Solar Energy: What's next?

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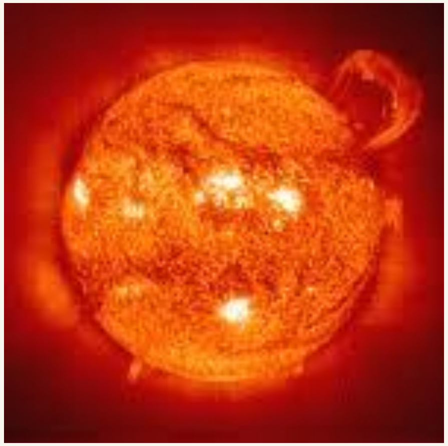
Vice President for Research and Associate Provost
Rochester Institute of Technology

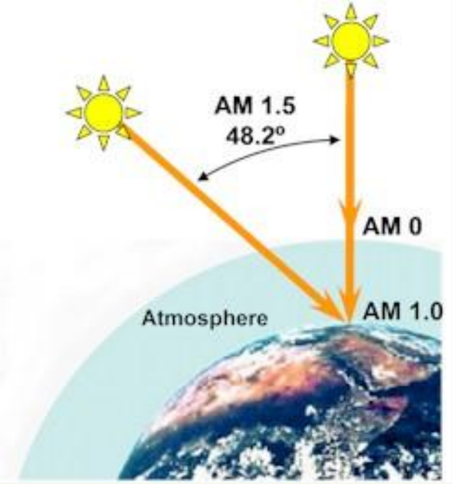
Let's Review

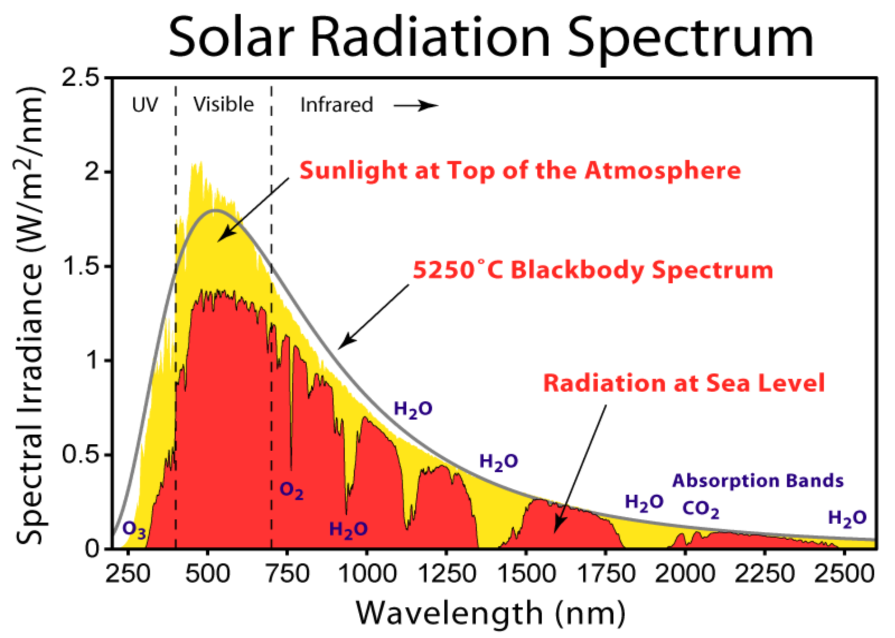
Roughly 4.6 billion years ago . . .

"Let there be light"

Solar Energy







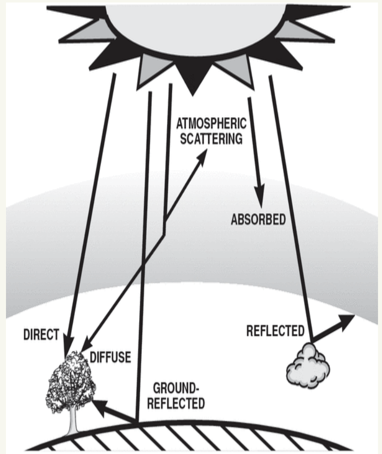
Air Mass Zero (AM0) - Space
Air Mass 1.5 (AM1.5) - Terrestrial

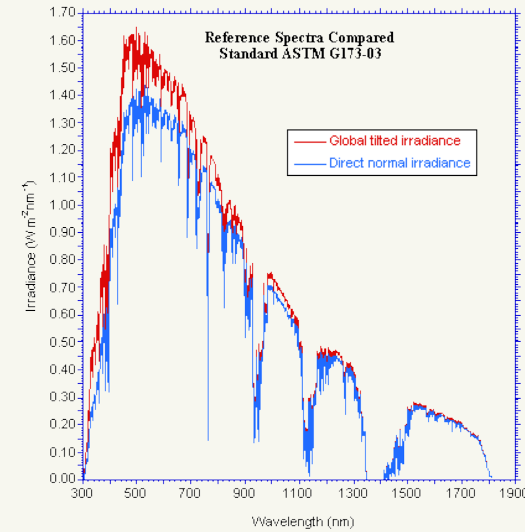
Solar Constant
(1 Sun = 1360 W/m^2)

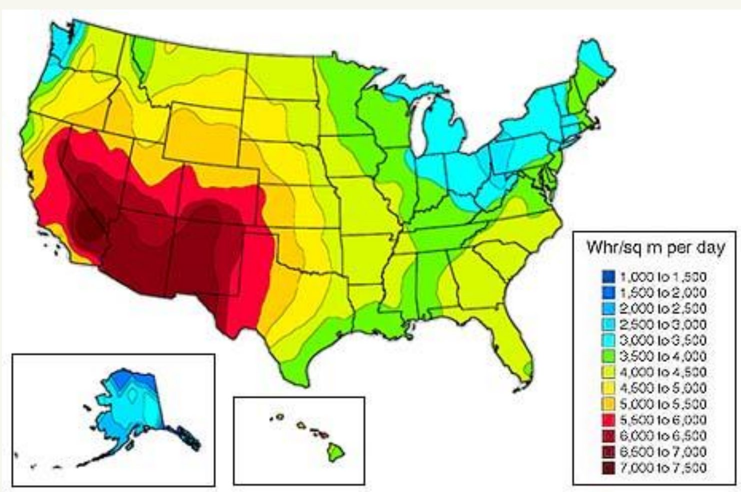
Standard Test Conditions (STC)
Air Mass 1.5 (1000W/m^2, ASTM G173-03 and IEC 60904-3) at 25 ^{o}C

Direct vs. Diffuse Sunlight

The amount of sunlight, as well as the relative amounts of direct versus diffuse sunlight will vary geographically.



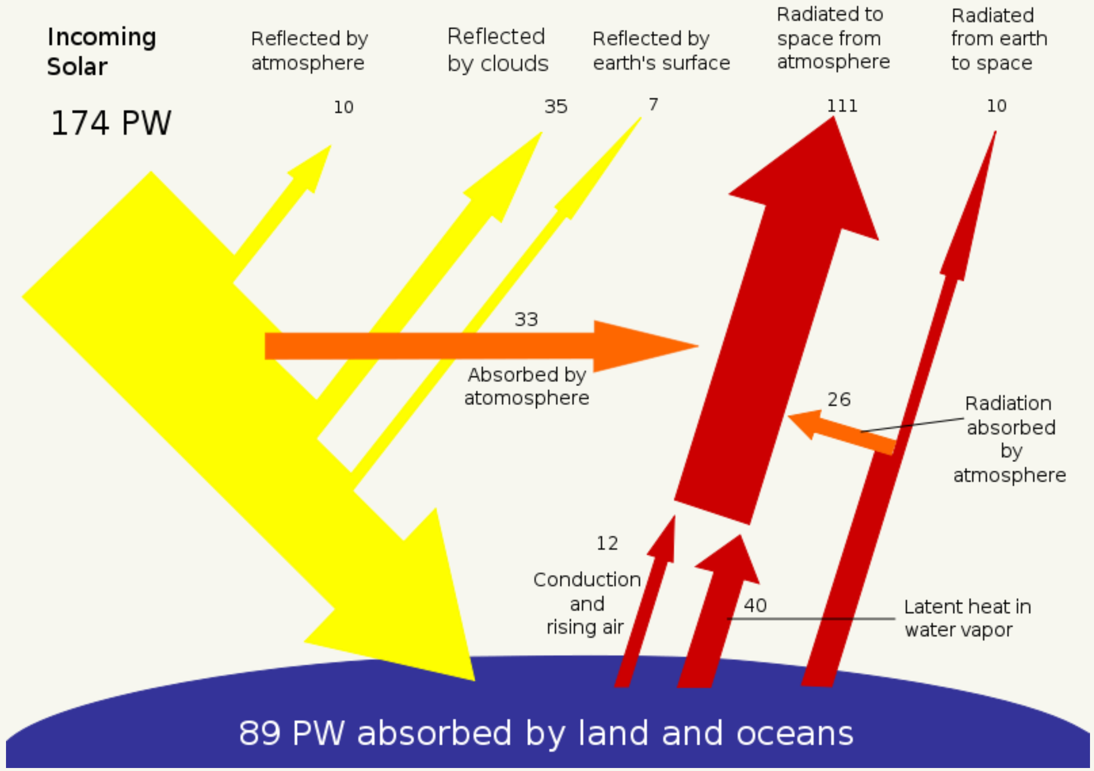




Solar resource for a concentrating collector

Integrated over the surface of the Earth and accounting for reflection and absorption in the atmosphere the sun provides ~ 89×10^{15} W or 89 PW

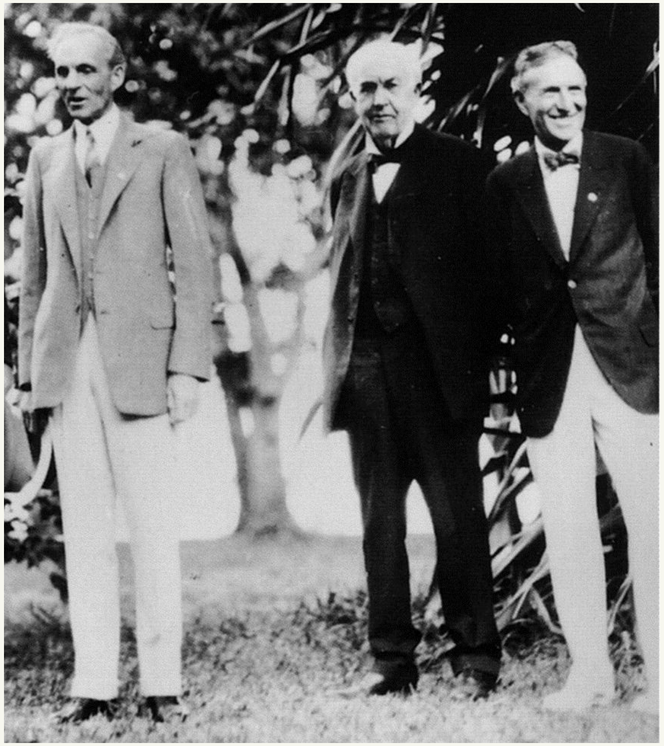
Worldwide energy use per hour ~20×10^{12} W or 20 TW



More solar energy hits the earth's surface in 1 hour than mankind uses in 1 year

1931

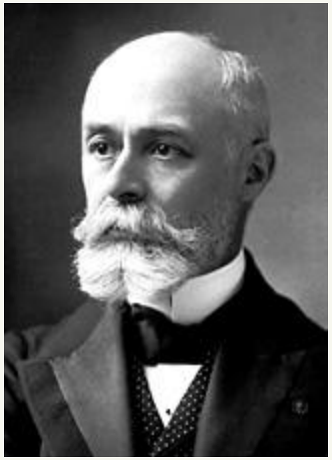
"We are like tenant farmers chopping down the fence around our house for fuel when we should be using Nature's inexhaustible sources of energy — sun, wind and tide. ... I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."



