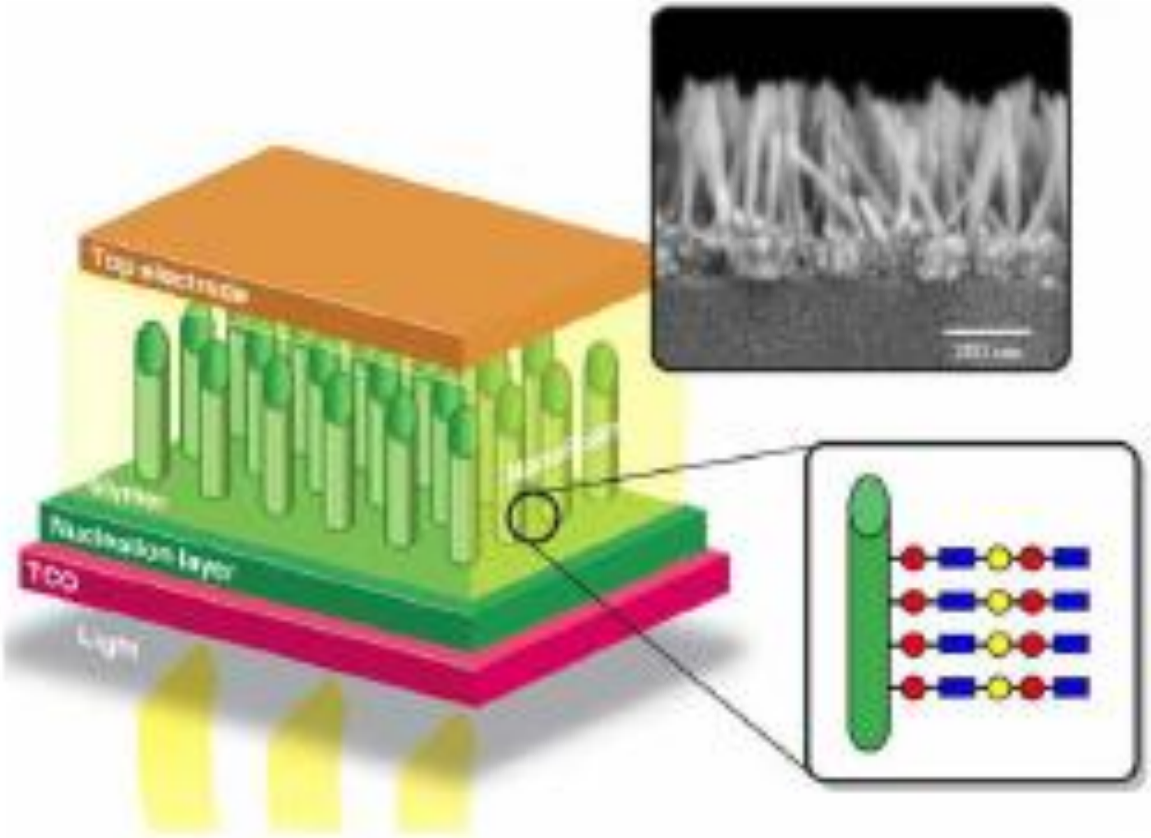


Figure 8 Structure for high-efficiency (50%) organic PV cell based on a nanostructured substrate onto which thin layers of molecular multi-junctions are grown and anchored onto the nanostructure surface. The red circle denotes an electron acceptor; the blue square, an electron donor; and the yellow circle, a metal nanoparticle.