Thomas Edison, in conversation with Henry Ford and Harvey Firestone as quoted in *Uncommon Friends : Life with Thomas Edison, Henry Ford, Harvey Firestone, Alexis Carrel & Charles Lindbergh* (1987) by James Newton, p. 31

1839

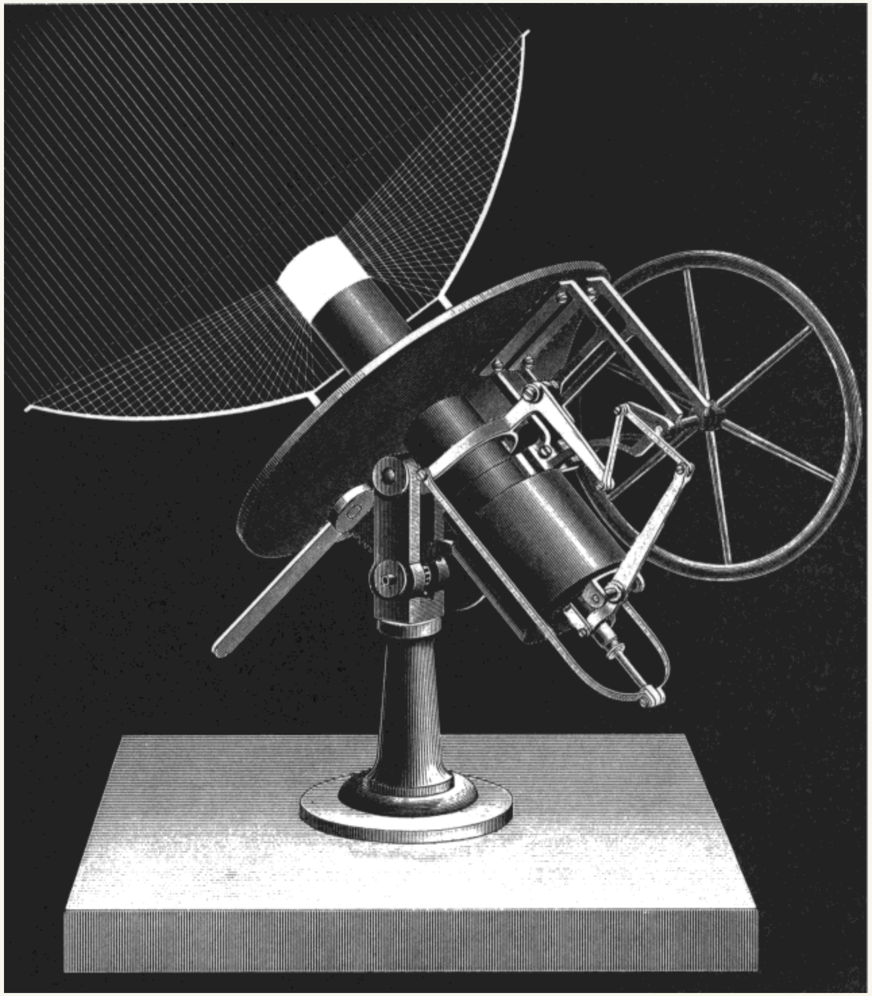
Edmund Becquerel discovers the photovoltaic effect.



1860 - 1881

Auguste Mouchout was the first man to patent a design for a motor running on solar energy.

1872
John Ericsson's developed his “Sun Motor.”



1873
Willoughby Smith experimented with the photocoductivity properties of selenium.

1883
Charles Fritts made a solid state solar cell by coating selenium with a thin layer of gold.

1940

Russell Ohl discovers the "p-n junction"

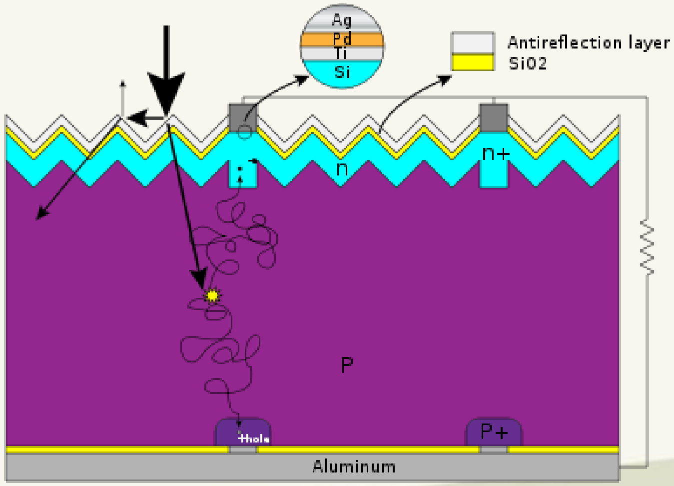
1941

Russell Ohl receives a US Patent 2402662, "Light sensitive device"

1954

AT&T Bell Labs unveils it new "solar battery" developed by Gerald Pearson, Daryl Chapin, and Calvin Fuller which was the first modern silicon solar cell.

Silicon Solar Cell



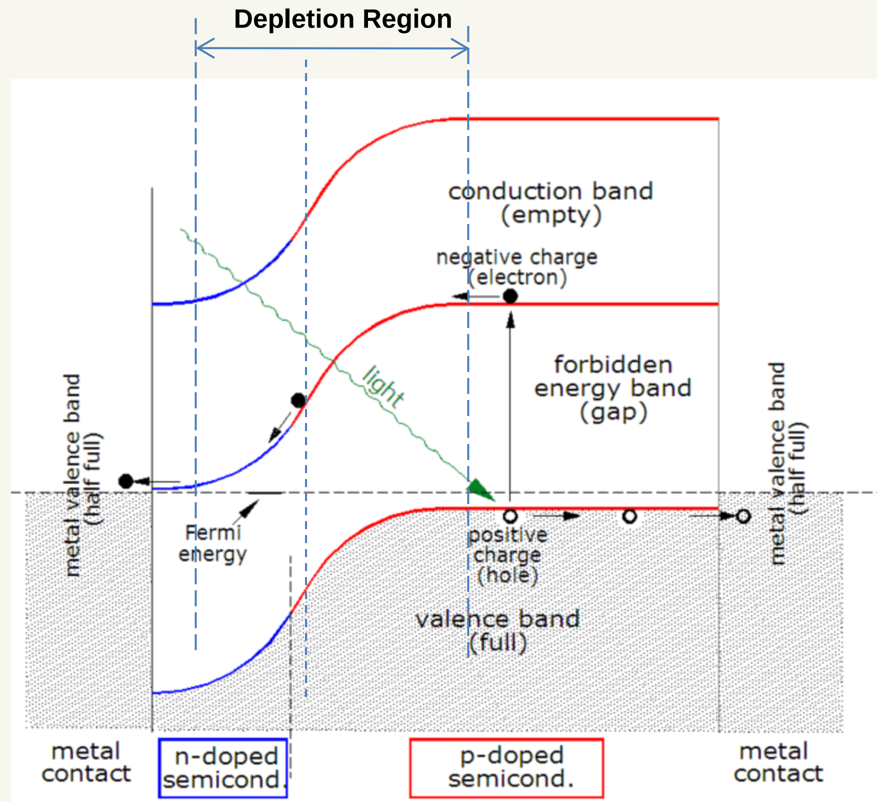


Photo-excited carriers that are not "collected" either radiatively recombine or non-radiatively recombine (i.e., heat up the cell)

1950’s

SIMPLE AND EFFICIENT—The ***Bell Solar Battery*** is made of thin, specially treated strips of silicon, an ingredient of common sand. It needs no fuel other than the light from the sun itself. Since it has no moving parts and nothing is consumed or destroyed, the ***Bell Solar Battery*** should theoretically last indefinitely.

New Bell Solar Battery Converts Sun's Rays Into Electricity

Bell Telephone Laboratories demonstrate new device for using power from the sun

Scientists have long reached for the secret of the sun. For they have known that it sends us nearly as much energy daily as is contained in all known reserves of coal, oil and uranium.

If this energy could be put to use there would be enough to turn every wheel and light every lamp that mankind would ever need.

Now the dream of the ages is closer to realization. For out of the Bell Telephone Laboratories has come the ***Bell Solar Battery***—a device to convert energy from the sun directly and efficiently into usable amounts of electricity.

Though much development remains to be done, this new battery gives a glimpse of future progress in many fields. Its use with transistors (also invented at Bell Laboratories) offers many opportunities for improvements and economies in telephone service.

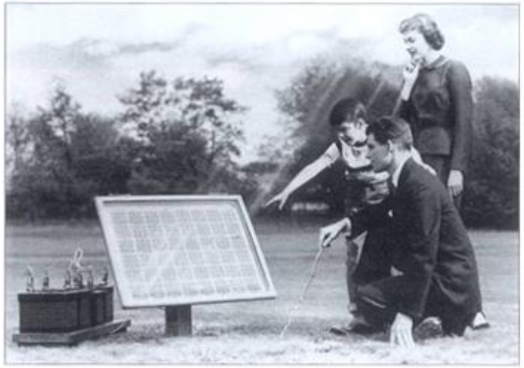
A small ***Bell Solar Battery*** has shown that it can send voices over telephone wires and operate low-power radio transmitters. Made to cover a square yard, it can deliver enough power from the sun to light an ordinary reading lamp.

Great benefits for telephone users and for all mankind will come from this forward step in harnessing the limitless power of the sun.

BELL TELEPHONE SYSTEM

Bell Labs, 1955

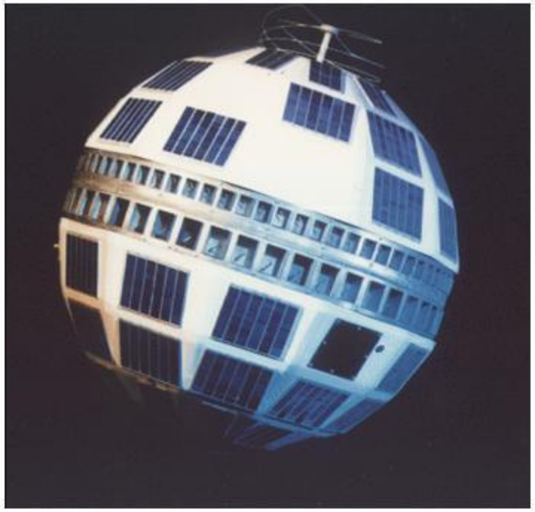
The original Bell Solar Battery (photovoltaic panel) is used in an early test in 1955 in Americus, Ga.



Advertisement photos, such as this one that appeared in the 1956 issue of Look Magazine, show off the "Bell Solar Battery" to the American public.

Space Power

In 1958, the first solar powered satellite – Vanguard is launched

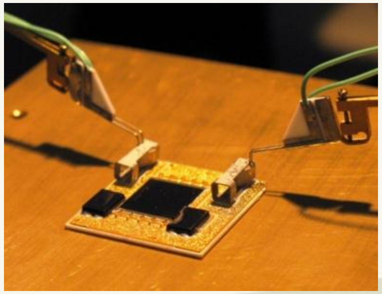


Bell Telephone Laboratories designed and built the Telstar spacecraft with AT&T corporate funds. It was launched in 1962, and was the first "comsat."

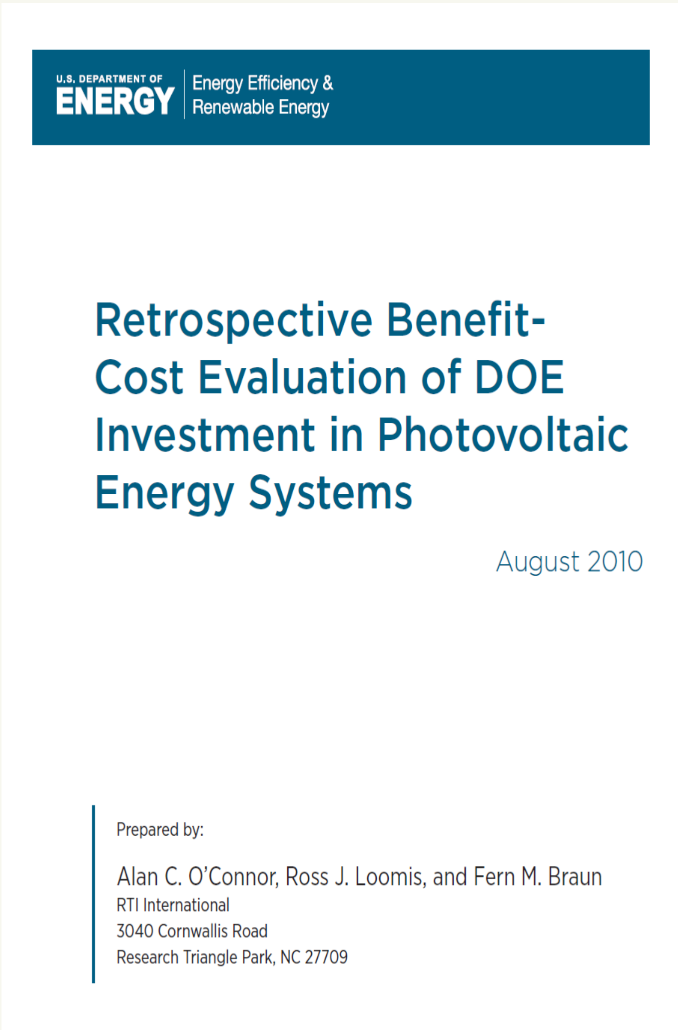
2009 Largest solar array in space, on the International Space Station is completed - 262,400 solar cells, covering an area of about 2,500 m^2 (27,000 sq. ft.)

Photovoltaic Timeline

- 1839 - photovoltaic effect discovered
- 1883 - first solar cell created
- 1941 - modern pn junction solar cell demonstrated
- 1954 - doped silicon first used in solar cells
- 1958 - first spacecraft to use solar panels (Vanguard I)
- 1977 - SERI begin operation
- 1989 - first dual junction cell created
- 1991 - NREL is established
- 1991 - terrestrial PV shipments exceeds 50 MW
- 1994 - 30% efficiency barrier broken
- 1996 - National Center for Photovoltaics chartered
- 1997 - terrestrial PV shipments exceed 100 MW
- 2004 - terrestrial PV shipments exceeds 1 GW
- 2006 - 40% efficiency barrier broken
- 2009 - terrestrial PV shipments exceeds 10 GW
- 2011 – terrestrial PV installments exceed 30 GW
- 2012 – total worldwide PV capacity exceeds 100 GW



U.S. Photovoltaic Development


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Retrospective Benefit-Cost Evaluation of DOE Investment in Photovoltaic Energy Systems

August 2010

Prepared by:

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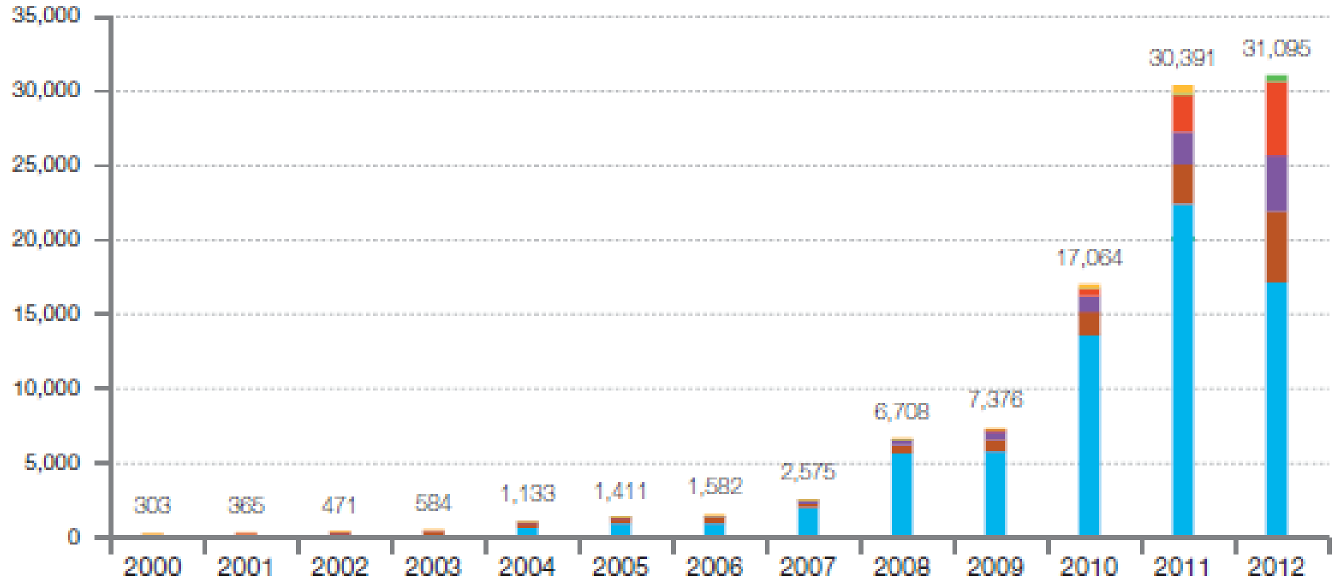
The history of PV and the history of NREL/SERI are synonymous.

No other entity has played as significant a role in the tremendous technological development and creation of this exploding marketplace than NREL.

It is estimated that without FSA, PVMat, TFP - **PV costs would be 66% higher today**.

All 8 of the top PV companies in the U.S. have significant ties to NREL, as well as 9 out of the top 10 world-wide.

Figure 2 - Evolution of global PV annual installations 2000-2012 (MW)

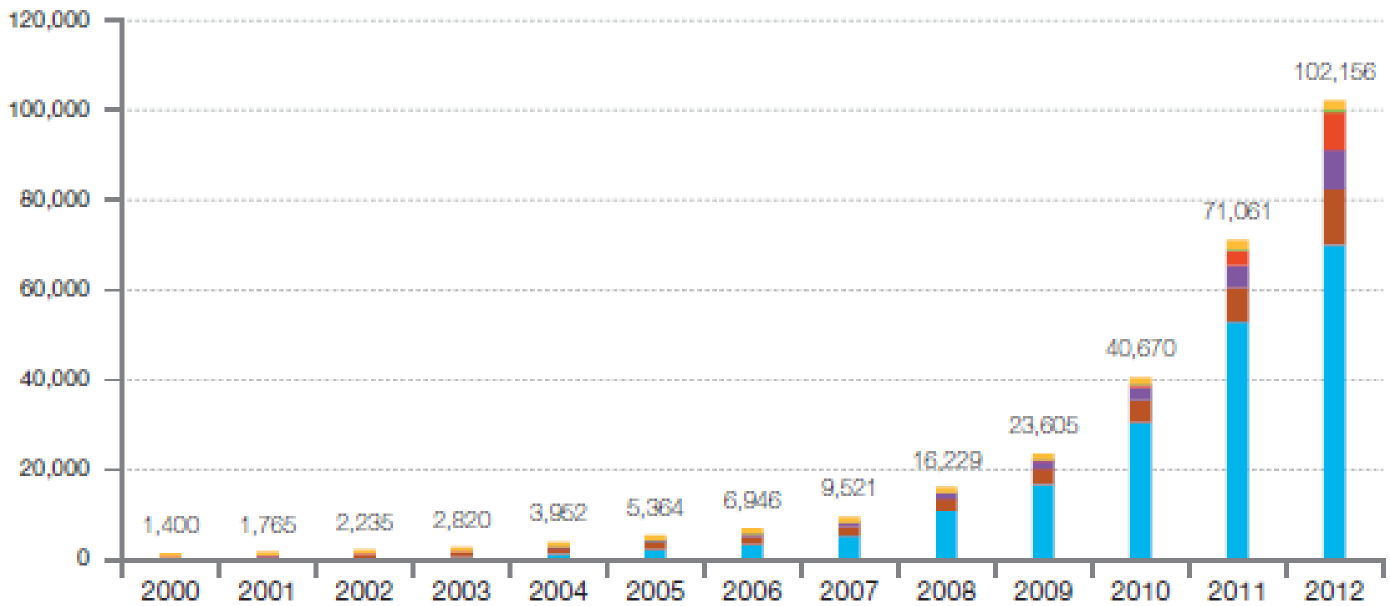


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
ROW	88	56	80	77	29	10	105	42	76	80	284	508	-*
MEA	n/a	n/a	n/a	n/a	1	n/a	n/a	1	1	22	46	121	410
China	19	5	19	10	10	8	10	20	40	160	500	2,500	5,000
Americas	24	32	47	66	104	106	150	213	346	543	1,029	2,179	3,758
APAC	117	140	191	230	282	303	324	271	535	742	1,583	2,672	4,769
Europe	56	133	135	202	707	984	992	2,028	5,710	5,830	13,622	22,411	17,159
Total	**303**	**365**	**471**	**584**	**1,133**	**1,411**	**1,582**	**2,575**	**6,708**	**7,376**	**17,064**	**30,391**	**31,095**

* From 2012 onwards, these figures are directly integrated into those of the relevant regions.

Source: SEIA

Figure 1 - Evolution of global PV cumulative installed capacity 2000-2012 (MW)

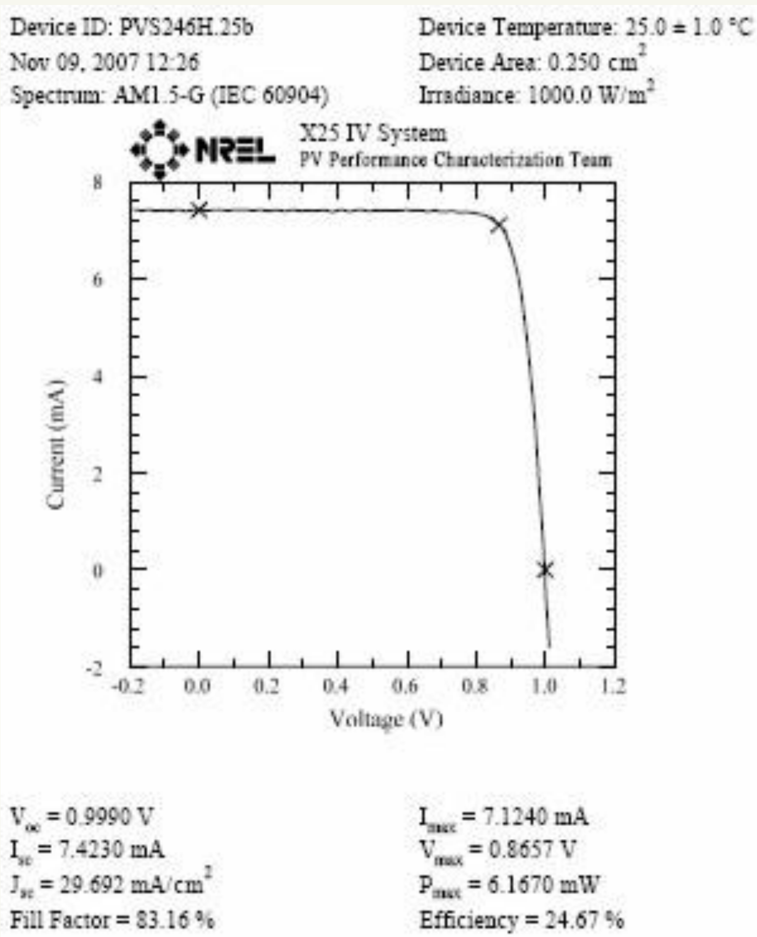


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	71	192	601
China	19	24	42	52	62	70	80	100	140	300	800	3,300	8,300
Americas	146	178	225	290	394	501	650	863	1,209	1,752	2,780	4,959	8,717
APAC	355	495	686	916	1,198	1,500	1,825	2,096	2,631	3,373	4,956	7,628	12,397
Europe	129	262	396	598	1,305	2,289	3,281	5,310	11,020	16,850	30,472	52,884	70,043
Total	**1,400**	**1,765**	**2,235**	**2,820**	**3,952**	**5,364**	**6,946**	**9,521**	**16,229**	**23,605**	**40,670**	**71,061**	**102,156**

ROW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.

Source: SEIA

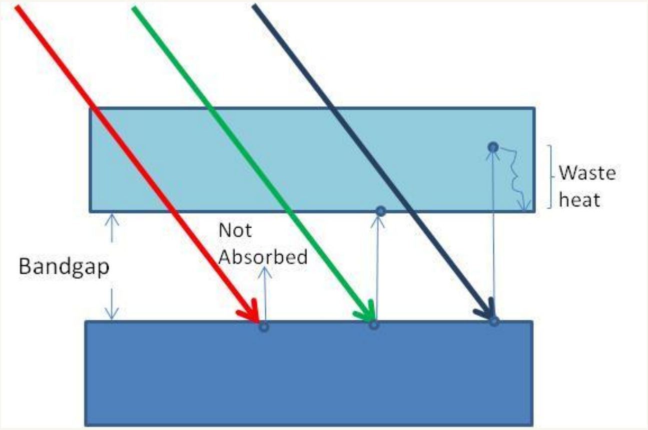
Solar Cell Efficiency

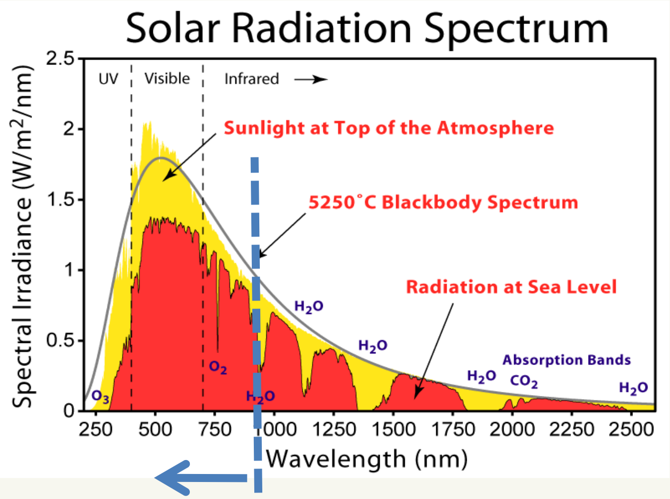


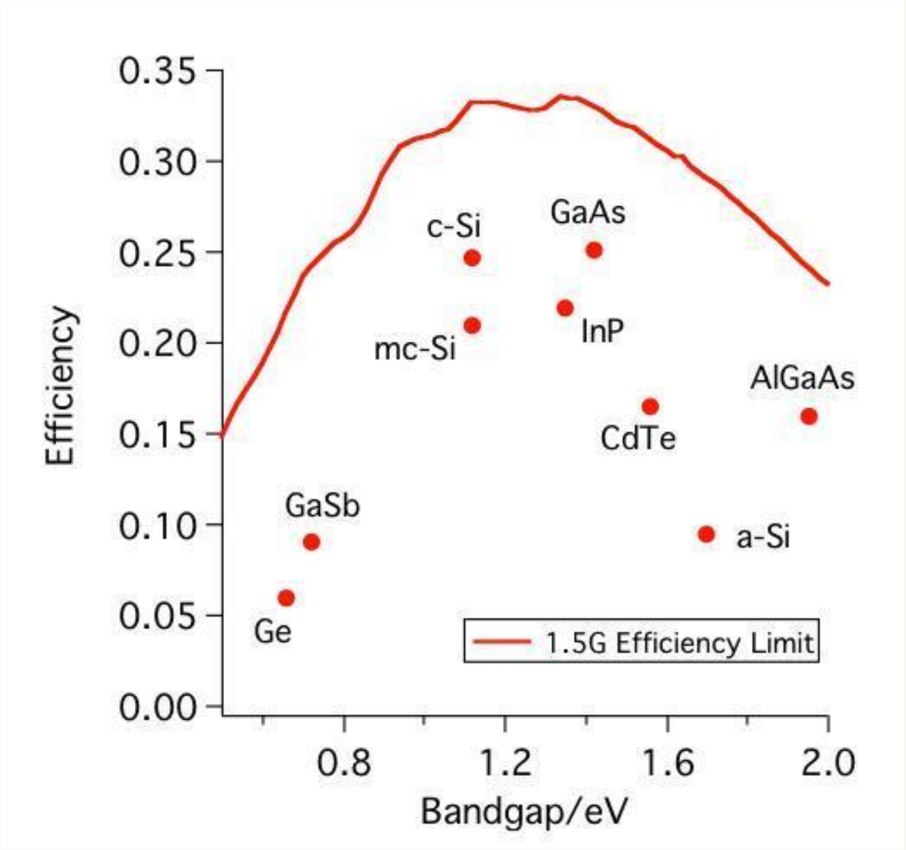
Solar cell efficiency is determined by **inherent losses** (i.e., solar photons with energies below the bandgap of the host material) and those primarily due to **optical or electrical losses** (i.e., reflectance, series resistance, etc.).

Certification indicates traceability paths to the National Renewable Energy Laboratory (NREL) in the United States, the National Institute of Advanced Industrial Science and Technology (AIST) in Japan or to the Physikalisch Technische Bundesanstalt (PTB) in Germany (i.e., Fraunhofer ISE). This certification is accredited by NIST.

Efficiency Versus Bandgap

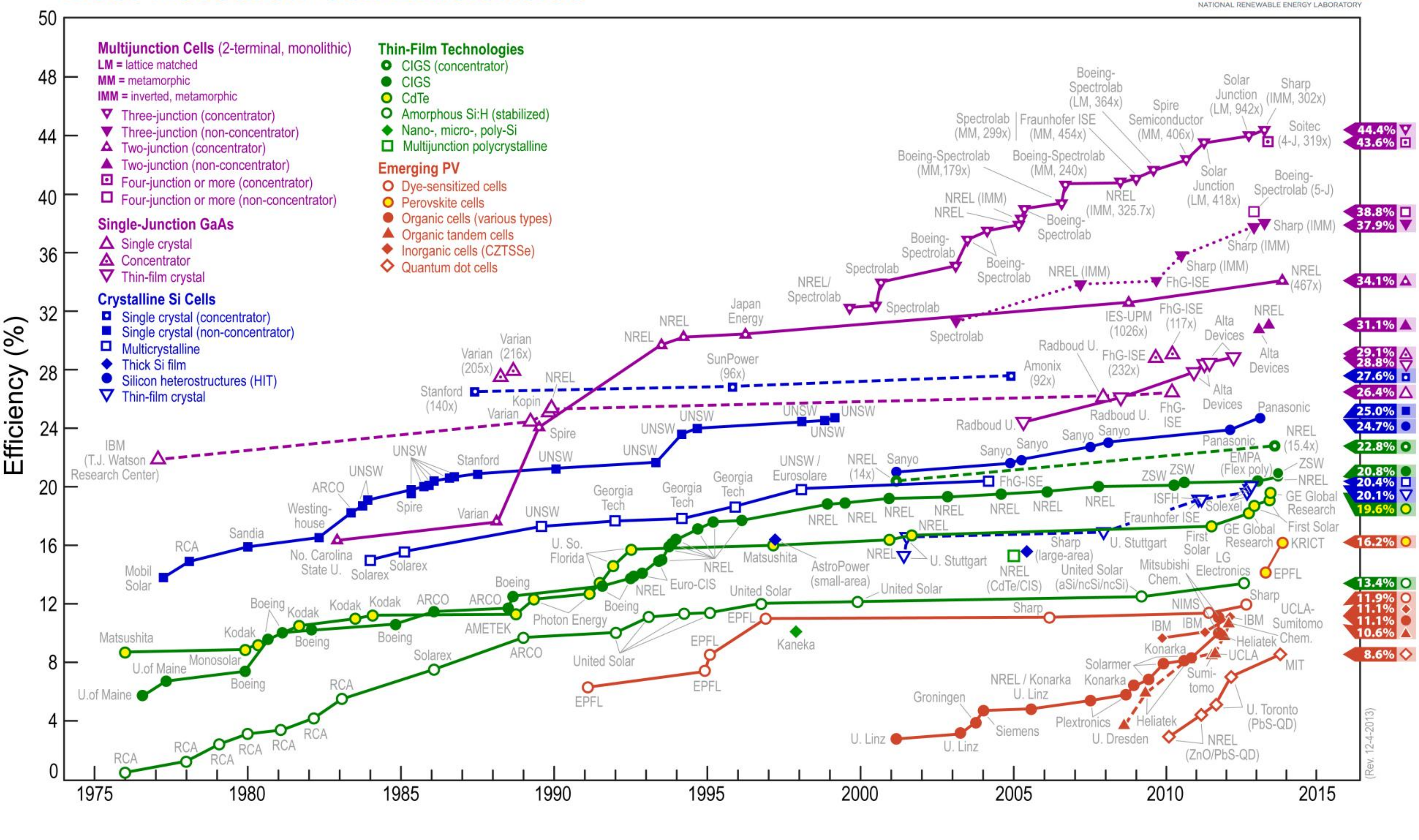




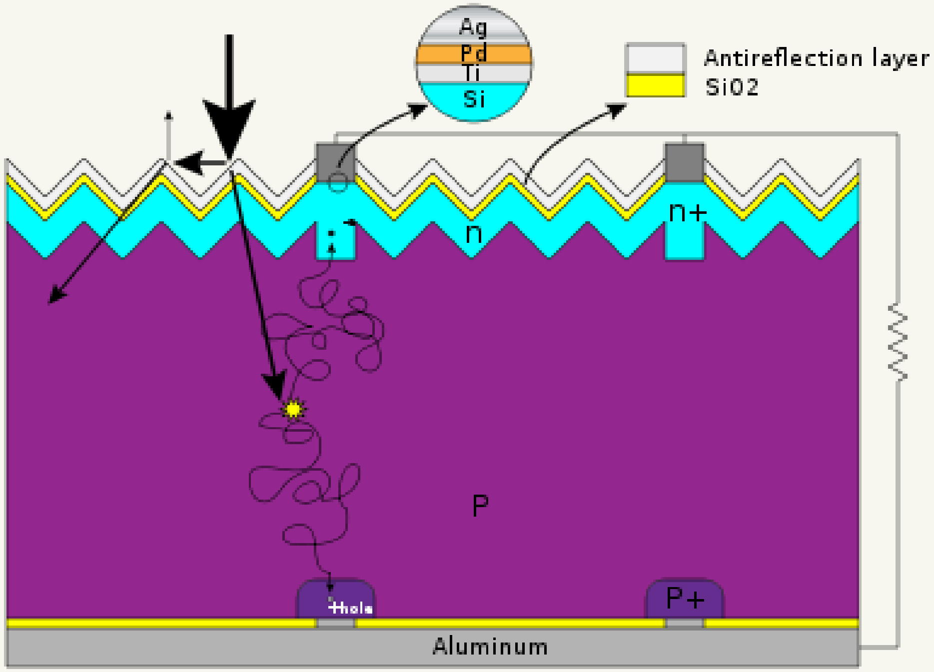


1.45 eV Optimum PV Bandgap

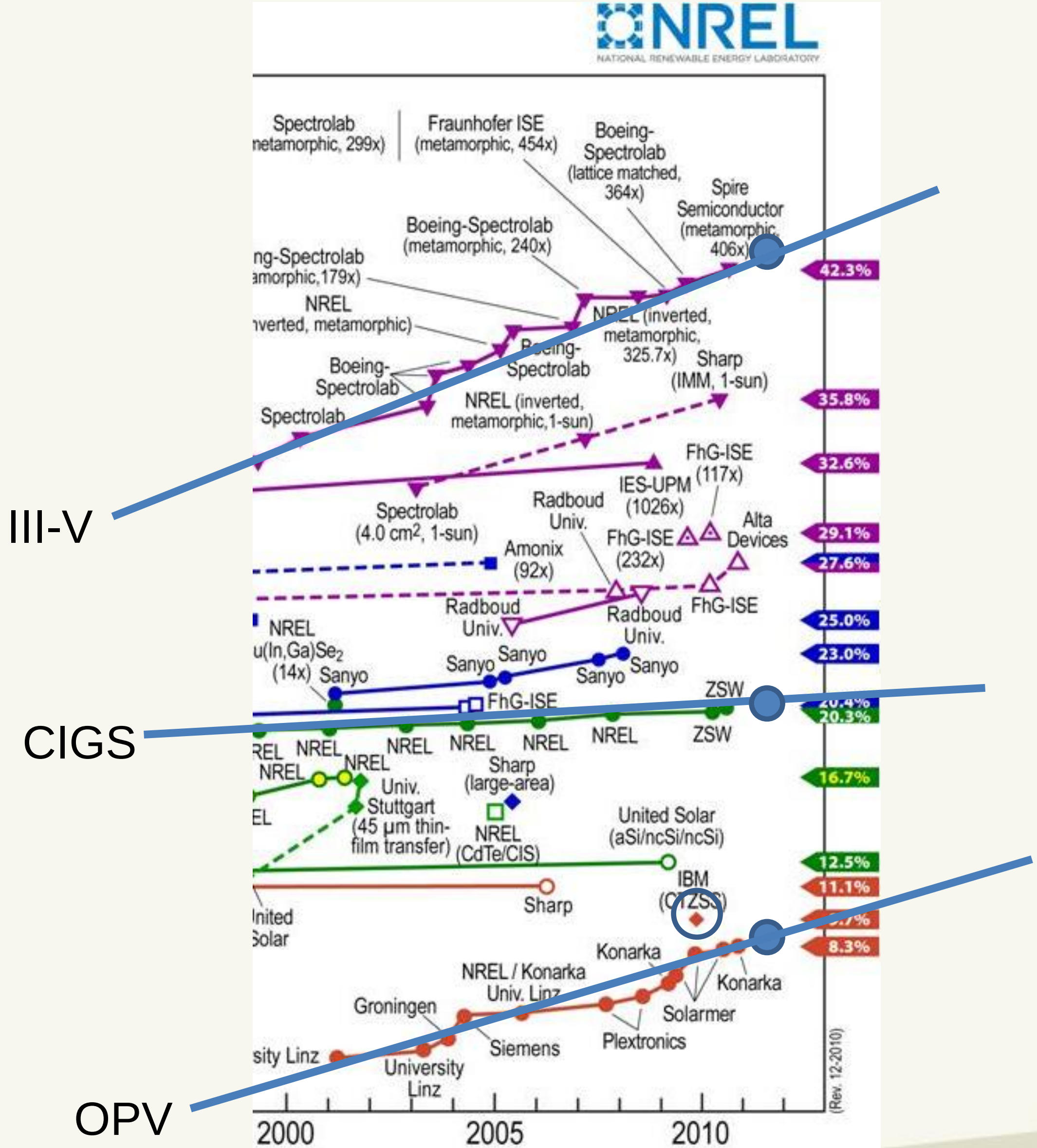
Best Research-Cell Efficiencies



Silicon Solar Cell Improvements



Advanced Grid Fingers
Anti-reflection Coatings
Texturing
Selective Emitter
Back Surface Fields
Back Surface Passivation
Back Point Contacts
Thin Cells



- New records just achieved for III-V, CIGS, OPV, and CZTS
- III-V MJ rate of improvement has been ~ 1%/year
- CIGS has been increasing at about ~0.3%/year
- OPV is approaching 10% and improving at about 0.8%/year
- New thin film material CZTS has achieved 10%

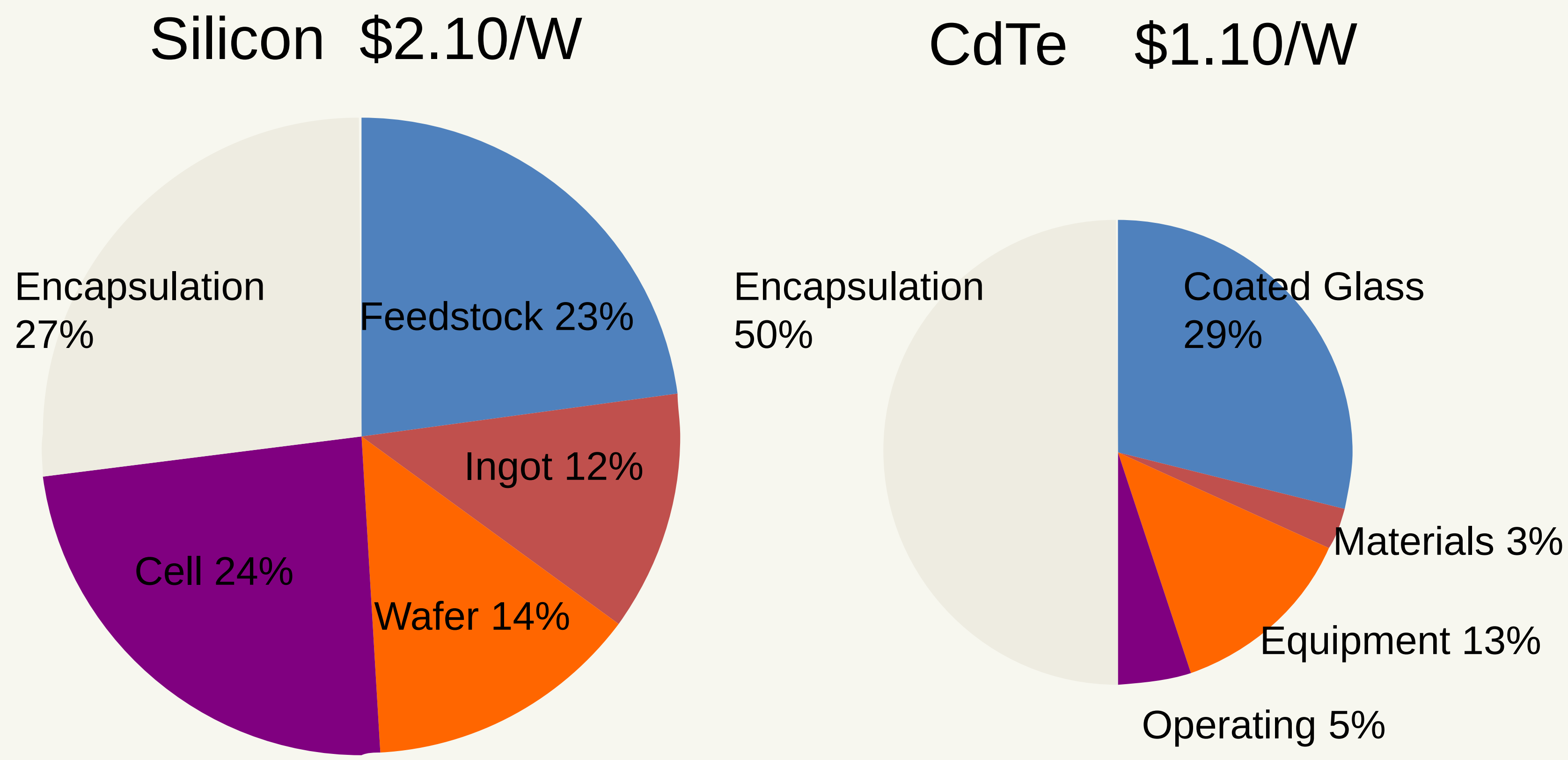
Thin Film PV

- Less material
- Low cost substrates (glass, SS, plastic)
- Variety of deposition methods
- Flexibility

- a-Si
- CdTe
- CIGS

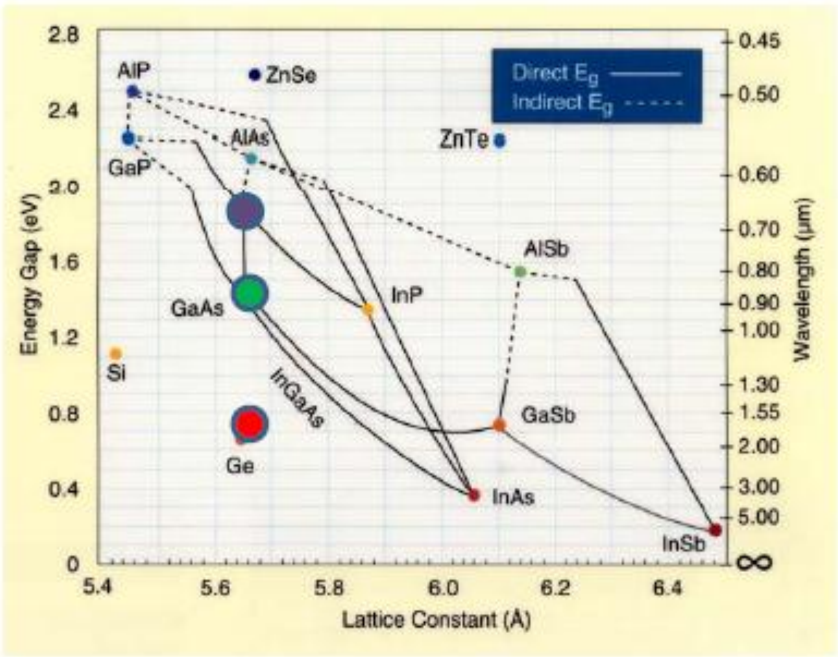
Ascent Solar

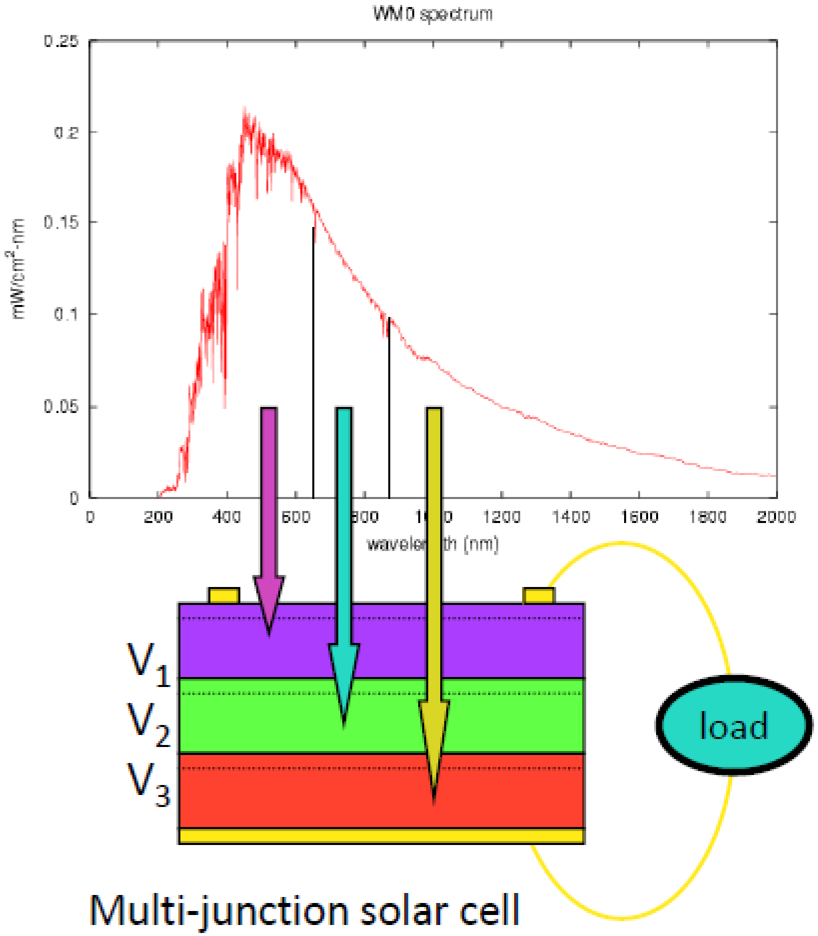
Materials Cost



Multijunction Solar Cells

1889, J. Olson and colleagues at NREL developed the III-V multi-junction solar cell. Within a couple of years they replace Si for space power and in 1995 break the 30% barrier.





Building Integrated PV

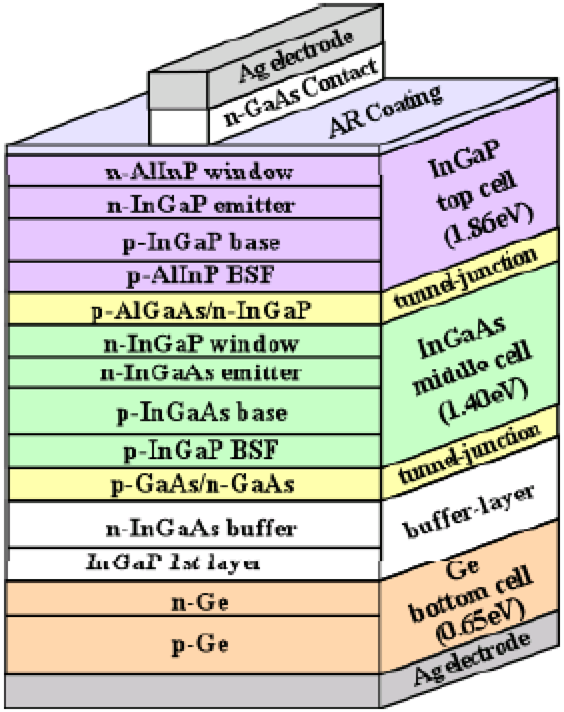
85kW Shell Solar CIGS in Wales

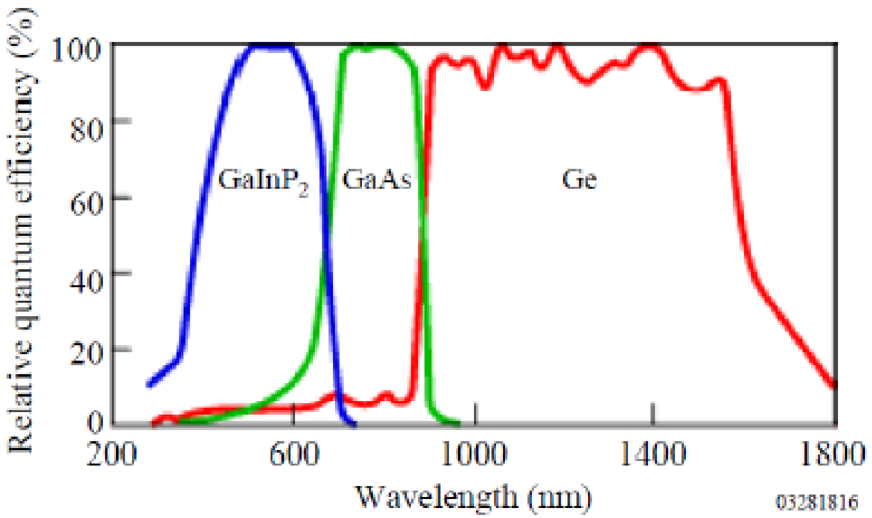
UNI-SOLAR
United Solar Ovonic

In Southern California

216 Würth CIGS modules in Tübingen, Germany

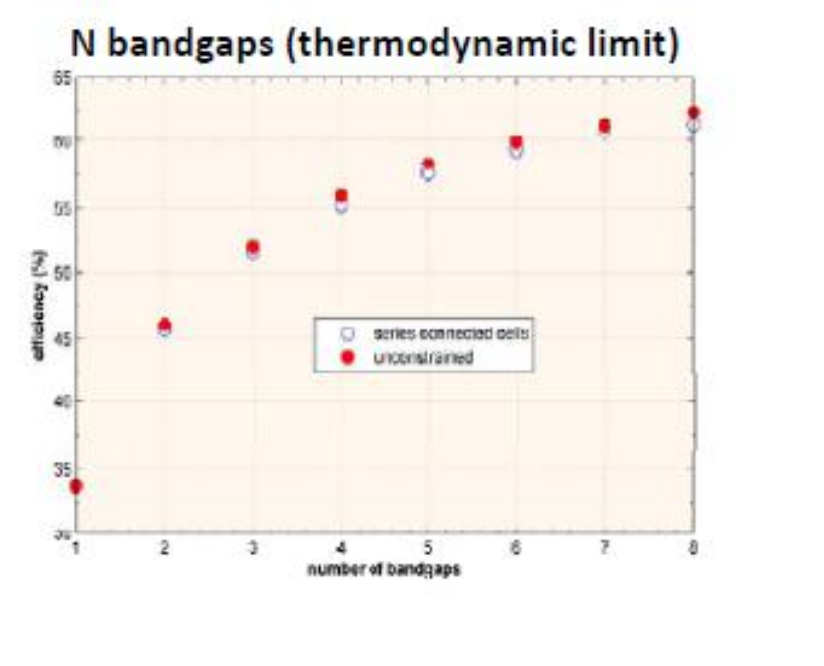
Conventional Triple Junction Solar Cells

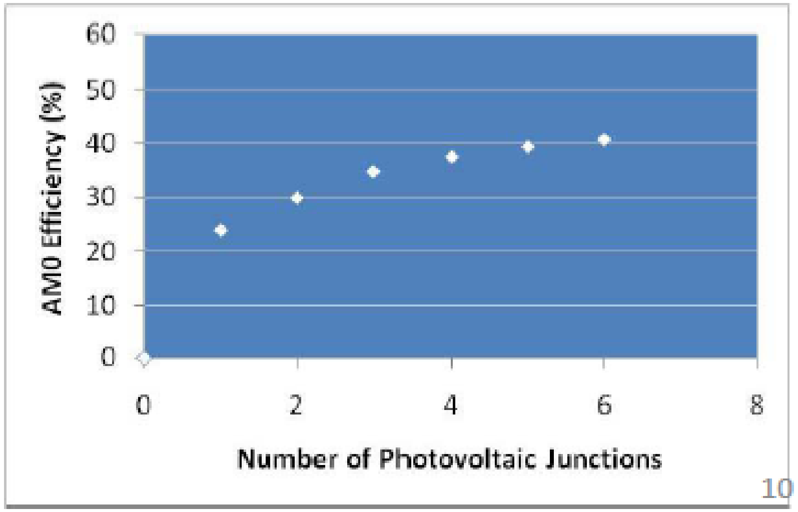




Basic design exceeds 30% efficiency. NREL and Fraunhofer have led the field. Commercially produced by Emcore, Spectrolab, and Azur.

What about just more bandgaps to get to 50%?



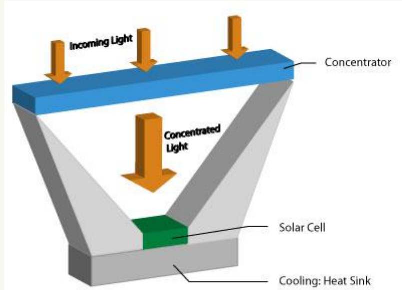


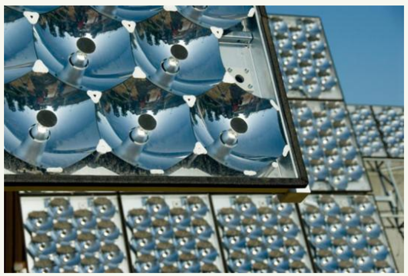
Courtesy P. Sharps, Emcore

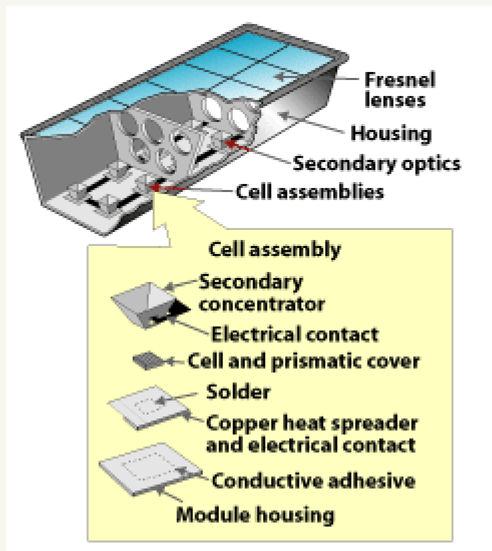
Thermodynamically – Yes

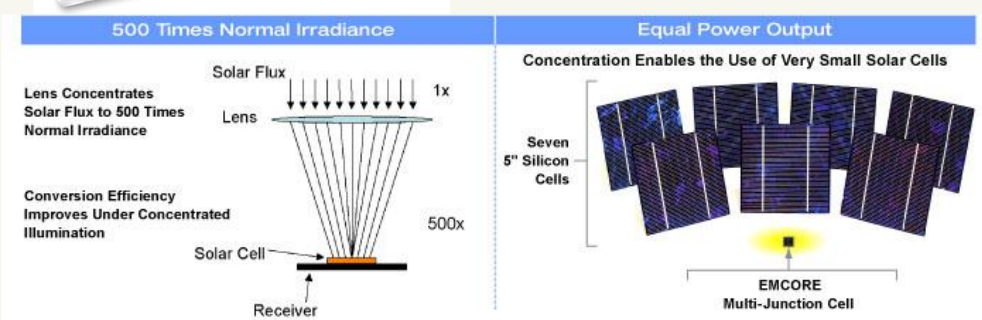
Practically speaking – probably not

Concentrating Photovoltaics









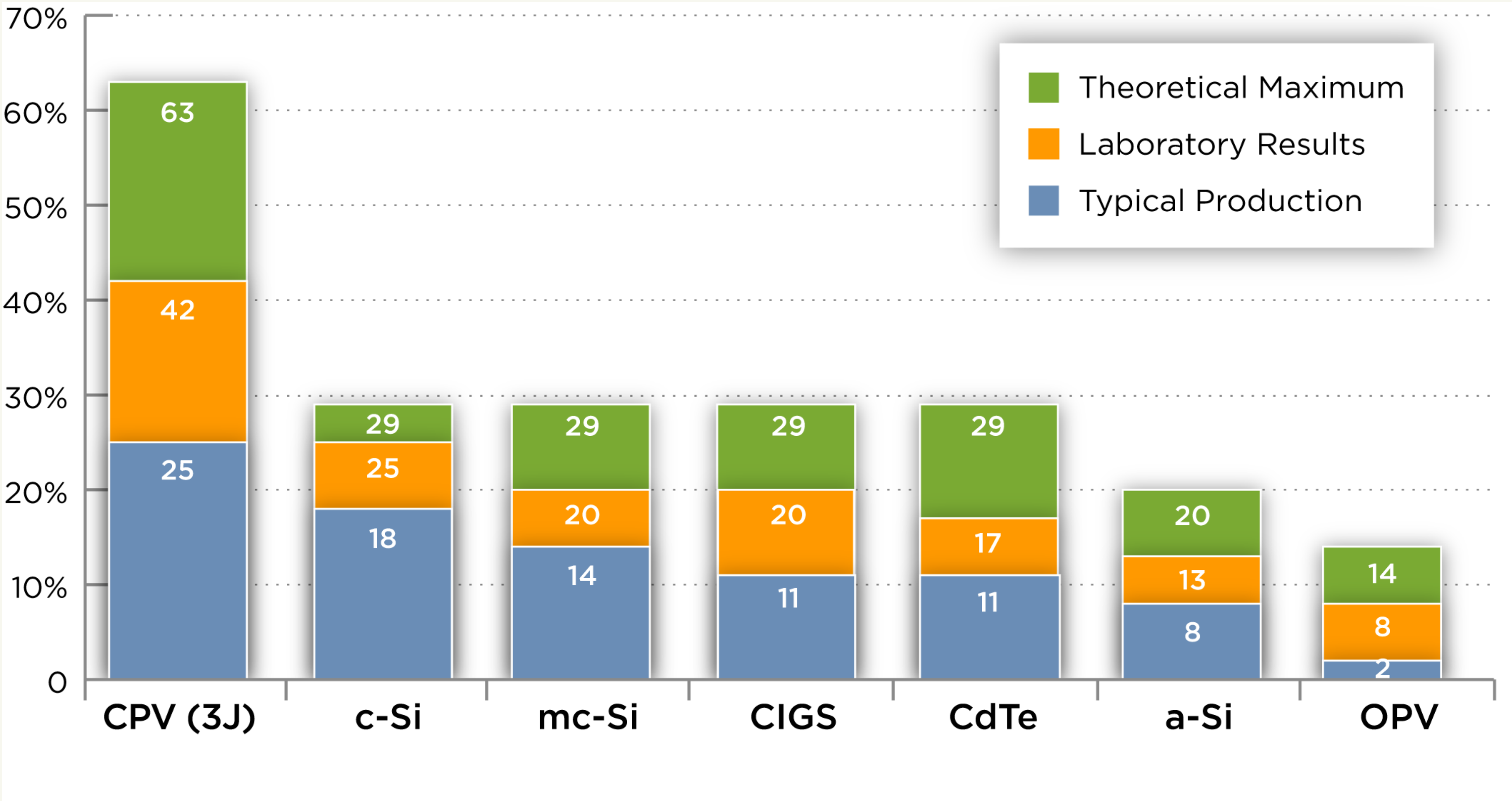
The use of reflective or refractive optics can be used to increase the intensity of light hitting the solar cell.

Solar cell efficiency increases with concentration.

Solar cell efficiency decreases with increasing temperature.

A trade does exist where concentration can result in higher system efficiency.   (There can be significant cost savings, but direct sunlight is required. System reliability becomes the paramount issue).

Efficiency Rules of Thumb



Photovoltaic Energy Systems

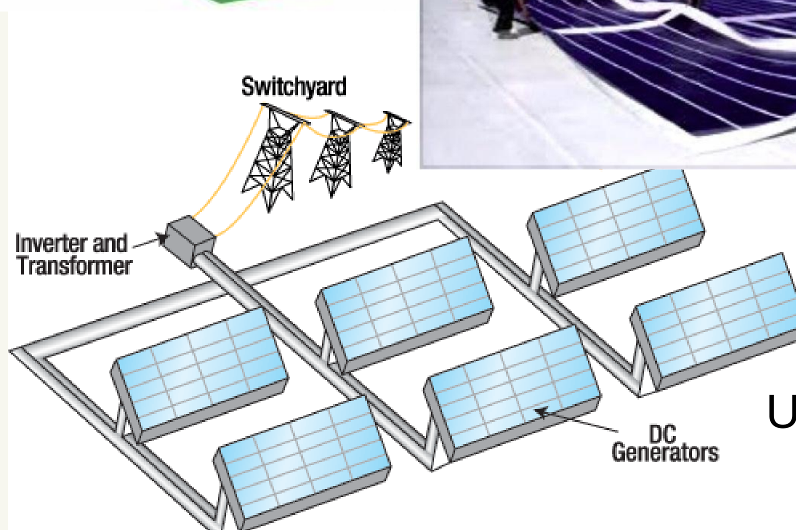
Cell

Panel or Module

Residential

Commercial

Array



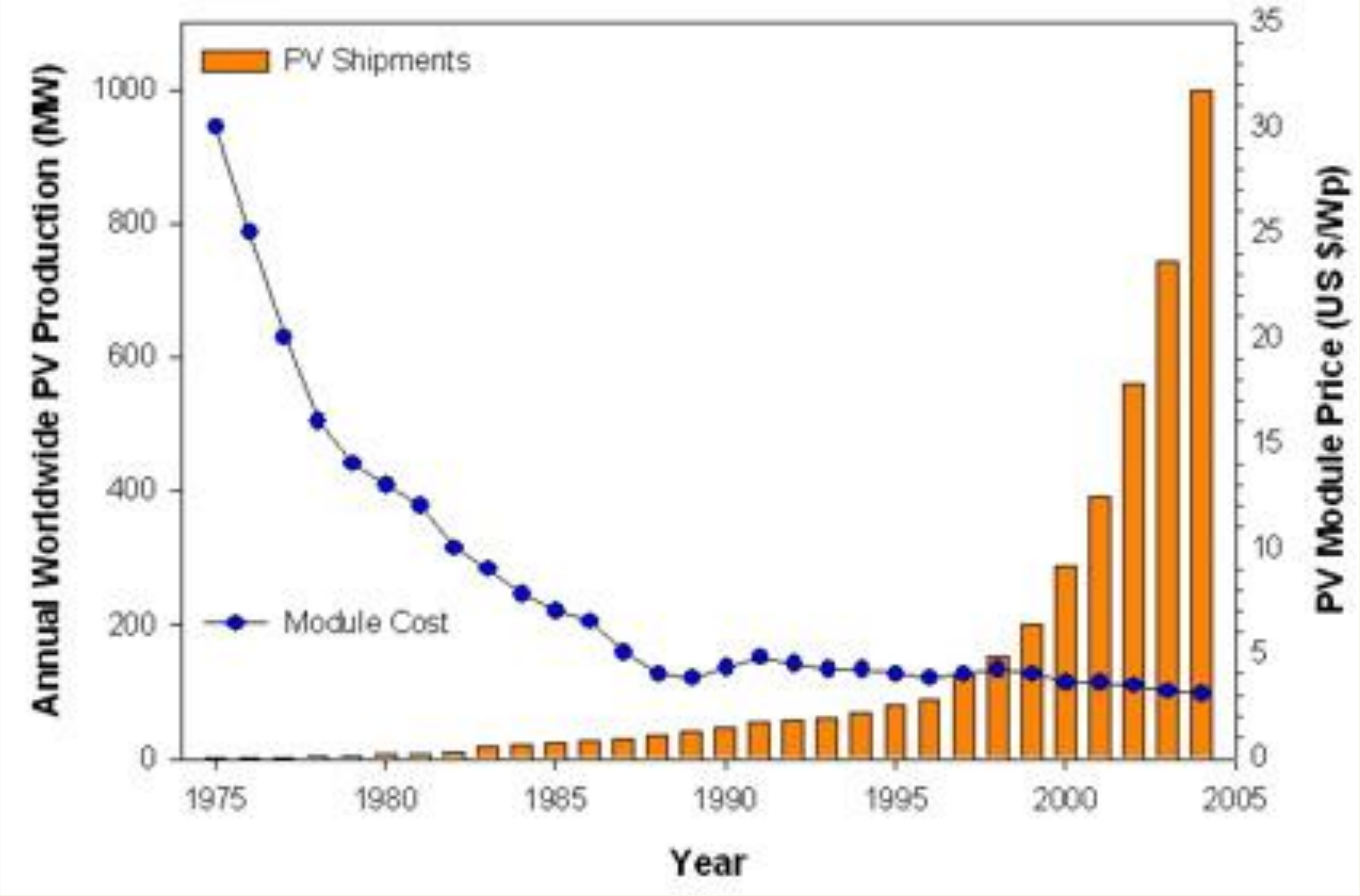
Utility Scale

Solar Energy Potential

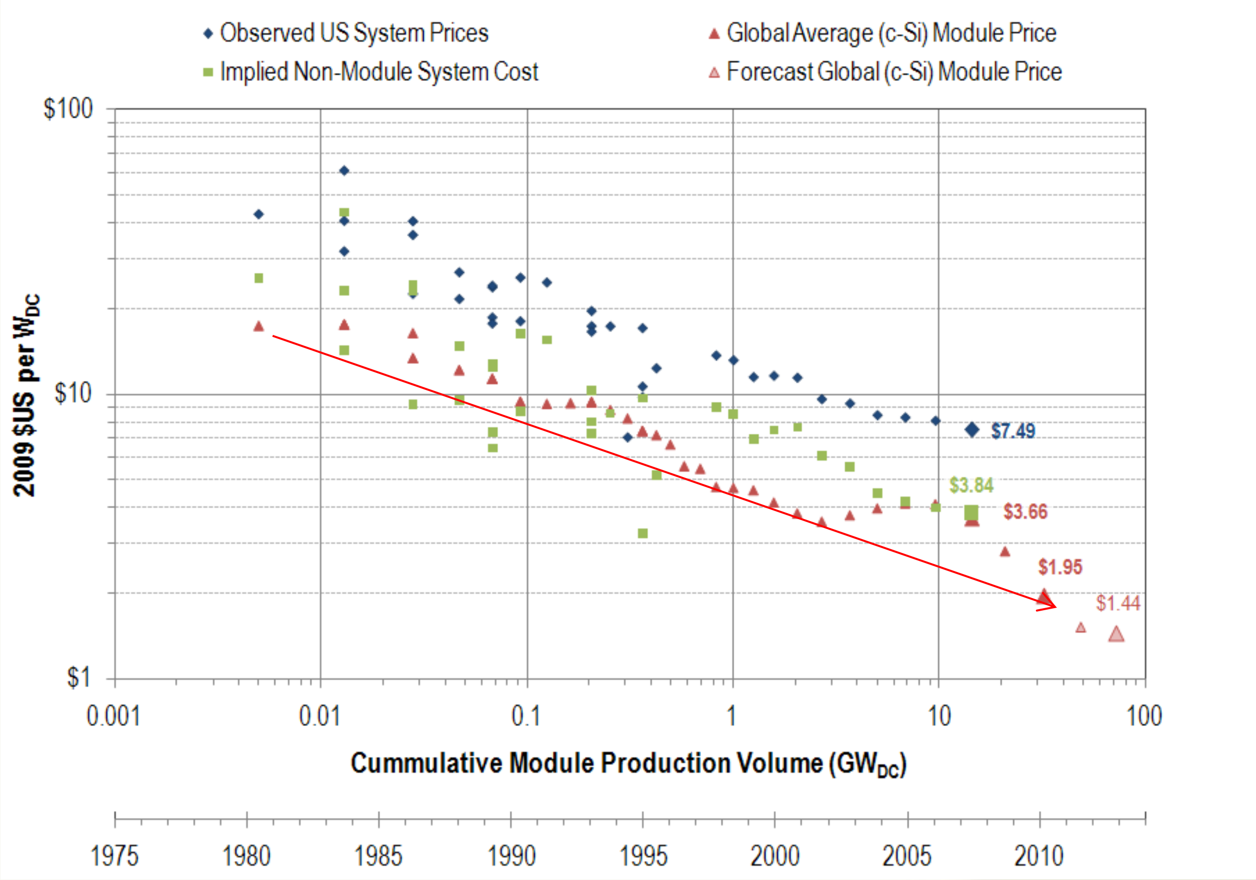
10% 20% 30% 40%

3.6 TW US Consumption

PV Costs and Production

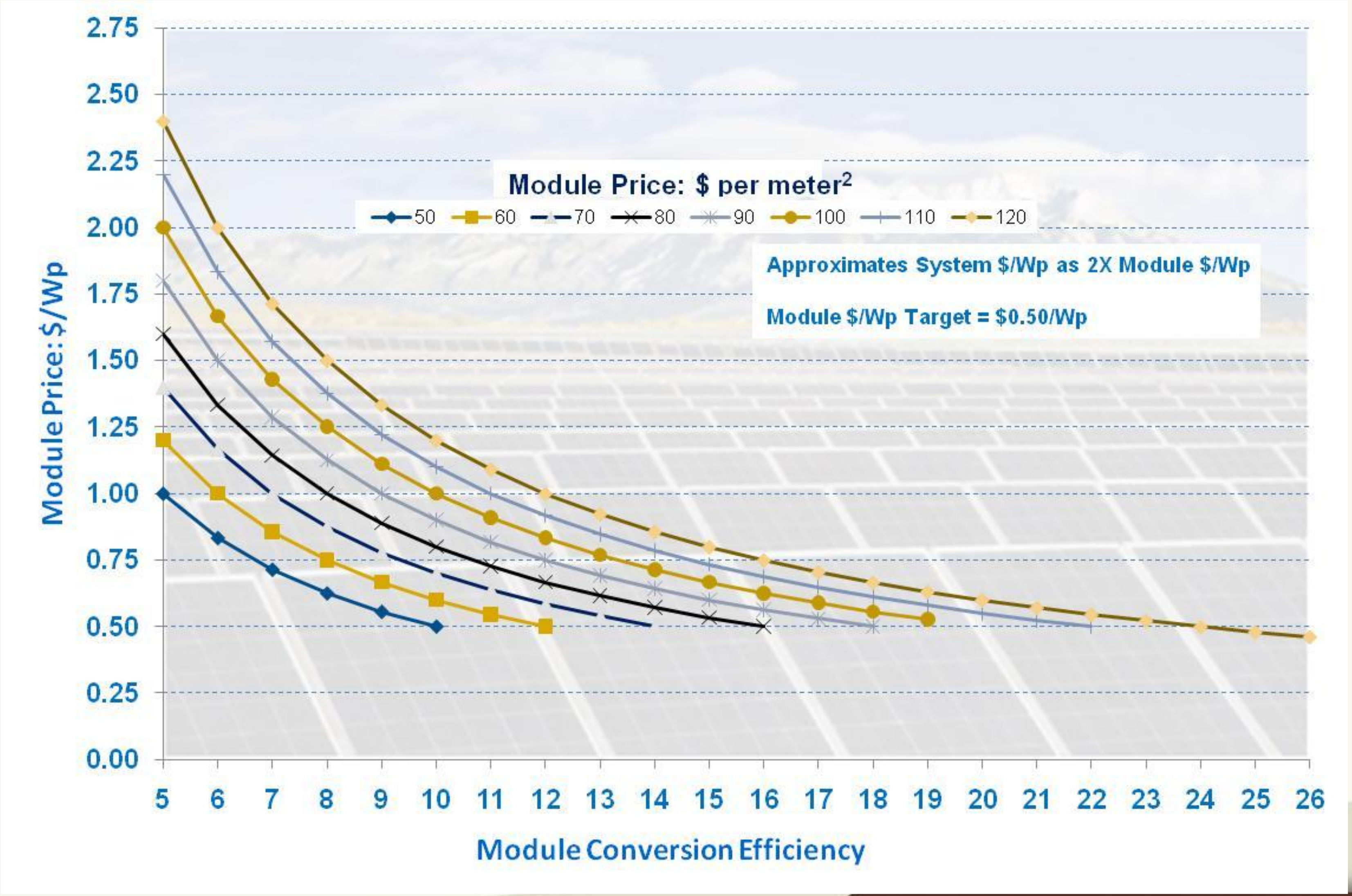


• PV prices have been in free-fall over past couple of years.
• Large differences in utility scale versus commercial rooftop and residential.

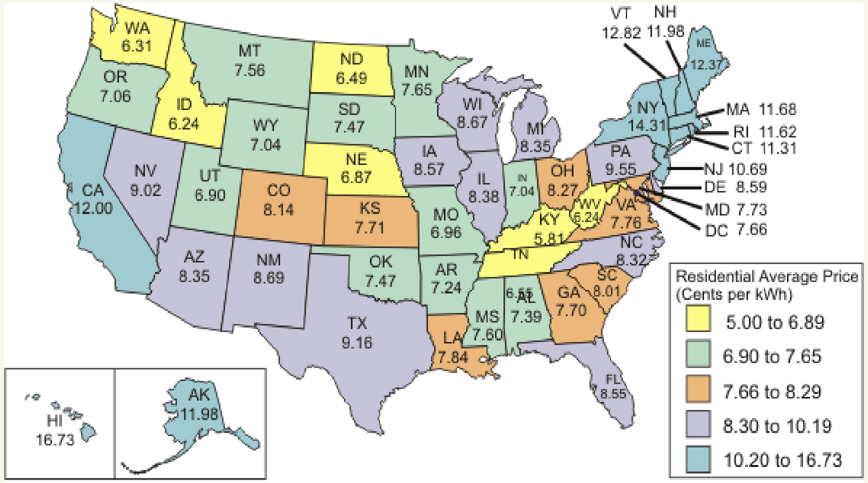


Reasons:
• Efficiency Increases
• Economies of Scale
• Increased Competition

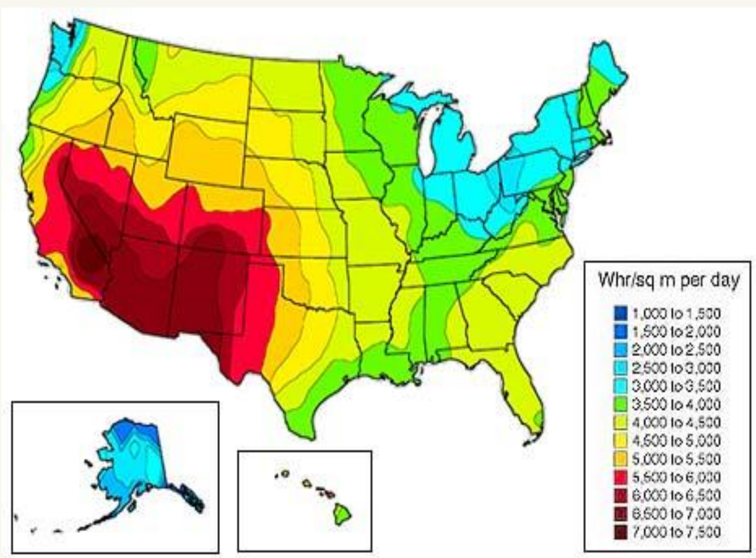
"$1/$W_p$"



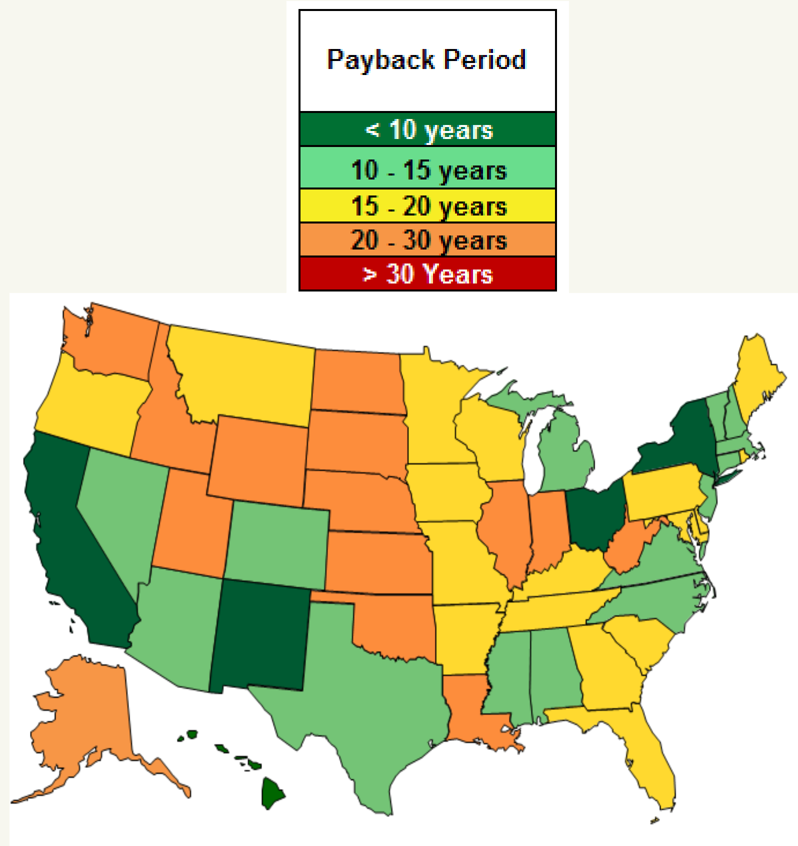
Module Price: $ per meter²
50
60
70
80
90
100
110
120
Approximates System $/Wp as 2X Module $/Wp
Module $/Wp Target = $0.50/Wp
Module Price: $/Wp
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Module Conversion Efficiency



Source: Energy Information Administration, Form EIA-861, "Annual Electric Power Industry Report."



Solar resource for a concentrating collector

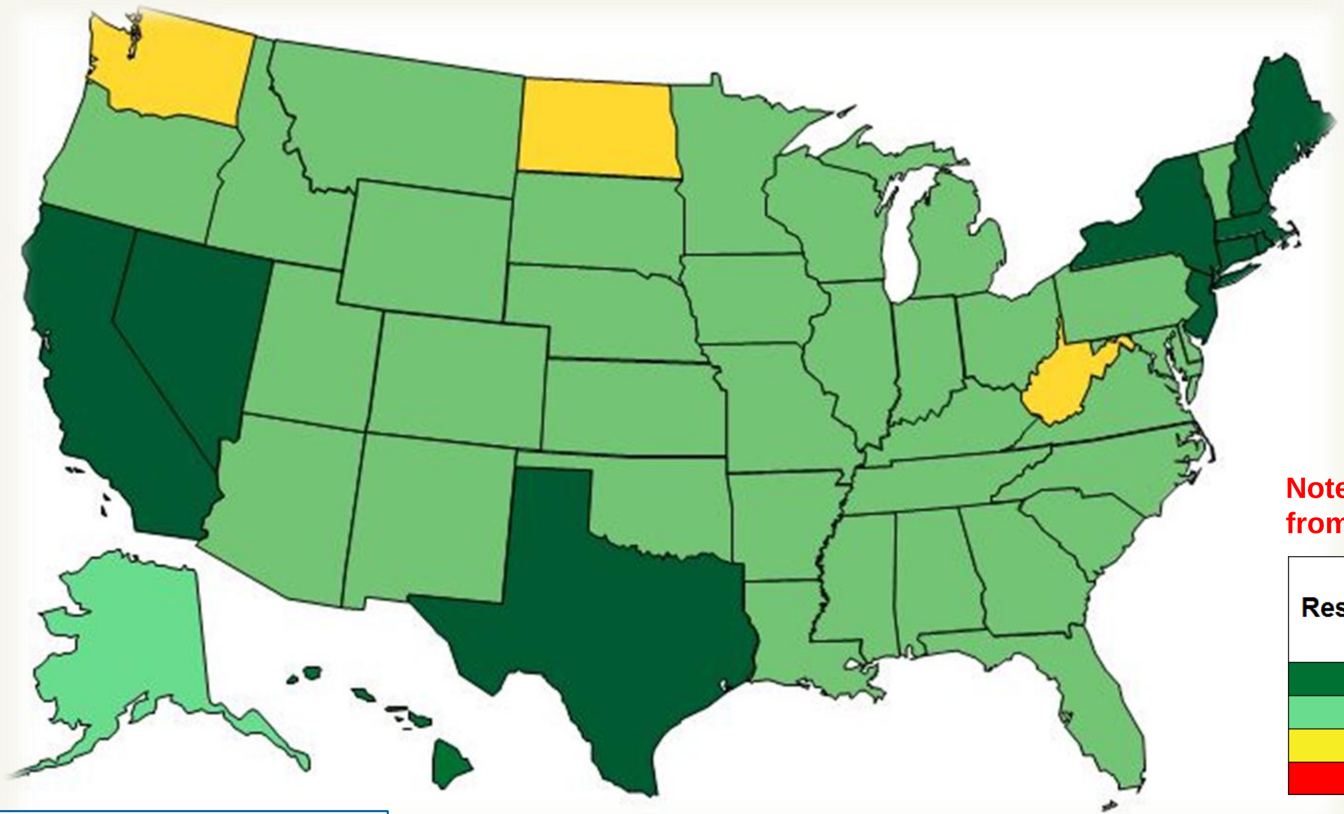


Solar Advisor Model with real inputs (i.e., South facing, 25 degree fixed tilt,4.3 kW DC system size, Local, state, and federal incentives as of October 2010, and the PV system financed as part of a 30 year home loan)

Cost Projections

$1/Watt

Cash purchase. **Unsubsidized.** State average retail electricity rates.

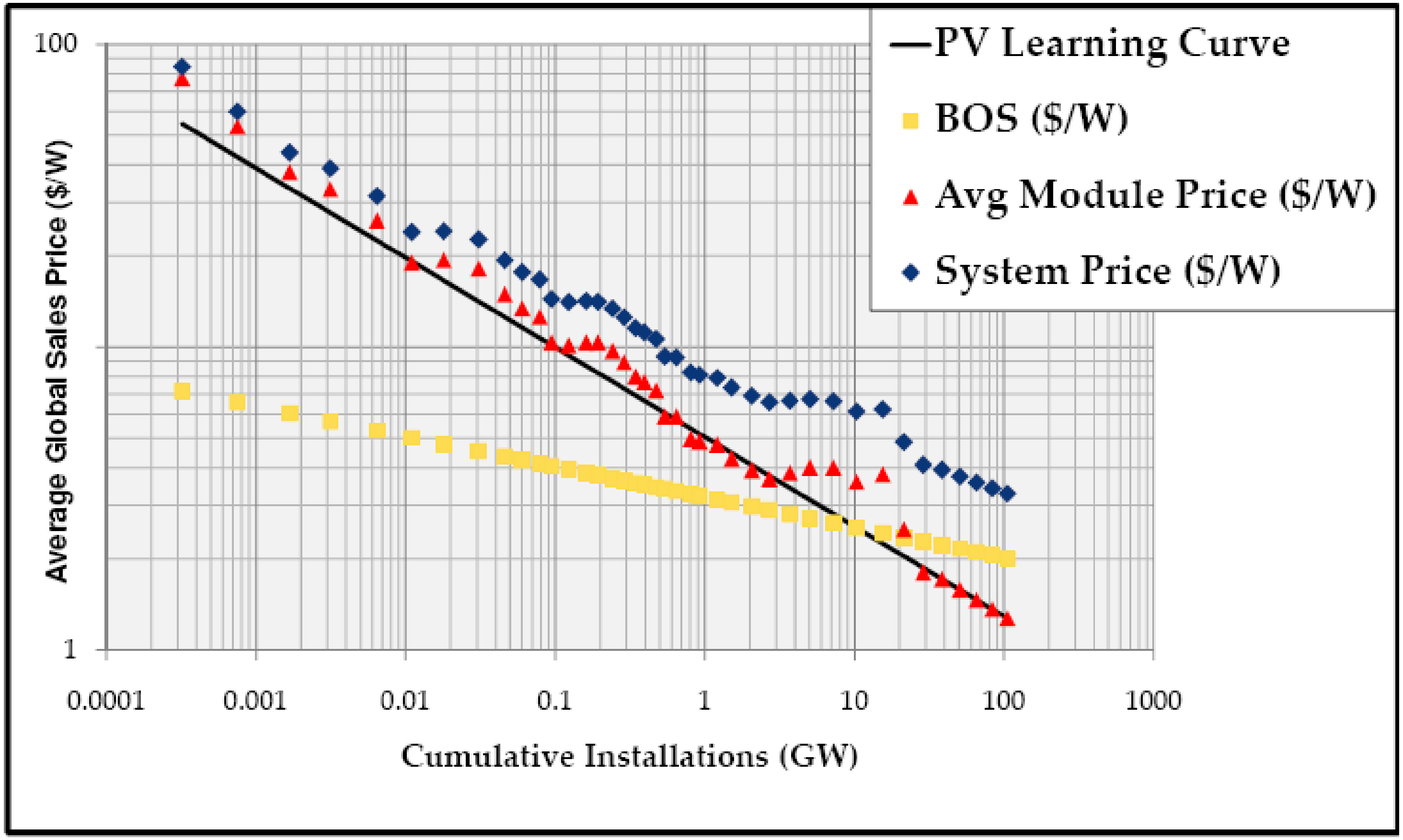


Note: Change to legend from previous slide.

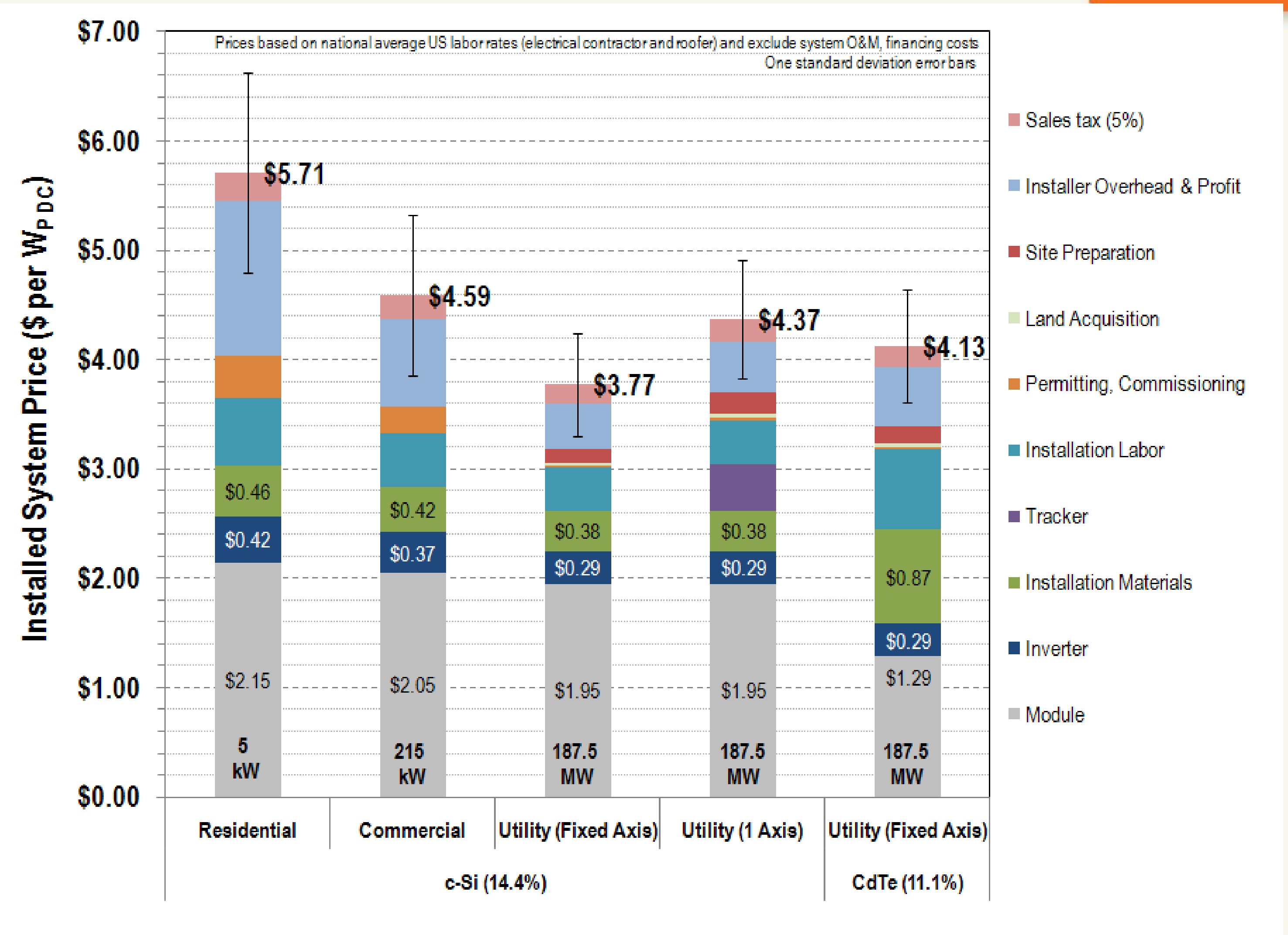
Residential Payback
< 5 years
5 - 10 years
10 - 20 years
> 20 years

Principal Analyst:
Sean Ong, NREL SEAC

Balance of Systems



Source: Navigant Consulting



- Markup on all materials (module, inverter, BoS) included in ‘Installer Overhead & Profit’
  Residential $0.89/W$_{DC}$, Commercial $0.55, Utility (fixed) $0.31
- Reflects inventory costs (interest during construction), contingency

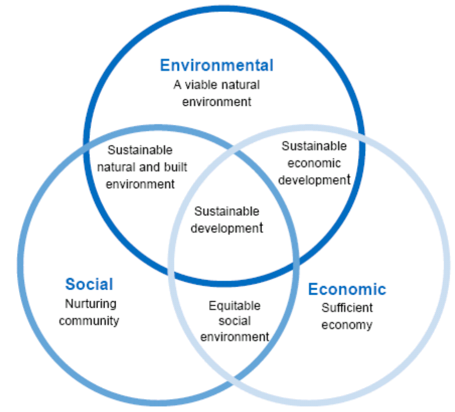
The Future

“Making predictions is very hard . . . especially about the future” – Y. Berra

Predictions

- No one size will fit all.
- Silicon will continue to dominate in the near term, but thin films and concentrated photovoltaics will gain ground.
- Don’t ever count Si out (i.e., film Si).
- New economic models will emerge.
- Policy will play a big role in whatever happens.
- PV will continue to become more sustainable.

Making PV More Sustainable



Economical
- *Raw materials use %*
- *More abundant Materials (less In, Au, Ag)*
- *Manufacturability (low temp, non-vac, R2R)*
- *Low cost flexible substrates*
- *Cell efficiency*
- *Durability*

Environmentally Safe
- *Non-toxic alternatives (less Cd, Te, Se)*
- *Aqueous based materials (less solvents)*
- *Re-use, Reman, Recycle*

Societal
- *Reliability*
- *Building Integrated (BIPV)*

All these issues grow with success.

Perhaps not big issues now, but to achieve large scale grid penetration (TW levels).

A vision of the future should include high rate, high volume manufacturing using Earth abundant and benign materials.


Thank You
Questions?

25 Year 80% BOL warrantees are the industry standard.

<1% degradation/year

Arrays installed after 2000 have been much more reliable, especially in the case of thin films.